Institution: University of Nottingham

Unit of Assessment: 15 General Engineering

Title of case study: Measuring Changes in Land and Sea Levels

1. Summary of the impact

The University of Nottingham has played a key role in shaping public policy in relation to flood risk management. Its work on novel methods of measuring and projecting changes in land and sea levels has provided new information on subsidence in the South East of the UK, leading to revised and more accurate estimates of how flood risk will develop over the course of the 21st century. These insights are being used to help protect more than a million people and billions of pounds' worth of property and are also being applied to major Europe-wide studies intended to inform civil protection agencies, disaster-management organisations, transport authorities and the wider public.

2. Underpinning research

It is well understood that the general pattern of changes in land level in the UK over the past few thousand years has been one of uplift in Scotland and subsidence in the South of England. With a shift of around 1 to 2mm per year, this means the UK is effectively "tilting". Given that the management of flood risk needs to consider the net effect of projected rises in sea level and changes in land level, it is vital to establish whether such long-term changes are representative of current movements.

Historically, research in this area has struggled to achieve high accuracy. In light of this enduring difficulty, studies by the University of Nottingham (UoN), led by Dr Richard Bingley (Associate Professor and Reader in Geodetic Surveying 1990 to present) and Dr Norman Teferle (2000 to 2010) set out to develop a novel approach that would provide a much-needed bridge in geosciences between geodetic monitoring and geology.

The origins of this work can be traced back to the 1990s, when UoN's then Institute of Engineering Surveying and Space Geodesy (now the Nottingham Geospatial Institute) first began developing techniques for using the Global Positioning System (GPS) to measure vertical land movement (VLM) at tide gauges in the UK. This led to the establishment of continuous GPS (CGPS) stations at a number of such sites. Using a time-series approach, it was shown how the method could be used in combination with an absolute gravity (AG) technique to provide site-specific estimates of VLM. Much of this work was subsequently cohered in a 2006 paper [2.1].

Later research used CGPS measurements to obtain estimates of crustal velocities – the speed and direction of movements of the Earth's crust – in Great Britain. These were compared with predictions from a model of glacial isostatic adjustment (GIA) – the rise of land masses depressed by the weight of ice-sheets during the last Ice Age – to reveal a high correlation of observed and predicted values. This led to the conclusion, presented in a 2008 paper, that GIA is the dominant geodynamic process contributing to VLM [2.2].

In recognition of its expertise in CGPS, UoN was invited by Defra and the Environment Agency to lead two major studies, one national and one regional that drew and expanded on its work. Conducted from 2003 to 2007, these projects employed a combination of CGPS, AG and a third monitoring technique, Persistent Scatterer Interferometry (PSI), to investigate how best to combine all three to obtain reliable estimates of current changes in land level.

For the national study [2.3, 2.5], which involved UoN and the NERC Proudman Oceanographic Laboratory (POL), CGPS stations were established at 10 tide gauges around the British coast, with AG measurements also made at three of these. For the regional study [2.4, 2.5, 2.6], which involved UoN, POL, the British Geological Survey and satellite-mapping specialist Nigel Press Associates Ltd, episodic GPS (EGPS) data from a network of stations and PSI data from hundreds

of thousands of persistent scatterer points were analysed to investigate changes in land level in the Thames Estuary region. The regional study represented the first attempt to directly measure current changes in land level by integrating satellite-based remote-sensing techniques with GPS and AG.

Combining CGPS and AG estimates from the national study with EGPS and PSI estimates from its regional counterpart showed land subsidence in the South East to be 0.9 to 2.1mm per year rather than the previously assumed 0.8mm per year. In tandem with a projected rise in sea level of 3.1mm per year, this suggested that by the year 2100 the net increase in sea and land level changes would be 52cm – not, as previously believed, 39cm.

3. References to the research

References (*Items marked with an asterisk indicate 3 most significant papers);*

2.1 Teferle, F.N., Bingley, R.M., Williams, S.D.P., Baker, T.F. and Dodson, A.H., 2006, Using Continuous GPS and Absolute Gravity to Separate Vertical Land Movements and Changes in Sea Level at Tide Gauges in the UK, *Philosophical Transactions of the Royal Society, Series A: Mathematical, Physical and Engineering Sciences*, 364, 971-930, doi:10.1098/rsta.2006.1746

2.2 *Bradley, S., Milne, G.A., Teferle, F.N., Bingley, R.M. and Orliac, E.J., 2008, Glacial Isostatic Adjustment of the British Isles: New Constraints from GPS Measurements of Crustal Motion, *Geophysical Journal International*, 178(1), 14-22, doi:10.1111/j.1365-246x.2008.04033.x

2.3 *Teferle, F.N., Bingley, R.M., Orliac, E.J., Williams, S.D.P., Woodworth, P.L., McLaughlin, D., Baker, T.F., Shennan, I., Milne, G.A., Bradley, S.L. and Hansen, D.N., 2009, Crustal Motions in Great Britain: Evidence from Continuous GPS, Absolute Gravity and Holocene Sea Level Data, *Geophysical Journal International*, 178(1), 23-46, doi:10.1111/j.1365-246X.2009.04185.

2.4 *Bingley, R.M., Teferle, F.N., Orliac, E.J., Dodson, A.H., Williams, S.D.P., Blackman, D.L., Baker, T.F., Riedmann, M., Haynes, M., Press, N., Aldiss, D.T., Burke, H.C., Chacksfield, B.C., Tragheim, D., Tarrant, O., Tanner, S., Reeder, T., Lavery, S., Meadowcroft, I., Surendran, S., Goudie, J.R. and Richardson, D., 2008, The Measurement of Current Changes in Land Levels as Input to Long-Term Planning for Flood Risk Management Along the Thames Estuary, *Journal of Flood Risk Management*, Volume 1, Issue 3, 162-172, doi:10.1111/j.1753-318X.2008.00018.x, copy available on request.

2.5 Bingley, R.M., Teferle, F.N., Orliac, E.J., Dodson, A.H., Williams, S.D.P., Blackman, D.L., Baker, T.F., Riedmann, M., Haynes, M., Aldiss, D.T., Burke, H.C., Chacksfield, B.C. and Tragheim, D., 2007, Absolute Fixing of Tide Gauge Benchmarks and Land Levels: Measuring Changes in Land and Sea Levels Around the Coast of Great Britain and Along the Thames Estuary and River Thames Using GPS, Absolute Gravimetry, Persistent Scatterer Interferometry and Tide Gauges, DEFRA/Environment Agency Joint R&D FCERM Programme, R&D Technical Report FD2319/TR, PB Number 12643. Pdf available on request.

2.6 Aldiss, D.T., Burke, H.C., Chacksfield, B.C., Bingley, R.M., Teferle, F.N., Williams, S.D.P., Blackman, D.L., Burren, R. and Press, N., 2013, Geological Interpretation of Current Subsidence and Uplift in the London area, UK, as shown by High Precision Satellite-based Surveying *Proceedings of the Geologists' Association*, DOI 10.1016/j.pgeola.2013.07.003.

Grants;

Joint Defra/Environment Agency Flood and Coastal Erosion Risk Management R&D Programme FD2319, 2003-2007, £320,000 (Bingley)
Environment Agency Thames Estuary 2100 project EP20, 2003-2007, £324,000 (Bingley)
Further Environment Agency funding HOWM0000119 22869, 2009-2010, £216,000 (Bingley)

4. Details of the impact

By providing an "engineering solution" to bridge the gap in geosciences between geodetic monitoring and geology, UoN has played a significant role in influencing public policy in relation to flood risk management. The insights derived from its work are helping to protect more than a million residents and billions of pounds' worth of property in the UK, as well as increasingly being applied in major projects spanning Europe.

The national study that saw CGPS stations established at 10 tide gauges around the British coast provided direct input to the UK Government's Climate Impacts Programme report (UKCP09) [4.1], published in June 2009 as validation of the UK's adopted map of vertical land movement (VLM). The report set out to "provide... a set of scenarios that may be used to assess how vulnerable particular sites or sectors are to future climate change" [4.1], noting: "Good estimates of what could happen in the future marine environment and how this might impact issues as diverse as flooding, habitat conservation and food safety are becoming of increasing importance for adaptation and risk planning" [4.1]. Citing all of UoN's underpinning research, the document acknowledged the value of new techniques "to produce a comprehensive study of spatial patterns of vertical velocity measurements" [4.1] and included a detailed explanation of the use of CGPS in an annex devoted to the various measurement methods employed [4.2, 4.3].

This national study fed into its regional counterpart, which made an important contribution to the Environment Agency's Thames Estuary 2100 (TE2100) project. The first major flood risk management scheme in the UK to put climate-change adaptation at its core, TE2100 sets out how 1.25M people and £200Bn worth of property will continue to be protected from increasing tidal flood risk through to the end of the century.

The significant revision in projections of the net effect of changes in sea and land levels by the year 2100 is highlighted in the Environment Agency's TE2100 Plan Consultation Document [4.4], which was published in April 2009. Chapter 4 (page 20) notes: "Land levels in the south-east of England are slowly sinking as an after-effect of the last Ice Age, when the northern part of the country was covered in a mass of ice. The result of this, quantified through our studies, is that the land level is going down relative to sea levels by around 1.5mm per year." This increased accuracy has given the Environment Agency much greater confidence in terms of planned expenditure – allowing it to appreciate, for example, that measures that were previously thought potentially necessary in the first half of the century may be safely deferred until the second half. Acknowledging UoN's contribution, Owen Tarrant, an Environment Agency Principal Scientist, has remarked: "Predicting and then monitoring the rate of net sea-level rise [SLR] over the coming century is the cornerstone of our approach to adaptive flood risk management in the Thames Estuary, as both the magnitude and rate of SLR dictate what type of innovation we may have to make and, perhaps more importantly, when. Planners and investors can now be reassured that there is an effective plan to manage flood risk today and for future generations." [4.5].

A major European Space Agency (ESA) Global Monitoring for Environment and Security (GMES) project, Terrafirma [4.6], has also drawn on the UoN-led Thames Estuary study. Terrafirma uses satellite radar data acquired from 800km above the Earth's surface, in conjunction with expert interpretation by national geoscience organisations, to support risk assessment and mitigation in all 27 EU member states. The project considered 40 test sites around Europe, with London one of only three that were advanced to the stage of developing a geologically modelled product to explain the changes in land level. In June 2009, ESA subsequently produced the Terrafirma Atlas [4.7], a compendium of the results obtained during the project, in which Dr Don Aldiss, the British Geological Survey's Principal Mapping Geologist, said of the London findings: "The geological interpretation of the GPS-aligned PSI data... was more successful than we could have hoped. It yielded some entirely unforeseen results, which we could not have obtained using any other technique." [4.7].

The Thames Estuary study has subsequently also been used to inform EU FP7-funded GMES downstream projects such as SubCoast (2009-2011), which aims to map the potential for ground

deformation along the entire EU coastline, and PanGeo (2011-2014), which focuses on the interpretation of geohazards. With these projects increasingly providing freely available information online, the wider European public are benefiting from the insights that first emerged from the original Thames Estuary research. Professor Stuart Marsh, ex Head of Spatial Geoscience at the British Geological Survey (Professor of Geospatial Engineering, University of Nottingham since October 2013), has said: "The 'London result' has proved to be a landmark. It continues to be a demonstration of the potential for similar measurements and modelling in other low-lying, coastal cities/areas around the world." [4.8]

5. Sources to corroborate the impact

4.1 Lowe, JA, Howard, T, Pardaens, A, Tinker, J, Holt, J, Wakelin, S, Milne, G, Leake, J, Wolf, J, Horsburgh, K, Reeder, T, Jenkins, G, Ridley, J, Dye, S, and Bradley, S (2009): *UKCP09 UK Climate Projections Science Report: Marine and Coastal Projections,* Met Office Hadley Centre, Exeter, UK http://ukclimateprojections.defra.gov.uk/media.jsp?mediaid=87906&filetype=pdf (pages 5 and 29 of main text)

4.2 Lowe, JA, Howard, T, Pardaens, A, Tinker, J, Holt, J, Wakelin, S, Milne, G, Leake, J, Wolf, J, Horsburgh, K, Reeder, T, Jenkins, G, Ridley, J, Dye, S, and Bradley, S (2009): *UKCP09 UK Climate Projections Science Report: Marine and Coastal Projections,* Met Office Hadley Centre, Exeter, UK http://ukclimateprojections.defra.gov.uk/media.jsp?mediaid=87897&filetype=pdf (Annex)

4.3 Jason Lowe, Head of Knowledge Transfer and Mitigation Advice, Met Office

4.4 Thames Estuary TE2100 Plan Consultation Document (published April 2009) http://www.medway.gov.uk/pdf/TE2100_PlanConsultationDocumentExclZones6-7.pdf (see page 20)

4.5 Owen Tarrant, Principal Scientist, Environment Agency

4.6 Terrafirma, European Space Agency (ESA) Global Monitoring for Environment and Security (GMES) project, http://www.terrafirma.eu.com/

4.7 Terrafirma Atlas http://esamultimedia.esa.int/multimedia/publications/TerrafirmaAtlas/pageflip.html (pages 66 - 67 and 61)

4.8 Professor Stuart Marsh, Head of Geoscience Technologies, British Geological Survey (until September 2013). Professor of Geospatial Engineering, University of Nottingham (October 2013 to current).