

**Understanding the role of wave impact in driving coastal rock cliff evolution, Yorkshire****Dr Nick Rosser & Emma Norman**

Institute of Hazard, Risk &amp; Resilience, Durham University, South Road, Durham DH1 3LE

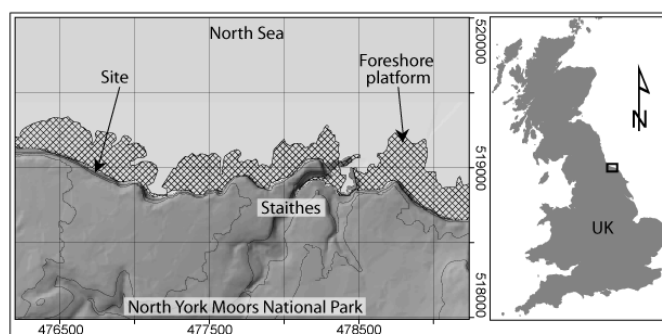
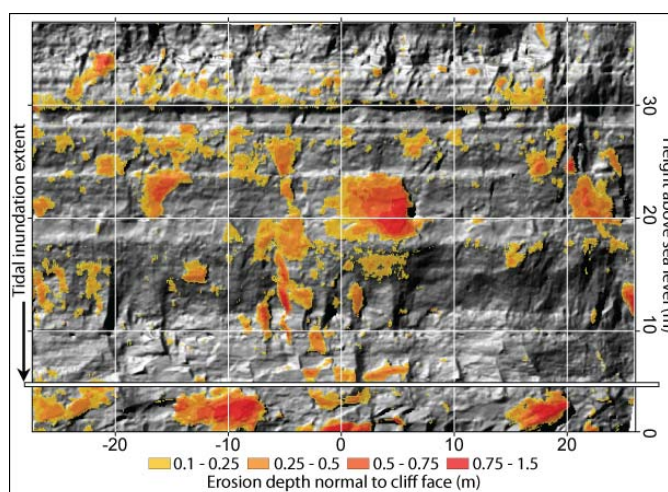
Tel: 00 44 191 334 1918; Fax 00 44 191 334 1801; e-mail: [n.j.rosser@dur.ac.uk](mailto:n.j.rosser@dur.ac.uk)**Abstract**

The energy delivered to hard rock cliffs from the sea is acknowledged to be a key control on cliff erosion, via hydraulic and mechanical processes. Although direct wave attack amplified by shoaling, foreshore wave set-up and reflection is widely acknowledged to be the dominant driver of coastal cliff erosion, the energy delivered and its variation through time and in relation to cliff change have not yet been quantified. Previous studies have relied upon modeling the transformation of offshore wave-buoy data, which overlooks near-shore and foreshore modification of the wave climate.

The study of microseismic ground motion of coastal cliffs potentially provides a valuable method to directly examine energy delivery to the coast. NERC GEF loan #879, and its extension, provided 10 broadband seismometers, which were installed in an array on the top of a coastal cliff, which has an existing extensive array of monitoring equipment including weather, 3D cliff change, laser-based water-surface measurement and a rock-face monitoring system. Using ground motion velocity as a proxy for energy delivery has enabled the interactions between the cliff change and environmental conditions to be explored. Data has allowed us to question existing models of cliff erosion, in particular to assumptions associated with using far-field data, or simplified models such as cliff inundation durations, as adequate ways of describing the changes observed.

**Background**

The cliffs of the North York Moors National Park [Figure 1] are comprised of complex c. 90 m high near-vertical rock faces cut in near-horizontally interbedded Lower Jurassic bitumens shales, mudstones and limestones, capped with c. 20 m of fine grained sandstone and glacial till. Sites are c. 20 km south of the fulcrum of zero post-glacial isostatic rebound in the UK, providing constraint on the influence of relative sea level on coastal erosion rates during the Quaternary. The cliffs are fronted by an extensive low angle [ $< 2^\circ$ ] essentially sediment free foreshore platform that, at low-tides, extends c. 300 m offshore. One hypothesis suggests that the present foreshore extent reflects the net transgression of the cliff since the last glacial maximum. Platform length derives a first-order estimate of long-term average cliff retreat of c.  $0.02 - 0.03 \text{ m yr}^{-1}$ . The coastline varies from crenulous coves separated by headlands, to embayments that often coincide with coastal fault exposures. The coast experiences two daily tides that cycle between spring and neap highs over a c. 6 m range, inundating 3 m of the cliff toe, the vertical reach of which is enhanced during storms and high swells from

**Figure 1:** Location map**Figure 2.** Cliff erosion monitored using terrestrial laser scanning

the open aspect to the North Sea; the coast remains sheltered from prevailing south-westerlies. Analysis of historic maps and photographs derives an average annual retreat rate of  $0.05 \text{ m yr}^{-1}$  during the last century. Notably, this rate falls beneath the mapping precision achievable at this scale and interval. A visitor to these cliffs will witness an almost constant spalling of small rock fragments, interspersed with occasional larger failures, evidencing an active rock face.

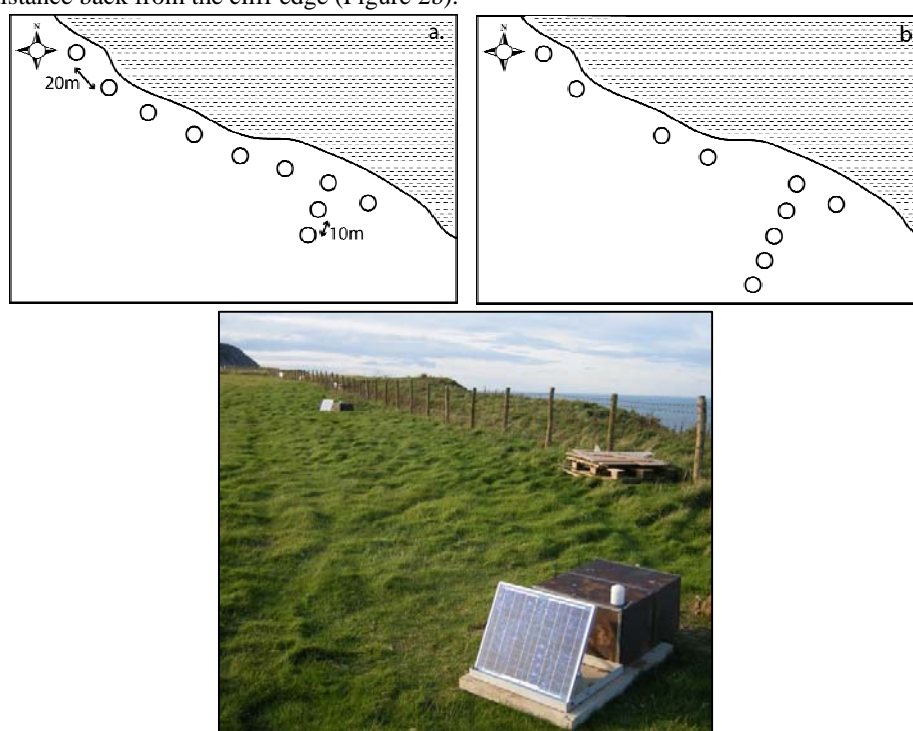
Cliff erosion at this field site has been monitored for 5 years previous to this study, using terrestrial laser scanning, and has provided a detailed insight into the nature of cliff change (Figure 2). This assessment of erosion shows the significance of material loss from both the dry cliff face, in addition to that in the inundated zone at the toe.

Objectives of the research are:

- O1: To quantify the cliff ground motion response to wave, tide and wind conditions across a range temporal scales;
- O2: To constrain the attenuation of marine energy with distance from the cliff edge;
- O3: To assess the effectiveness of tidal inundation duration in determining the distribution of energy delivery;
- O4: To produce a new conceptual model of coastal cliff change behavior based on the quantified relationships observed by the study.

### Data quality and collection

During the two year loan the 10 Guralp 6TD broadband seismometers were set-up as 2 different arrays upon the cliff top (Figure 3). A mounting system for batteries, cabling and the solar panels was designed to minimize the visual impact of the installation in the National Park as requested by the land-owner. Initially the design of the array was to examine spatial variation of energy delivery across the cliff face (Figure 2a), and secondly the attenuation of marine energy with distance back from the cliff edge (Figure 2b).

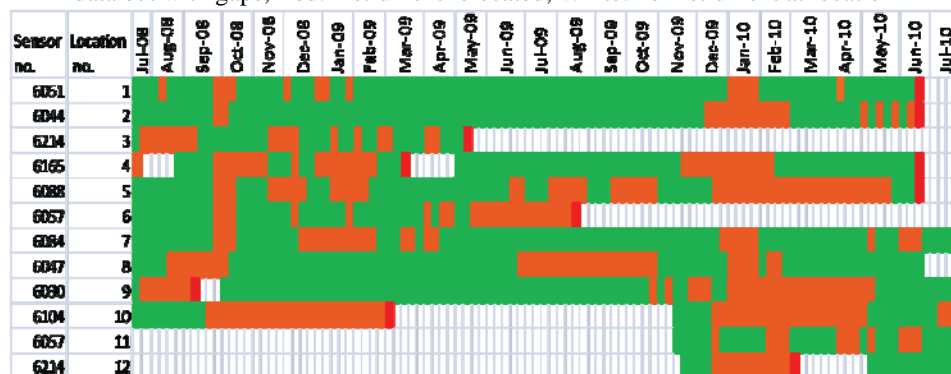


**Figure 3.** Seismometer array design, the locations of the initial array (a) and the second distribution of instruments (b). The stippled area represents the sea. The photograph below illustrates the final design for housing the battery, cabling, GPS and for protecting the seismometer buried beneath.

The seismometers sampled at 100 Hz so as to ensure the full range of frequencies associated with the environmental sources of interest were captured, which required a monthly download of data. The seismometers were installed at approximately 0.8 m depth into the glacial till, bedded into sand, as recommended by Seis-UK (Figure 3). Concurrent data of tide, wave and wind conditions were also collected to explore their relationships with energy delivery to the cliff. Met Office wind speed and direction data collected at Loftus (approximately 3km north west of the site), UK National Tide Gauge Network data from Whitby (approximately 20km south east) and Cefas WaveNet wave buoy data from Tees (approximately 20km north west) were used. Erosion activity at the cliff was monitored at monthly resolution using a Trimble GS200 terrestrial laser scanner throughout the monitoring period however analysis of this dataset is ongoing.

The array was installed and maintained to collect a continuous stream of data for the 2 year monitoring period. Data loss was experienced principally as a result of water penetration via connectors into the seismometers, battery problems in winter, in addition to significant problems from cables being eaten by vermin. Our revised design for the installation of the instruments overcame many of these issues. Table 1 shows the continuity of the data collected during the project.

**Table 1.** Ghant chart showing the deployment of the 10 Guralp 6TD seismometers. Green: data collected; Orange: data but with gaps; Red: instrument relocated; White: no instrument at location



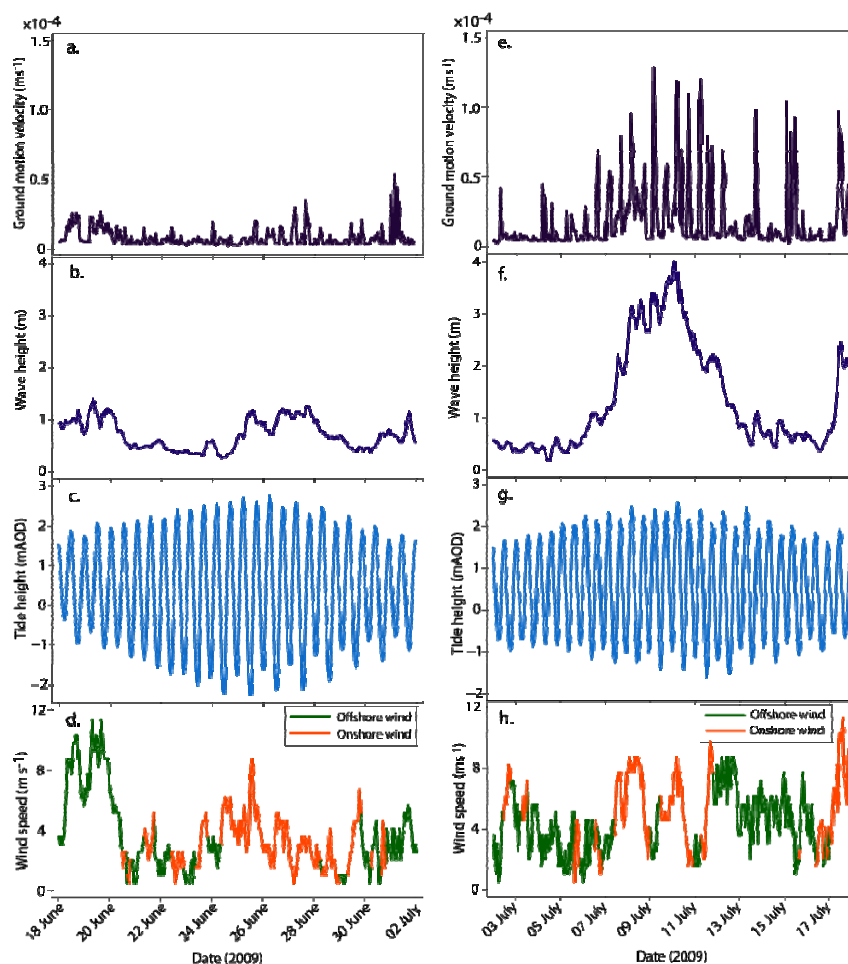
### Data processing and modelling

The data has been examined in the time and frequency domains in order to fully explore the marine and wind features within the ground motion data. Data processing to date has focused upon differentiating the influence of winds, wave and tides through time, examining an apparent asymmetry in seismic response during rising and falling tides, identifying individual wave impacts, and assessing tidal cycle variations in cliff velocity. Critically, our analysis is concerned primarily with the type of background signal which much seismic software filters out, so analysis of the time-series collected has proved to be quite unconventional for seismic data. The resolution at which the seismic data has been sub-sampled and analyzed is determined by that of the concurrent environmental data, with the full 2-year dataset examined using hourly maximum or average (medians, modes & means). Time-series data is processed and analyzed using code scripted in Matlab and Stata software, using standard time-series routines such as wavelet analysis. In exploring the frequency spectrum of the 2-year dataset we have derived hourly average power spectral density, calculated using PQLX, and then analyzed further using Matlab. All data has been archived with SEIS-UK.

### Interpretation to date and Preliminary findings

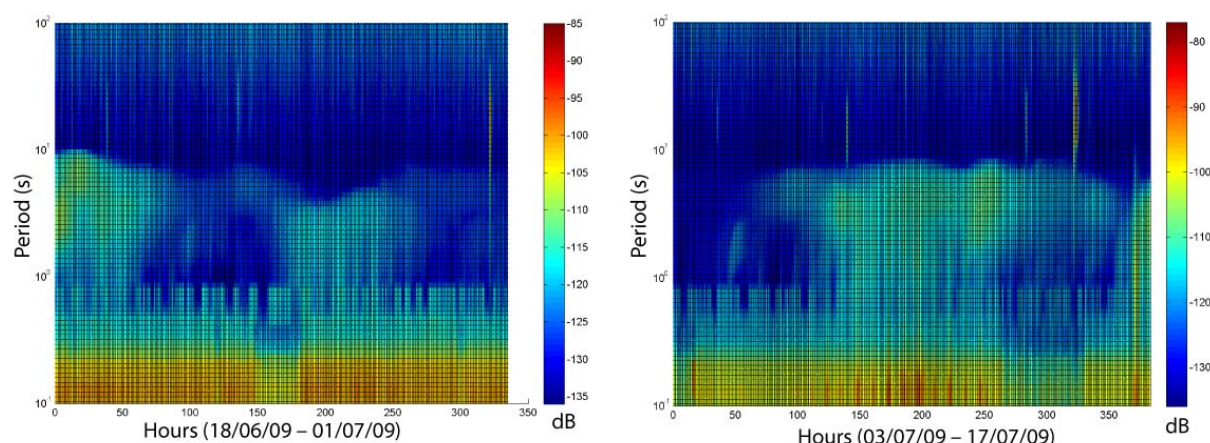
Analysis of the time series data demonstrates ground motion velocity to be highly sensitive to both marine (wave and tide) and wind conditions (Figure 4), which suggests the potential for using microseismics as a proxy for wave energy delivery. The performance of the 6-TDs appears adequate for this application, although at long periods the signal approaches the noise floor of the instrument. Figure 4 shows two periods of data, each covering two-week tidal cycles (neap tide to spring tide to neap tide) and the associated ground motion velocity, wave and wind

conditions. Despite the similar tide conditions (heights) during the two periods, the data in Figure 4a shows a period of relatively low ground motion velocity compared to that in Figure 4e. When wave height conditions during the two periods are assessed (Figures 4a & b and 4f & g) it is clear that wave height during high tides significantly influences ground motion velocity. During the first period (Figure 4a and b) waves over 1 m result in small peaks in ground motion velocity and during the second period (Figure 4e and f) the much higher waves, extending from 1 m to 4 m, result in larger peak values of ground motion velocity. Peak velocities occur during high tides, with high waves, rather than dissipating significant energy during shoaling upon the foreshore, as other authors have previously suggested. Frequencies more widely attributed to wind loading – over and above the influence of wind on wave climate – also appears to deliver significant energy to the cliff, affecting ground motion velocity, in Figure 4a and d. Peaks in velocity at the start of the period coincide with high wind speeds of over  $8 \text{ ms}^{-1}$  and in Figure 4e and h we see high ground motion velocity occurring with onshore winds also over  $8 \text{ ms}^{-1}$ . To quantify the significance of wind energy delivery and the relative contributions of all three environmental forcing mechanisms we are building a regression model of the ground motion velocity against combined tide, wave and wind conditions.



**Figure 4:** Two-week tidal cycle of time series data for a-d) 28 June – 01 July 2009 a) hourly maximum ground motion velocity; b) hourly mean wave height; c) hourly mean tide height and d) hourly mean wind speed for onshore (orange) and offshore (green) wind directions; e-h) covers the period 02 July – 17 July 2009 e) hourly maximum ground motion velocity; f) hourly mean wave height; g) hourly mean tide height and h) hourly mean wind speed for onshore (orange) and offshore (green) wind directions.





**Figure 5.** PSD plots for 28 June – 02 July 2009 (left) and 03 July – 17 July 2009 (right).

Analysis of the seismic data in the frequency domain reveals the microseismic response across frequencies between 0.01 - 10hz (Figure 5). The signal of wave heights is clear in the passage of storm conditions through these two periods, under various conditions of onshore and offshore winds. At frequencies of 1 - 2 hz the influence of tidal inundation is apparent, which reduces with reduced frequency. High power values at high frequencies of the cliff is apparent with a clear tidal signal, exacerbated during periods of high wave heights.

### Conclusions and recommendations

The examination of ground motion activity of a coastal cliff has demonstrated it to be a useful intermediary to explore and quantify interactions between environmental forcing mechanisms and coastal cliffs. This longevity, frequency and coverage of data is unique. The preliminary results demonstrate the sensitivity of cliff ground motion to marine and wind conditions and that energy delivery to the cliff is highly variable over time depending on the combinations of environmental conditions active at the cliff. The most significant source of energy delivery is derived from large waves during high tides when bottom frictions and wave depths are sufficient to maintain wave energy at the cliff toe and face. The cliff face, above the inundated zone, may also be sensitive to loading from winds, however this needs further investigation via multiple regression analysis of all the environmental variables collected. Also the comparison of wind effects between the stations perpendicular to the cliff face (Figure 2b) will help to ascertain whether wind effects are due to features of the instrument setup (such as solar panels) or buffeting of the cliff face itself. Further analysis of the time series and spectral composition of the data will be undertaken to address the remainder of the project's objectives. Resolution of the time series analysis of the ground motion velocity has been limited by that of the environmental variables that have been simultaneously monitored, the sampling resolution of which is determined by the authorities who run them. It is recommended that to be able to explore in finer detail the interactions between coastal cliffs and environmental conditions that conditions are monitored directly at the cliff, in particular sea level conditions, and at higher resolution. During this project we have trialed a Doppler radar sensor for water height measurement at the cliff toe and more recently a laser based system, with promising results. These systems provide data at high frequencies (up to 100 hz), which will allow more direct comparison with the velocity data collected in future.

### Outputs arising from project:

The analysis of the seismic data collected during this campaign will also form a substantive element of the data of Emma Norman's PhD thesis, which will be submitted in Spring, 2011. A NERC standard grant proposal was submitted in June 2009 to continue this work beyond the end of the GEF loan period, but was unfortunately unsuccessful. Related, the PI has been awarded a NERC pilot study award for CRN dating of foreshore rock platforms, which relates directly to the monitoring of process rates undertaken here. Further, the PI and E Norman

are currently in talk with Dr M Dixon of University of Auckland with regards submitting a proposal that brings together the work undertaken on using microseisms for monitoring rock coasts together, to provide post-doctoral funding for E Norman. Further funding has been recently secured from Redcar & Cleveland Borough Council, which will include the deployment of a seismometer at Staithes, North Yorkshire, to continue this work over the next 5 years.

#### **Publications:**

- Rosser, N.J., Norman, E.C. and Lim, M. in prep. Seasonal, tidal, and weather driven variations on cliff microseismic motion. *Geology*.
- Norman, E., Rosser, N., Lim, M., Petley, D., Barlow, J. & Brain, M. (2010) Exploring the relationship between tidal duration and energy delivery to a coastal cliff, in *Geologically Active*, Proceedings of the 11<sup>th</sup> Congress of the IAEG, CRC Press, The Netherlands, pp.2273-2279.

#### **Conference presentations:**

- Norman, E., Rosser, N., Lim, M., Petley, D., Barlow, J. & Brain, M. (2010) Exploring the relationship between tidal duration and energy delivery to a coastal cliff, 11<sup>th</sup> Congress of the IAEG, Auckland New Zealand.
- Norman, E.C. 2009. Advances in monitoring coastal rock cliffs. Annual General Meeting of the Remote Sensing and Photogrammetry Society, Leicester, September.
- Norman, E., Rosser, N., Lim, M., Petley, D. 2010 Exploring energy delivery to coastal rock cliffs, European Geoscience Union, Vienna, Austria. (EGU2010-9233).
- Norman, E.C., Rosser, N.J., Lim, M., and Petley, D.N. 2010, Energy Delivery to Cliffs from waves, tides and storms, 7<sup>th</sup> International Conference of Geomorphology, Melbourne, Australia.
- Norman, E.C., Rosser, N.J., Lim, M. and Petley, D.N. Energy delivery to cliffs from waves, tides and storms. Poster presentation at the Annual General Meeting of the British Society for Geomorphology, Durham University, September, 2009
- Norman, E.C. and Rosser, N.J. 2010. Microseismic monitoring of coastal rock cliffs. Spring Field Meeting of the Engineering Geology Group of the Geological Society of London. North Yorkshire Coast, May.

#### **Invited seminars:**

- Norman, E.C., Rosser, N.J., Lim, M., and Petley, D.N. 2010, Microseismic monitoring of energy delivery to coastal rock slopes: 1 year of monitoring. Department of Geography, University of Auckland, September, 2010.
- Norman, E.C. 2009. Monitoring tidal inundation from cliff microseisms. Engineering Geology Group, Geological and Nuclear Sciences (GNS) Ltd., New Zealand.
- Rosser, N.J. 2010. Monitoring cliff face change: insights from terrestrial laser scanning and constant microseismic monitoring. Engineering Geology Group, Geological and Nuclear Sciences (GNS) Ltd., New Zealand.
- Rosser, N.J., Norman, E.C., Lim, M., and Petley, D.N. 2010, Innovations in monitoring of coastal rock slopes. Department of Geography, University of Aberystwyth, January, 2010.