Institution: University of East London

Unit of Assessment: 15

Title of case study: Correcting and Analysing Seismic Data

1. Summary of the impact

Accelerometer records of seismic events are routinely analysed and used in the design of buildings, bridges and other structures in order to improve their resistance to earthquakes. However, the instruments used to produce these records tend to distort the ground motion data. Moreover, ground rotations tend to tilt the instruments, making recovery of velocity pulses and displacement fling-steps problematic. Research undertaken at the University of East London has developed algorithms for decoupling the instrument response from that of the original ground motion and recovering the displacement. This helps to design better earthquake resistant structures by enabling displacement based design.

2. Underpinning research

Most legacy seismic records do not include any of the key instrument parameters required to de-couple the instrument response from the accelerometer data (as recognised by Dr Nicholas Alexander at Bristol University). Previous correction algorithms almost all required instrument parameters, and most used Fourier methods.

Recognising this as a system identification problem, research conducted at UEL by Andrew Chanerley (Senior Lecturer; joined UEL 1990) has focussed on the development of methods to overcome the lack of instrument parameters in the majority of the older (legacy) records and, indeed, the more recent digital records. More specifically, Chanerley has selected, modified and applied adaptive algorithms to address this problem by identifying the seismic instrument responses. The algorithms implemented were able to extract an inverse response at a gain of 0dB for those instruments whose cut-off frequencies were recorded, suggesting that it should be possible to achieve the same result even where cut-off frequencies and other key parameters are not known. His investigations identified QR-RLS and TLS algorithms (the latter a generalisation of least squares) as those producing the best estimates of the inverse instrument response. These tools were applied successfully to seismic data and did, indeed, allow de-coupling of the instrument response even from seismic records which did not provide the key instrument parameters normally required. The results of those applications were subsequently published in 2007 and 2008 [3, 6].

The next phase of the research at UEL involved the more complex development from the recorded acceleration of (after double-time integration) optimal estimates of velocity and displacement. These tasks have been attempted elsewhere, and some sophisticated methods already existed to achieve them. However, the novel method developed at UEL is automated, and recovered additional useful information from seismic acceleration time series. In contrast, the application of methods advocated in earlier research required a good measure of expertise; it was, moreover, apparent that relevant information additional to that which had hitherto been extracted was also embedded in the seismic data, but had not been recovered.

Chanerley addressed these issues in the next phase of the research, undertaken initially by Chanerley alone, and latterly in collaboration with Alexander (Bristol University). The principal outcome of these latter stages was the development of an automated method of recovering the low-frequency acceleration and velocity pulses and the displacement fling-step after integration. This automated method, which used the wavelet transform, has the additional advantage of being much simpler and requiring far less expertise to apply.

The principal result of the research was the development by 2010 of an algorithm using the wavelet transform to perform octave filtering to allow double-time integration [2, 4, 5]. Although the invention of the initial algorithm was a joint development, Chanerley modified it [2] to obtain the low-frequency 'fling' time history. Chanerley subsequently further modified the algorithm to extract the acceleration transients [1], whose origin lies in the gravitationally induced ground rotations, and whose presence within the recorded data is a cause of the problems in performing double-times integrations of recorded seismic acceleration time-histories.

3. References to the research

[1] Chanerley A A., Alexander, N A., Berrill, J., Avery, H., Haldorsson, B., Sigbjornsson, R (2013) 'Concerning Baseline Errors in the Form of Acceleration Transients When Recovering Displacements from Strong Motion Records Using the Undecimated Wavelet Transform',   Bulletin of the Seismological Society of America, Vol. 103, No. 1, pp 283-295 February 2013. http://dx.doi.org/10.1785/0120110352

[2] Chanerley A. A., Alexander, N A**.** (2010) 'Obtaining estimates of the low-frequency 'fling', instrument tilts and displacement time series using wavelet decomposition', *Bulletin of European Earthquake Engineering*, Vol 8, 231-255 http://dx.doi.org/10.1007/s10518-009-9150-5

[3] Chanerley A. A., Alexander, N A. (2008) 'Using a Total Least Squares approach for Seismic Correction of Accelerometer Data', *Advances in Engineering Software,* Volume 39, Issue 10, 2008 (October 20) pp 849-860 http://dx.doi.org/10.1016/j.advengsoft.2007.05.007

[4] Chanerley A. A., Alexander, N A. (2008) 'Automated Baseline Correction, Fling and Displacement Estimates from the Chi-Chi Earthquake using the Wavelet Transform' *9th International Conference on Computational Structures Technology* Athens, Greece, 2-5 September 2008 http://dx.doi.org/10.4203/ccp.88.197

[5] Berrill, J., Avery, h., Dewe, M., **Chanerley, A.**, Alexander, N. (2011) 'The Canterbury Accelerograph Network (CanNet) and some results from Sept. 2010, M7.1, Darfield Earthquake', *Proc. of 9th Pacific Conference on Earthquake Engineering*, Paper 181, 14-16th April 2011, Auckland, NZ. Available on request.

[6] Chanerley A. A., Alexander N.A. "Correcting Data from an unknown Accelerometer using Recursive Least Squares and Wavelet De-noising" *Journal of Computers and Structures,* Issue 21-22, 85 (November 2007), 1679-1692. http://dx.doi.org/10.1016/j.compstruc.2007.02.025

4. Details of the impact

The wavelet transform algorithm developed from the research outlined above uses a form of octave filtering, common in digital audio, which helps to reduce the level of expertise required for its use to that of an undergraduate student. As such, the research makes such analysis of earthquakes accessible to a wider audience, not necessarily just in academia, but in industry too. Whereas industry would previously had to turn to academic experts to obtain acceleration, velocity and displacement profiles, the new algorithm using the wavelet allows a much broader audience industry audience to access and benefit from the same information used for design.

A significant beneficial contribution made by the approach outlined above is that it returns the low-frequency acceleration and velocity pulses, as well as the displacement fling-step. Hitherto this information could not be directly obtained from the recorded accelerometer data. Instead, it had to be simulated in order to predict the seismic response of buildings from forward directivity pulses and damaging displacement fling-steps in near-fault ground motions such as inter-story drift. Moreover, the algorithm recovers information on ground rotations which may be the cause of tensional oscillations of a building during an earthquake.

This sort of additional information is useful in designing earthquake resistant structures. Civil engineers and seismologists working on earthquakes in New Zealand (in 2010) and Iceland (in 2008) used the algorithm to produce and publish the results of the acceleration, velocity and displacement profiles of those seismic events. That data elucidates the type of damage caused, the extent of the damage and its relationship to fault lines; it also helps understand the behaviour of faults and, indeed, helps find fault lines where none were known to exist. One important implication of this improved understanding is that the data can be used to improve the design of seismic resistant structures.

The research has also underpinned a commercial impact with Canterbury Seismic Instruments Ltd. (CSI), which manufactures seismographs in Christchurch, New Zealand. In 2011 the company expressed an interest in incorporating the algorithm into a commercial software package included with each seismograph sold to clients to enhance the capability and analytic accuracy - and therefore the desirability - of its products. This improved package may be sold to clients wishing to estimate parameters useful in designing seismic resistant structures. The design of the algorithm and particularly its ease of operation made it attractive to the company, since it allows its use by non-experts and produces rapid results. The commercialisation of the algorithm into a software package is under development **[a]**.

CSI was particularly impressed by the fact that the algorithm produced readings and profiles of low-frequency acceleration and velocity pulses and displacement fling-steps at the Darfield Station which aligned accurately with GPS displacement readings taken during the 2010 earthquake. The company published the wavelet-transform analysed results from data recorded by its instrument at the station [5]. The fact that the Darfield Station had seismographs manufactured by CSI at their site was, of course a bonus, since it was recorded data from their seismograph which the algorithm analysed so effectively.

The research outlined above has also led to collaboration with the University of Iceland, who have likewise expressed an interest in the software, and with whom results of their 2008 earthquake have been already published. This was of particular interest in [1], since the EERC researchers in Iceland had implemented a small aperture array of sensors which Chanerley helped embedded in the cellars of houses in Hveragerdi village during several visits to the EERC in Iceland. This array provided valuable data, from which Chanerley was able to form an argument based on evidence that the acceleration transients, which cause the baseline error in the acceleration time history, were caused by instrument tilts due to ground rotations.

Recently Chanerley has been collaborating with Professor Jack Baker's Research Group at Stanford University to ascertain and predict the impact of fling effects in near-fault ground motions. Chanerley provided acceleration and velocity fling pulses and displacement fling-steps from seismic events in Turkey, Taiwan, New Zealand, USA as well as from some physics based simulations.

5. Sources to corroborate the impact

[a] A letter from the CEO at CSI Ltd corroborating the company's desire for commercial collaboration in recognition of the benefits afforded by the performance of the algorithm is available on request. The CEO may also be contacted for further information about CSI's use of Chanerley's research.