3rd International Conference on Protection against Overtopping, 6-8 June 2018, UK

WireWall: a new approach to coastal wave hazard monitoring

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Abstract

WireWall will be the first agile in situ system to make field measurements of overtopping on a wave-by-wave basis. Such data will enable site-specific calibration of (i) numerical tools used in sea defence design, (ii) flood forecasting models and (iii) public safety tolerances used by shoreline managers. The new approach transfers existing laboratory and offshore wave monitoring capabilities to the problem of coastal hazard monitoring. The capacitance wire system will collect high frequency field data to quantify wave overtopping velocity and volume. Our approach will replace the use of water collection tanks, which provide very limited information, are cumbersome, and hence rarely deployed. The method will use a coupled modelling-observational-modelling approach. Industry standard overtopping tools will generate a numerical dataset of plausible overtopping conditions at our study site Crosby (NW England). This data will inform the configuration of the wire units to be used in dockside and flume tests prior to the design of the field rig. The newly collected field observations will allow site-specific calibration and validation of the numerical tools, which will then be applied for a range of storm and beach conditions to develop site-specific overtopping safety tolerances and identify overtopping trigger levels for the existing sea wall.

1 Introduction

In the UK £150bn of assets and 4 million people are at risk from coastal flooding (Horsburgh et al., 2010). Whilst the construction of basic sea wall defence schemes typically cost £12k-13k per linear metre, e.g., Dymchurch and Redcar, higher quality schemes cost £23k-24k per linear metre, e.g., Blackpool central and Cleveleys. In addition to building a sea wall there are also other costs associated with reshaping the coastal frontage to enhance its aesthetics as an amenity. For example, Rossall (Fig. 1) is a scale above everything done previously due to the size of the existing cross section. Here, the new 1.9 km scheme, north of Blackpool NW England, protects 7,500 properties from the risk of flooding and cost £63m. With reductions in public funding and 3200 km of coastal defences in England and Wales (Horsburgh et al., 2010), cost savings are required that do not cause a reduction in flood resistance. The design of new coastal flood defences and the setting of tolerable hazard thresholds requires site-specific information of wave overtopping during storms of varying severity. There are two main issues faced by stakeholder groups responsible for commissioning, designing and building coastal defences:

1) The numerical tools currently used to estimate wave overtopping are based on previous field measurements of overtopping volumes only. These data were largely obtained using collection tanks (e.g., Pullen et al., 2012), which are cumbersome, costly and hence rarely deployed. Crucially, the data were typically gathered at dikes and are unlikely to be representative of other,

more vertical, structures such as sea walls that may experience more violent overtopping.

2) Tank experiments do not provide data on the velocity of the overtopping water - an important factor since violent high-density spray and green water jets pose a key hazard to people, vehicles and infrastructure (see Sandoval and Bruce, 2017).

In the absence of such key in situ data, overtopping estimates are at best within a factor of three, and this can increase to three orders of magnitude in uncertainty when setting threshold levels for public safety. This may result in unnecessarily large safety margins being factored into the design of new schemes. The Government committed £2.5bn for flood defences over the period 2015-16 to 2020-21 (Priestley, 2017). A 10% reduction in the uncertainty in hazard estimates could allow defence crest heights to be safely reduced, equating to a 5% (£125m) saving in construction costs. To achieve this a new approach is needed to obtain the key field data required to:

- provide site-specific calibration of overtopping tools, e.g. the industry-standard empirical rules within EurOtop that derive overtopping from the incident wave and water level conditions for a particular type of structure; and,
- develop site-specific safety tolerances to inform flood risk response plans.

Figure 1. The Rossall scheme due to be completed in 2018. Drone photo provided by Balfour Beatty.

Recent advances in technology (Broeders et al., 2016) mean that existing wave height sensors can now measure at the high frequencies (a few 100 Hz) required to obtain overtopping data, making this the ideal time to initiate a step-change in coastal hazard monitoring capabilities. At Crosby, in the North West of England, the 900 m sea wall will reach the end of its design life in the next 5 years. This project will convert existing wave measurement technology into an overtopping monitoring system WireWall, and will deploy it at Crosby to provide our partners with the key site-specific data and calibrated overtopping tools that they need to design a new, cost-effective sea wall.

1.1 Crosby sea wall

Our case study site Crosby is impacted by fetch limited waves from westerly and north westerly directions that can include significant wave heights of up to 5.5 m. During large storm surge events the surge can reach up to 2 m with skew surge values over 0.8 m (Brown et al., 2010 a and b). The large tidal range (8.27 m mean spring tidal range, http://www.ntslf.org) means hazard from overtopping is limited to a few hours either side of high water when waves are able to impact the sea defence (Fig. 2).

Figure 2. The Crosby sea wall frontage, 5 December 2013. Photo provided by the Sefton Council.

This site also provides a challenging location as rubble debris on the beach is likely to come over the sea wall in extreme conditions. This will allow the testing of the WireWall system's built in redundancy to ensure appropriate data is still collected when the system sustains damage.

In Liverpool Bay long-term monitoring data of tides and water levels are available from the Liverpool Bay Wave Rider and (Liverpool) Gladstone Dock tide gauge. This provides offshore boundary conditions for numerical estimates. In addition to this monitoring the local authority (Sefton Council) collect bi-annual beach profiles, survey the defence and have recently (February 2017) deployed an Acoustic Wave And Current (AWAC) and "Rapidar" radar system (Bird et al., 2017) to collect more detailed information on the waves, water level and currents close to the shore. This will allow us to use the SWAN (Simulating WAves Nearshore, Booij et al., 1999) model to transform offshore wave conditions to the toe of the structure and setup EurOtop to estimate the overtopping hazard for recorded conditions.

Using the UK's flood forecasting system (wave predictions at the wave buoy site and surge predictions at the tide gauge location combined with a tidal prediction) an early warning formulation has been developed for emergency response planning based on previous XBeach simulations for the Sefton coast (Souza et al., 2013). When the winds are in the westerly quadrant the following criteria are assessed:

$\eta + \frac{1}{2} Hs \leq 7.2$, *no response*

$\eta + \frac{1}{2} Hs > 7.2$, *potential hazard to prom users*

$\eta + \frac{1}{2} Hs > 7.6$, *carpark closure due to flooding*

where η = total water level (m OD) and Hs = the offshore significant wave height (m). The thresholds are based on the prom level (7.2 m OD) and the splash wall (7.6 m OD) at the back of the prom fronting the carpark. When the waves break on the prom wave run-up into the carpark is expected, while wave impact on the sea wall still poses a hazard to pedestrians. This hazard is dependent on water levels either causing the wave overtopping to be thrown vertically upward and taken over the defence crest by wind, or the waves to overtop as a fast low level green water jet over the crest. Westerly winds exceeding 15 ms^{-1} (~ 30 mph) are considered strong enough to pose an overtopping hazard when offshore significant wave heights exceed 4 m and coincide with total water levels greater than 4.57 m OD (often a spring tide with surge). Under these conditions wind-blown spray following wave breaking on the sea wall often occurs.

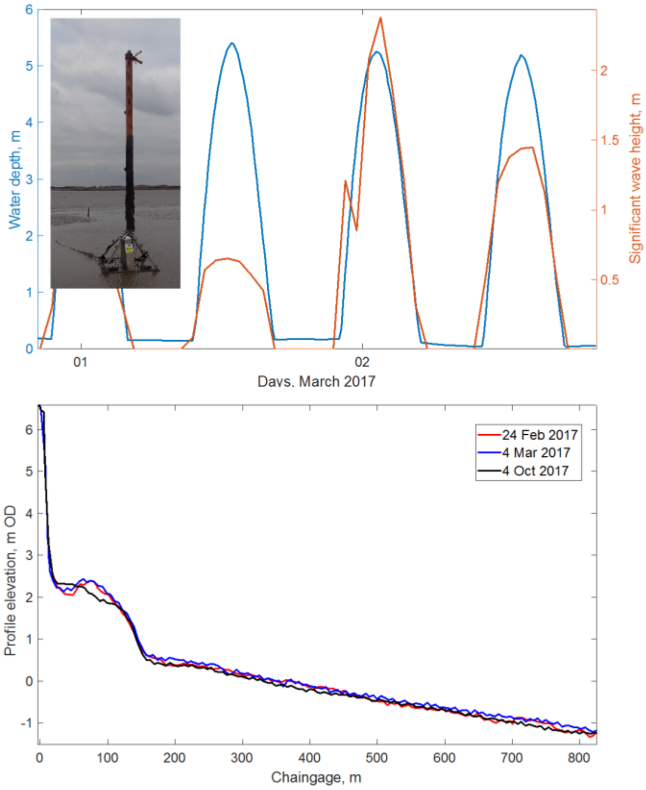
2 Methods

The WireWall approach will measure coastal wave overtopping at the high frequencies (few 100 Hz) required to capture key data on individual wave events. The system's design will target shoreline management needs associated with sea defence performance monitoring, new scheme design and flood modelling (whether hazard mapping or forecasting). It will be deployed at Crosby during the winter of 2018/19 to collect data to inform the planning of a new coastal scheme. More widely, the project will develop and disseminate a generic observational-numerical approach that reduces uncertainty in overtopping estimates used in sea wall design and early warning systems, which deliver regional Shoreline Management Plan (SMP) objectives. If successful, this will allow our partners to continue monitoring future events at Crosby, and other groups to initiate similar monitoring at other sites.

Three key activities are set to achieve our aim:

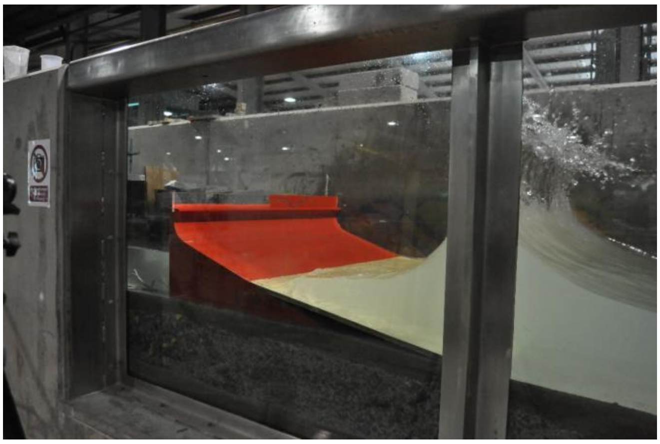
A1. Our numerical approach will follow the industry standards for designing new sea wall structures to be resistant to extreme events. The numerical methods within EurOtop (Pullen et al., 2007) for sea wall design will be applied to historical events at Crosby using our partners' coastal monitoring data (beach-structure transects and AWAC data, Fig. 3) and existing coastal monitoring networks (WaveNet and the National Tidal Sea Level Facility). The wave and water level data will be transformed from the point of measurement to the structure toe using SWAN. This information and the structure cross-section will be fed into the empirical methods within EurOtop to estimate the overtopping hazard for the historic events. Current practice is to only transfer wave conditions for static water levels and given wave return periods. Here, we will look at past events and beach conditions to (a) incorporate the effects of tidal modulation on the hazard, an important factor given the ~10 m mean spring tidal range at Crosby, and (b) the influence of seasonal change in the beach level, which can change the overtopping hazard (e.g., Phillips et al., 2017). The numerical estimates of wave overtopping volumes and velocities for historic events at Crosby will inform the appropriate configuration of the WireWall mesh and electronics. Numerical (SWAN-EurOtop) estimates of the range of wave and water level conditions that cause overtopping will also aid planning of field deployments, along with operational forecast information.

Figure 3. An example of the AWAC (top) and beach profile (bottom) data collected as part of the Northwest Coastal Monitoring Strategy.



A2. The mobile, battery-powered WireWall system will be configured to record wave-by-wave overtopping volumes and velocities at Crosby using a 3-D mesh of (cheap and easily replaceable) capacitance wires and accompanying electronics. It will be designed to withstand high velocity (40 m/s) jets and will incorporate redundancy to minimize the impact of data loss due to damage. It will be tested in the labs and at the dockside of the National Oceanography Centre (NOC) in Southampton. The system will be calibrated using tank data in the flume at HR Wallingford (HRW). Flume 1 (Fig. 4) is one of two primary wave flumes at HRW that will be used. They are 40 m long, 2 m deep and 1.2 m wide and are equipped with piston-type wave paddles controlled by HRW's Merlin software. The paddle has an active wave-absorbing system to reduce the effect of waves reflected from the test section and can generate non-repeating random sea-states to any required spectral form, including: JONSWAP, Pierson Moskowitz, bimodal spectra, and user-defined forms.

Figure 4. The HR Wallingford flume facility where the Wire-Wall configuration will be tested and calibrated, Flume 1 is shown.



Following flume tests the system will be transferred to the NOC in Liverpool for deployment at Crosby The system will use a modular approach to allow flexibility in the configuration. Each standalone module will consist of a frame carrying multiple capacitance wires all powered from, driven by and logged to, a single waterproof electronics unit to ensure high frequency data synchronization. The frames will be open faced and aligned with the oncoming wave direction to capture the velocity of the overtopping jet. Up to 6 frames will be mounted within robust rigs to form a 3-D mesh to capture spatial variability in overtopping and to provide redundancy. The field rigs will be sized to fit within the railing spacing at Crosby and will be rigidly secured to the existing infrastructure. The system will be deployed in the field for 24 hour periods at multiple vulnerable locations (determined by Sefton Council) on the sea wall during conditions that are forecast to cause overtopping. The most likely position will be in front of the carpark at the northern end of the slipway, which aligns with the Hall Road profile line. Here the sea wall is positioned at the mean high water spring mark and beach levels are lower, enabling overtopping hazard on high tides. Towards the south of the sea wall higher beach elevations and a setback sea wall position limits this hazard. The deployments will target both typical (winter spring tide) and extreme (storm) wave and water level conditions that cause overtopping during the winter 2018/2019. All spring tides exceeding mean high water spring (4.46 m OD) will be watched as potential trial deployment windows, as typical winter wave and wind conditions are likely to cause some overtopping, even if low impact, for a short period at high water. Extra deployments on the slipway (Fig. 5) near the vulnerable northern end of the sea wall will allow testing in lower impact conditions. Pre- and post-event beach profiles will be collected using a Leica GNSS Rover (antenna), coupled with a Leica CS15 Viva Controller (handset) and data from the WaveNet and UK tide gauge network during the deployment will be obtained. This will provide concurrent input to the numerical tools set up in A1 to validate the numerical overtopping estimates against the observed Crosby overtopping events in A3.

Figure 5. The northern end of Crosby sea wall where overtopping hazard to the carpark occurs.

A3. Field data from the system will be used to quantify the local overtopping hazard at Crosby and calibrate EurOtop and validate SWAN (A1) for the observed events, thus delivering a method to use measurements from WireWall to calibrate flood forecasting systems (e.g. Pullen et al., 2008) and hazard mapping systems (e.g., Prime et al., 2015). Once calibrated/validated these tools will be used to provide new overtopping estimates for historic events, expanding the numerical results to supplement the observational data from the project. This dataset will be used to calibrate site-specific tolerances in safety thresholds for a wide range of storm conditions to better inform the design of the new scheme at Crosby. The methodology will also provide others with an approach to inform thresholds in safety margins associated with overtopping (e.g., Richardson et al., 2002; Pullen et al., 2009) for other management needs. This will provide coastal managers with a dataset and a valid method to calibrate industry standard approaches to site-specific overtopping hazards, against which to assess potential new sea wall designs. The data will also improve understanding of the local conditions that cause overtopping and will allow our partners to test their flood forecasting and early warning services.

Workshops in June 2018 and 2019 with the project’s Wider Interest Group (WIG) will be focused on ensuring the system is transferable to other sea defence infrastructure and flood management assets. This group will be engaged to determine the design and data requirements for the system so that it meets the wider needs of coastal practitioners and academic research, i.e. ensuring WireWall is suitable for future deployments at a range of UK (and potentially global) defences. The WIG members represent those groups monitoring and modelling overtopping in the UK for coastal management purposes, and will help to maximise the future impact of WireWall.

3 Planned results

Initial numerical results to inform the design specification of the physical modelling and field work will be generated by April 2018. Flume experiments will then be performed May to July 2018 and field deployments will take pace winter 2018/2019. At the end of the project (June 2019) processed field data, calibrated model data and executables to process WireWall data will be made available along with a report describing the approach using Crosby as a worked example. Dissemination of the advances in monitoring made by the WireWall approach will be through our partners’ roles in national and regional Coastal Groups; workshops with our WIG and reporting through the National Network of Regional Coastal Monitoring Programmes (http://www.channelcoast.org/ccoresources/wirewall/).

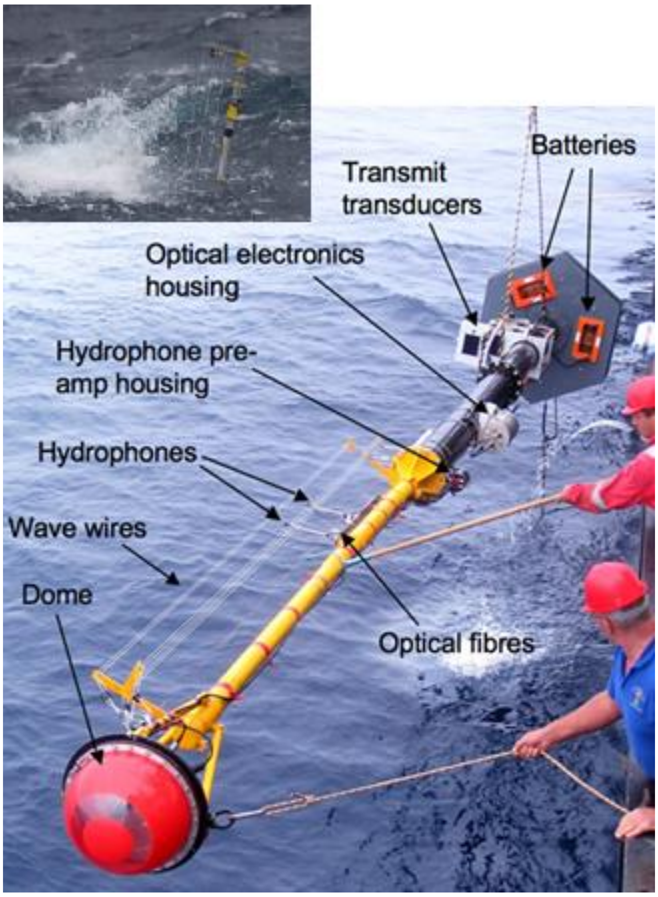
The key outputs from WireWall will be:

1) A validated WireWall system for monitoring in situ wave-by-wave overtopping.
2) In situ data of mean and peak overtopping volumes and velocities for Crosby.
3) Calibration of overtopping estimates from EurOtop for the Crosby sea wall.
4) Calibration of admissible overtopping thresholds specified in industry design guidance to site-specific hazard ratings (structural damage, public safety) at Crosby.

4 Discussion

WireWall will be the first agile in situ system to make field measurements of overtopping velocity on a wave-by-wave basis. This key parameter is required by the coastal defence infrastructure sector to quantify overtopping hazards, but field measurements have not previously existed. The measurements will be made possible by the novel application of a technology previously used for other purposes.

Figure 6. An example of the spar buoy capacitance wire system deployed in the Southern ocean (top left insert) and North Atlantic (main figure).



Capacitance wave wires have long been used to measure wave height spectra (up to ~10 of Hz, e.g. Killen, 1952). Expertise in using capacitance wires on spar buoys (Fig. 6) for measuring offshore wave and wave-breaking (Pascal et al., 2011) will be used to adapt this technology to measure overtopping volumes and velocities from individual waves, using a 3-D mesh of capacitance wires to sample at the high frequencies required (few 100 Hz). The approach will be validated in the HRW flume. This will result in the first adaptable, low-cost system that can be easily and quickly deployed above a sea wall to provide site-specific data to calibrate industry estimates of overtopping that are largely based on previous data from Dutch dikes: current estimates of public hazard from overtopping can have three orders of magnitude in uncertainty.

Continued use of the WireWall approach beyond the end of the project by Coastal Groups could allow data collection to improve the design and management of a range of flood management assets in a routine fashion for the first time. This could eventually lead to an overtopping monitoring system that is built into new flood defences as part of existing shoreline monitoring programmes.

5 Conclusions

Crosby, in the North West of England, is a site where the Sefton Council have recently begun intense monitoring of waves, water levels and beach profiles in order to inform the decision-making process associated with planning a new coastal scheme. The overtopping observations by WireWall will be used to: assess and calibrate the industry standard approach (EurOtop) used when designing the new sea wall; reduce uncertainty in wave overtopping estimates at this site; and reduce construction and maintenance costs by reducing overdesign. While this project is focused on the development of a prototype instrument using Crosby as a case study the system (physical instrumented rig, numerical approach and data processing algorithms) will be designed to be transferable to other locations collecting generic data of value to support a range of flood risk management requirements.

Demonstrating the success of the WireWall approach to quantifying overtopping hazard will be a significant step towards a brand new, cost-effective monitoring system capable of obtaining data on key parameters that have previously not been available. Along with our partners and WIG we will evaluate WireWall’s future potential to be routinely incorporated in coastal monitoring schemes. This could support SMPs by gathering site-specific data for monitoring long-term changes in flood hazard due to defence degradation, climate variability and beach evolution (see Wadey et al., 2015).

Acknowledgments

This research was funded as part of the NERC Innovative Monitoring Approaches call (grant no. NE/R014019/1). We would like to acknowledge the

national monitoring programs and organizations responsible for data delivery WaveNet (CEFAS), National Tidal Sea Level Facility (NTSLF) who deliver date through the British Oceanographic Data Centre (BODC), and the Northwest Coastal Monitoring Programme for the provision of long-term monitoring data in Liverpool Bay.

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