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WireWall – a new approach to measuring coastal wave hazard

J.M. Brown, M.J. Yelland, R.W. Pascal, T. Pullen, C.L. Cardwell, D.S. Jones, R.C. Pinnell, E. Silva, C. Balfour, G. Hargreaves, B. Martin, P.S. Bell, T.D. Prime, J. Burgess, L.A. Eastwood, A. Martin, I. Gold, C. Bird, C. Thompson & B. Farrington

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National Oceanography Centre
Joseph Proudman Building
Brownlow St Liverpool
L3 5DA

Email: jebro@noc.ac.uk

Executive Summary

In the UK £150bn of assets and 4 million people are at risk from coastal flooding, whilst the construction of sea wall defence schemes typically cost at least £10,000 per linear meter. With reductions in public funding, rising sea level, changing storm conditions and 3200 km of coastal defences (i.e. about £3bn), 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. By converting an existing wave measurement technology into a prototype overtopping monitoring system "WireWall", field observations of the wave-by-wave horizontal overtopping speeds and volumes were made at our case study site Crosby, in the North West of England. The new data quantify the wave overtopping conditions observed, which varied with the wind, waves and tide, allowing better understanding of how wave hazard at Crosby changes with the local conditions. The new system collected time-series of observations during typical winter spring tide overtopping conditions that provided site-specific data to:

- calibrate overtopping tools, e.g., the industry-standard empirical rules within EurOtop, for nuisance overtopping hazards;
- validate operational flood forecasting services, including the forecast and alert thresholds applied; and,
- develop site-specific safety tolerances to inform flood risk management plans.

At Crosby, the 900 m sea wall will reach the end of its design life in the next 5 years. Deployments at this site have provided the North West Coastal Group with the site-specific data and calibrated overtopping tools that they need to design a new, cost-effective, carbon-reduced sea wall. The deployment of WireWall at Crosby is the first step towards the development of an overtopping monitoring system that could ultimately be integrated into new coastal schemes as part of the UK's regional shoreline monitoring programmes.

Following the update of the EurOtop manual and the BayonetGPE tool behind the guidance in 2018, all numerical wave overtopping estimates used in the WireWall project were reproduced. It is this version of SWAN-BayonetGPE that is applied to the 15 min field data to compare with the WireWall field measurements, while the Environment Agency's warning system is based on guidance in EurOtop (2007). *In this report we used photographic evidence of previous overtopping events at Crosby (from 2013 to 2017) along with archived monitoring data to develop a database of overtopping events and conditions. These data (see "summary" boxes in Sections 4.1, 4.2, 4.3 and 4.4), along with the field deployments of the WireWall system (see "summary" boxes in Section 4.13), showed that at the northern end of the Crosby sea wall:*

- Conditions are depth limited, which means the wave height at the structure toe is more important than that offshore.
- The beach level within 5 m of the structure toe seems to have much more impact on the overtopping discharge than the ridge-runnel profile of the upper beach.
- At this site water levels are most important for setting thresholds for hazard warnings. When water levels > 4.46 m OD (MHWS) and there is an onshore

(westerly) wind component > 10 mph (4.5 m/s) overtopping is expected if offshore wave heights > 0.5 m.

- The overtopping hazard thresholds used by the EA flood forecasting system and in the EurOtop (2018) manual look suitable for this site, and were occasionally exceeded or at least met during our field deployments.
- The EA forecasting system could incorporate a larger range of wave conditions for wind speeds < 30 mph in the forecast matrix and would benefit from an approach to account for variability in beach levels. While the EurOtop guidance could be expanded to include lower wave heights (< 1m) for vertical sea walls to support the coastal management of typical overtopping that now occurs more frequency on windy spring tides.

Recent advances in technology mean existing wave height sensors can now measure at the high (400 Hz) frequencies required to obtain overtopping data, making this the ideal time to initiate a step-change in coastal hazard measurement capabilities. *The novel WireWall system was validated using tests in the flume at HR Wallingford and compared with BayonetGPE estimates (the neural network tool behind EurOtop applied here using the latest available version in October 2019, O19). These tests (see "summary" boxes in Sections 4.7 and 4.8) were designed using the observed photographic conditions and showed that:*

- The overtopping volume data from WireWall agreed well with those from collection tanks, and were generally within the limits of the tank uncertainties which were at least +/- 20% (possibly up to +/-40% if pumps were used to prevent the tanks overflowing).
- The benefits of using WireWall over the traditional tank approach are: the ability to measure cross-flume variability, no tank-capacity limitations and minimal interference with the distribution of overtopping water as it travels inland.
- There was no consistent bias between WireWall/tank data and BayonetGPE (O19) estimates. The difference in values can be up to a factor of 3 but the WireWall/tank discharge measurements fell within the +/- 1 s.d. uncertainty in the mean BayonetGPE (O19) value.

WireWall was deployed at Crosby during nine spring high tides between October 2018 and March 2019. Thresholds developed from the photographic evidence were used to target conditions when overtopping was expected. Results from these deployments (Sections 4.9 to 4.13) showed that:

- Overtopping during a tidal cycle is not symmetrical around the time of high water: WireWall data showed that total overtopping volumes prior to high water were 4 or 5 times greater than those after high water.
- WireWall measures over the full overtopping window to collect data that are out of range in the BayonetGPE (O19) database.
- When there is a large vertical component to the overtopping plume much of the water falls back to sea and does not travel inland past the handrail. For hazard management we suggest using overtopping data measured at wire3 (located at the handrail) when setting hazard thresholds and validating numerical tools.
- Uncertainty in the WireWall results occurs due to overtopping water coming from an alongshore direction through the rig.
- Out of the nine deployments measurable overtopping occurred during four tides. The BayonetGPE (O19) estimates agreed with the WireWall measurements (i.e. were within the BayonetGPE +/- 1 s.d. bounds) on two occasions, but underestimated by more than 1 s.d. on two occasions. However, BayonetGPE (O19) does not

incorporate wind influence, which is critical at Crosby and was a key driver of the wave overtopping during our deployments.

- The numerical estimates give us confidence that the WireWall field data are representative of typical winter conditions, i.e. more frequent than a 1 in 2 year event. A longer study period is required to capture more extreme events.
- The data for the field measurements expand the conditions observed by the Facebook record and show higher overtopping discharges can occur for low-energy conditions than first expected.

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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 (and carbon emissions) associated with reshaping a coastal frontage to enhance its aesthetics as an amenity. For example, Rossall 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 North West 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 and carbon savings are required that do not cause a reduction in flood resistance. Accurate early warning flood forecasting systems will also be required where adaptive management approaches facilitate “living with nature”. 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 very limited 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 (with associated costs and carbon emissions) 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:

1) provide site-specific calibration of overtopping tools, e.g. the industry-standard empirical rules within EurOtop (2018), that derive overtopping from the incident wave and water level conditions for a particular type of structure; and,
2) develop site-specific safety tolerances to for local flood risk management planning and refinement of early warning thresholds in flood forecasting service.

Recent advances in technology (Broeders et al., 2016) mean that existing wave height sensors can now measure at the high frequencies (400 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 has radically converted existing wave measurement technology into a prototype relocatable overtopping measurement system "WireWall", and deployed it at Crosby to provide our project partners with the key site-specific data and calibrated overtopping tools that they need to design a new, cost-effective sea wall and refine overtopping hazard forecasts for the existing structure in the interim.

WireWall is the first agile in situ field system that can measure the inland distribution of overtopping volume and horizontal speed on a wave-by-wave basis. Such data will enable site-specific calibration of:

1) numerical tools used in sea defence design;
2) flood forecasting models; and,
3) public safety tolerances used by shoreline managers.

The new WireWall approach uses existing understanding of wave overtopping behaviour from the laboratory (Pullen et al., 2009) and transfers offshore wave monitoring capabilities (Pascal et al., 2011) to the problem of coastal hazard monitoring (Figure 1.1). The project aimed to develop and disseminate a transferable approach to reduce uncertainty in overtopping estimates used in sea wall design and early warning systems, and provide new insight into the overtopping hazard posed in order to deliver regional Shoreline Management Plan (SMP) objectives (see Appendix I, IV and V for outputs).

Those involved in the WireWall project were: the National Oceanography Centre (NOC), HR Wallingford (HRW), Sefton Council (SC), Channel Coastal Observatory (CCO), the Environment Agency (EA), Balfour Beatty (BB) and Marlan Maritime Technologies (MMT).

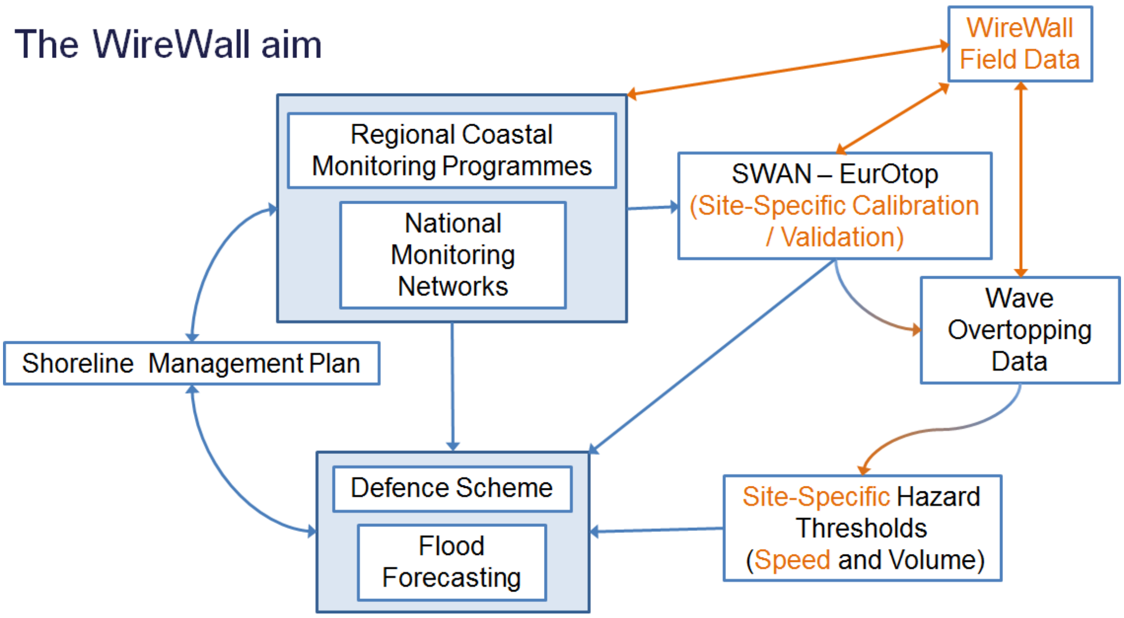


Figure 1.1: WireWall's intended integration with existing shoreline management practices.

The capacitance wire system was designed and tested at the NOC's Southampton dockside and then validated in HRW's flume facility during the summer of 2018. It was subsequently deployed to collect high frequency field data to quantify winter wave overtopping volumes and horizontal speeds at our study site Crosby, North West of England, during October 2018 to March 2019. Our prototype instrument successfully demonstrated its potential to replace the use of water collection tanks, which provide very limited information, are cumbersome, are impractical to deploy at many sites, and hence are rarely deployed. The WireWall approach used a numerical-observational-numerical design and assessment methodology (Figure 1.2).

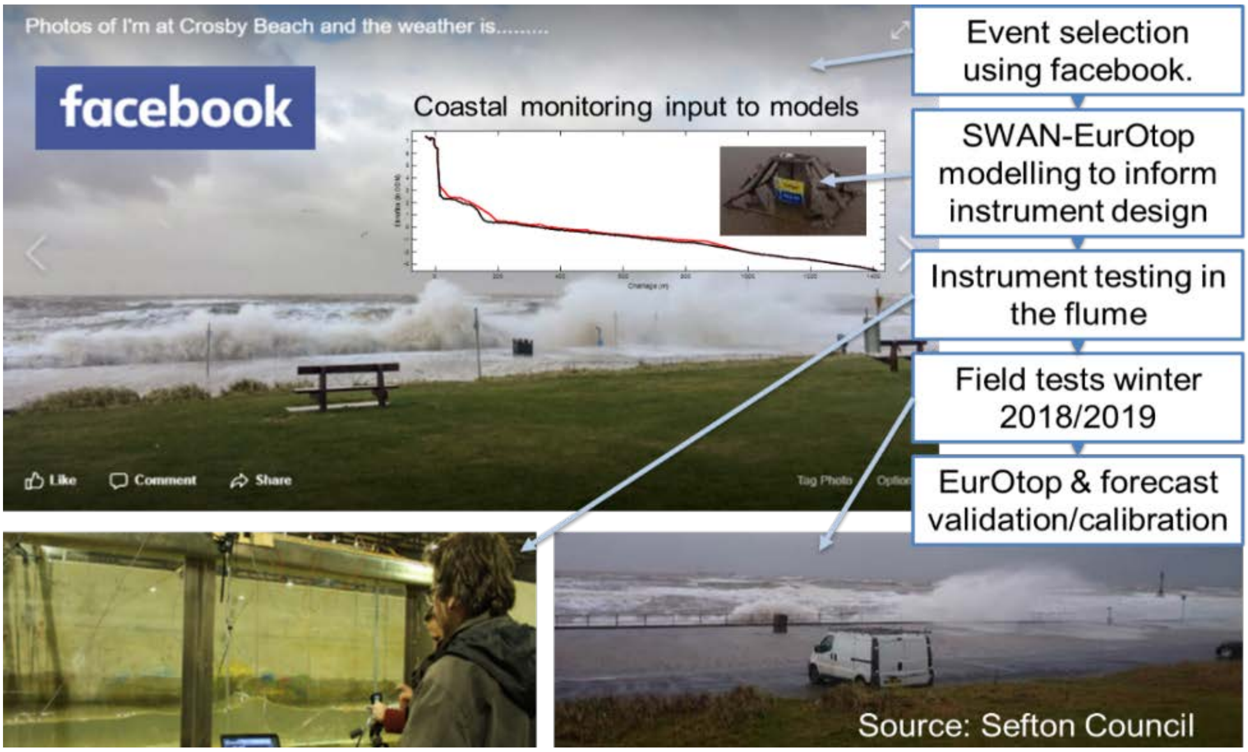


Figure 1.2: The WireWall approach to collect new observations required to identify site-specific safety thresholds & calibrate models used in scheme design.

The industry standard overtopping tool, BayonetGPE (Pullen et al., 2018), which forms the database behind the latest EurOtop guidance (2018), was used to generate a numerical dataset of plausible overtopping conditions at Crosby (NW England). This tool is most suitable for assessing the impact of extreme events, such as those used in coastal scheme design. However, with limited alternative tools it is also often used in public safety alert systems, which also require accurate overtopping estimates for more typical, less extreme, conditions. The safety thresholds provided in EurOtop (2018) are given in Table 1.1. BayonetGPE was applied to the north end of the Crosby sea wall structure using available data (Appendix II). These monitoring data were used as input to the SWAN (Simulating WAves Nearshore, Booij et al., 1999) model to transform offshore wave conditions and nearshore water levels to the toe of the existing sea wall. The BayonetGPE data and expert judgment informed the design of the WireWall system. The newly collected field observations enable site-specific calibration and validation of the numerical tools (SWAN – BayonetGPE, see Section 4.11 to 4.14) under different winter conditions (see Appendix III) for the existing sea wall structure. These tools (SWAN and BayonetGPE) and the input monitoring data are the same as those being used (by Coastal Engineering (UK) Ltd) to develop a business case for a new coastal scheme at Crosby and the most recent version of the tools also used in 2009 to set up the EA's flood forecasting service for this site. The numerical tools were applied for a range of storm and beach conditions identified using photographic records from a dedicated Facebook site (I'm at Crosby Beach and the weather is….). The reults were used to calibrate site-specific overtopping safety thresholds, identify overtopping trigger levels and understand the local processes to inform how to best apply SWAN-BayonetGPE in the business case when designing a new Crosby Coastal Scheme. The data generated as part of this study (Appendix IV and V) are archived with the British Oceanographic Data Centre (BODC) and the links are publicly shared through CCO (https://www.channelcoast.org/) alongside the North West Regional Monitoring Programme.

Table 1.1: Tolerable overtopping limits for people and vehicles from EurOtop (2018). The hazard to people at a sea wall or dike crest assume they have a clear view of the sea. The hazard to cars is if they are on a sea wall or dike crest and the hazard to a railway is if it is close behind the crest.

Mean overtopping discharge (l/s/m)	Max volume l/m	Hazard description
0.3	600	People, $H_{m0,t} = 3$ m
1	600	People, $H_{m0,t} = 2$ m
10 – 20	600	People, $H_{m0,t} = 1$ m
No limit	No limit	People, $H_{m0,t} < 0.5$ m
< 5	2000	Cars and Rail, $H_{m0,t} = 3$ m
10 – 20	2000	Cars and Rail, $H_{m0,t} = 2$ m
< 75	2000	Cars and Rail, $H_{m0,t} = 1$ m

2. Case Study

2.1 Location of field trials

The prototype WireWall instrument was trialled at our case study site Crosby, north of Liverpool (England). This location, situated in the eastern Irish Sea, faces west-south-west (about 245 degrees) and is impacted by fetch limited waves from westerly to north westerly directions. The offshore significant wave heights can reach up to 5.5 m and the longest periods reach around 10 s. During large storm events the surge can be 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 existing sea defence (Figure 2.1).

The WireWall study focused on the northern end of the sea wall in front of the Royal National Lifeboat Institution (RLNI) station. This site is vulnerable to wave overtopping, easy to access with a vehicle and close to the Hall Road beach survey profile, which extends offshore into Liverpool Bay (unlike the profile lines further south that extend towards the Wirral Peninsula). This profile was thus appropriate for both numerical and observational study. The numerical approach and physical modelling were based on the Hall Road cross-shore profile (ref no. 11A02250), which extended from the side of the slipway about 30 m to the south of where the fieldwork took place (Figure 2.1). The fieldwork was positioned where local effects due to the slipway (from which the profile line extends) and edge effects from the corner of the sea wall would not alter the overtopping typically experienced by the more uniform sections of the sea wall. Such small scale local effects would not be captured within the numerical tools, thus a location that was more representative of the general hazard along the northern section of the sea wall structure was selected. Visual observations during the WireWall project found the slipway area was slightly more susceptible to overtopping. Further to the south the sea wall structure changes and the beach levels are higher so considerable alongshore spatial variability in overtopping will occur at this site.

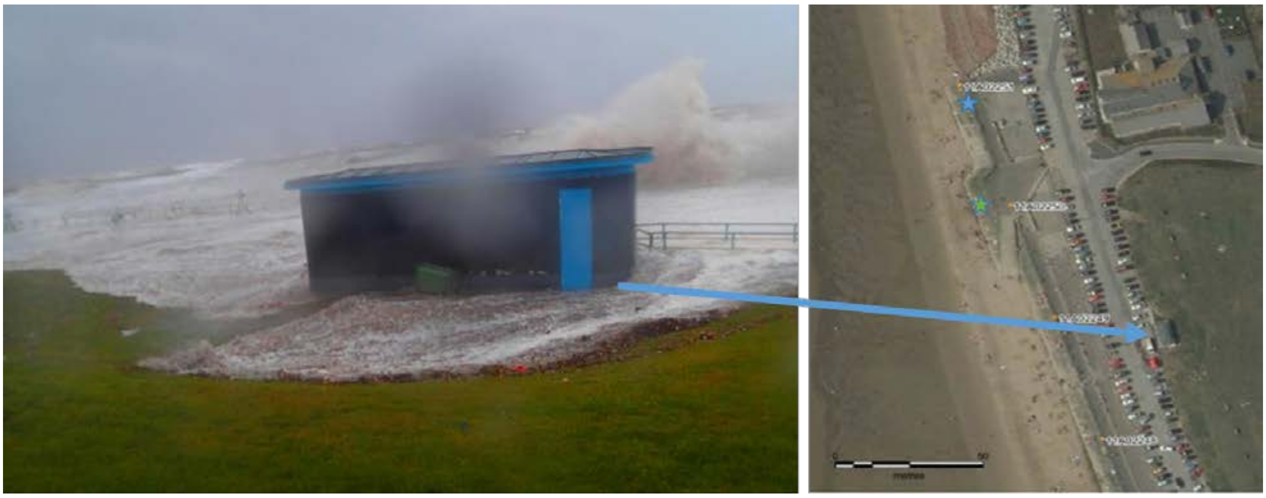


Figure 2.1: The Crosby sea wall frontage, 5 December 2013 (left) and the northern section of the car park at Hall Road (right). Images provided by the Sefton Council. The blue star marks the WireWall deployment location on the promenade and the green star the start of the survey line where numerical estimates were generated on the slipway. The slipway has a similar cross-shore profile to the promenade but is advanced slightly seaward of the main defence line.

This site provided a challenging location to test the new instrument as rubble debris on the beach (known as Blitz Beach) was likely to come over the sea wall in extreme conditions. However, there were no extreme events during winter 2018/2019 and only a little debris came over the sea wall during deployments. Limited testing of the WireWall system's built in redundancy (to ensure sufficient data are collected when the system sustains damage) was therefore performed.

2.2 Current approach to hazard and flood forecasting and warning

In Liverpool Bay long-term monitoring data of waves and water levels are available from the Liverpool Bay wave buoy and (Liverpool) Gladstone Dock tide gauge. This provides coastal boundary conditions for numerical estimates. In addition to this monitoring the local authority (SC) collect bi-annual beach profiles, inspect 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 at Crosby. This allowed us to use the SWAN (Booij et al., 1999) model to transform offshore wave conditions to the toe of the structure and setup BayonetGPE to estimate the overtopping hazard and assess the EurOtop guidance thresholds for hazard using past and present events.

Our method was chosen to follow a similar SWAN-EurOtop approach as used to generate the database that underpins the EA’s flood forecasting service for the North West region, namely TRITON. TRITON (Defra/Environment Agency, 2004) is considered best practice for flood forecasting in England and Wales. For Crosby, TRITON provides hazard forecasts for north Crosby (in Hall Road car park) approximately 125 m south of where our numerical study is performed. In 2008 the EurOtop setup was reviewed and updated, followed in 2014 by an adjustment to the hazard thresholds following the storms during the winter 2013/2014. The structure and conditions in our numerical approach were compared and considered to be representative, while we incorporate any updates to EurOtop since 2007 (e.g., the updates to neural network behind EurOtop, known as BayonetGEP, now supported by HRW). Discrepancies between the methods could also occur due to the resolution and limited extent of water level, wind and wave conditions within the look-up table that forms the forecasting database. For north Crosby the EA issue a flood alert or flood warning for still water level flooding if the total water level exceeds 6.9 m OD and 7.1 m OD respectively. Hazard thresholds are given relative to Ordnance Datum (m OD) Newlyn to be easily comparable to the beach and structure surveys measured relative to OD in the vertical. For wave overtopping flood hazard, an alert or warning is issued for a mean overtopping discharge of 0.002 m^2/s (2 l/s/m) or 0.025 m^2/s (25 l/s/m) respectively, or an alert is issued if the cumulative overtopping volume exceeds 2500 m^3 (i.e., the ~300 m frontage where there is parking becomes flooded). The forecasts use mean overtopping estimates, while newer versions of the BayonetGPE tool also provide information about the 1st and 2nd upper and lower standard deviations (s.d.) around the mean value to capture uncertainty in the overtopping estimates for design and forecasting purposes. This uncertainty relates to there being a range of plausible parameter settings to represent the processes during wave interaction with the structure (EurOtop, 2018, see section 1.5.1, page 17, of the manual).

Due to the lack of local alerts issued by the EA, SC have developed an early warning formulation for emergency response planning based on previous research and the UK's public forecasting services (wind forecasts and surge predictions at the tide gauge location combined with a tidal prediction). XBeach (wave run up and dune erosion) simulations for the natural (Sefton) coast north of Crosby (Souza et al., 2013) provide key information about hazardous water level and wind conditions, which have been adapted for the structure at Crosby and are currently applied as hazard criteria when the wind is between south west to north west as follows:

- $\eta + ½ H_{m0} \leq 7.2$ m OD, no hazard
- $\eta + ½ H_{m0} > 7.2$ m OD, hazard to promenade users and car park
- $\eta + ½ H_{m0} > 7.6$ m OD, likely car park closure due to flooding

where η = total water level (m OD) and H_{m0} = the offshore zero moment wave height (m). The thresholds are based on: 1) the splash wall level (7.2 m OD) at the landward edge of the promenade fronting the car park; and, 2) the toilet block platform level (7.6 m OD) that is just above the inland elevation of the car park, which is between 7.3 m and 7.4 m OD where it interfaces with the grass/sand embankment. When the waves break on the promenade wave run-up into the car park is expected, while wave impact on the sea wall still poses a hazard to pedestrians in the form of dense spray. 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 on the waves overtopping as a fast, low-level green water flow over the crest.

Operationally hazard criteria are applied for Flood and Coastal Erosion Risk Management, i.e., to close the car park entry, plan post-event defence and beach level inspections. Water level and wind forecasts provide a 5 day warning to monitor conditions as follows:

No hazard: 4.57 m ODN < η < 7.2 m OD, wind speed ≤ 16 mph from west to north west
Alert: 4.57 m ODN < η < 7.2 m OD, 16 < wind speed < 30 mph from west to north west
Warning: 4.57 m ODN < η < 7.2 m OD, wind speed ≥ 30 mph from west to north west,
Warning: $\eta \geq 7.2$ m ODN, any wind condition

3. Method

The WireWall approach transferred offshore wave measurement technologies to the problem of coastal flood hazard measurement using expert understanding and laboratory studies to develop a system able to collect required data in the field. Numerical analysis was required to identify the expected conditions to design the measurement system and plan field deployments. A prototype system was developed using dockside tests at the NOC (Southampton) prior to flume tests performed in HRW's Physical Modelling Laboratory. Given the uniqueness and complete novelty of this approach it was crucial to validate the WireWall system and understand any uncertainty before making field measurements. The field rig was then deployed at Crosby beach in front of the RLNI station at the Hall Road car park when conditions were expected to generate some level of measurable wave overtopping within the winter 2018/2019 period.

3.1 Numerical analysis

The WireWall numerical approach follows industry standards for coastal flood forecasting and coastal scheme design/redesign. The methods within EurOtop (Pullen et al., 2007) for estimating overtopping at sea walls were applied to past events at Crosby using our partners' coastal monitoring data (beach-structure transects and AWAC data) and existing coastal monitoring networks (WaveNet and the National Tidal Sea Level Facility). The wave data were transformed from offshore to the structure toe for the nearshore water levels using SWAN. This information and the structure cross-section were fed into the empirical methods within BayonetGPE to estimate the overtopping hazard for the past events. Current practice when assessing a proposed scheme design's resistance to extreme events is to use a combination of statistical wave and water level conditions that represent different return period levels. The numerical estimates typically apply a static high water level combined with the required range of wave conditions each represented by a significant wave height and peak period. The uncertainty (1 s.d. to 2 s.d.) in the mean overtopping discharge accounts for plausible variability of heights and periods within the spectrum of waves that make up that condition and uncertainty in the parameters setting to represent the wave-structure interactions. We simulated a range of past events and beach conditions to (a) incorporate the effects of tidal modulation and (b) the influence of seasonal change in the beach level on the wave overtopping hazard. We looked at more typical (rather than extreme) conditions as these are important for public safety management.

The past events were identified from photographic evidence provided by SC, BB and available on the "I'm at Crosby beach and the Weather is…" Facebook site. The latter records were individually checked to ensure the image was associated with the correct date and the study location. Forty nine images were gathered from 2013 to 2017. The Facebook site was started December 2013 following extreme storm events. Photos are available from 5th December 2013 and were collected to 31st December 2017 for this project, which started 1st January 2018. Additional photos from project partners were provided for 30th and 31st January 2013, 11th August 2014 and 8th February 2016. Waves and water levels were obtained from available measurements for a 6 hour period centred over high water for the day the photo was taken and for the night time high tide before and after. This time period ensured the numerical estimates covered the tidal stage when water levels enabled wave run up or the waves themselves to impact the structure. While a 4 hour window is more likely to be associated with wave overtopping, extreme storm surges could elevate water levels near to the high water level and increase the overtopping window. We therefore analyse over a longer period to ensure we capture the full potential overtopping period for past events. The water level data were obtained at 15 minute intervals (provided as an average of the interval with the time stamp at the centre of the averaging period), the waves at 30 minute intervals (sampled over 1600 s with the time stamp at the start of the sampling period) and the wind at hourly intervals (as a 10 minute averaged value with the time stamp at the centre of the averaging period). The latter were linearly interpolated to the higher frequency to allow an increased number of data points over the high water analysis window, but the lower frequency of observations will influence the accuracy of the time variability in the conditions modelled within the hour at the toe of the structure. Although events are likely to have been missed as the record relies on people taking and publicly sharing photos, it provides a good indication of the range of different conditions that cause overtopping - from bright and breezy days to the extreme storms during winter 2013/2014, which are considered some of the worst on record (Wadey, et al., 2015). By expanding the conditions to include the night time tides, when people were not on site taking photos, allowed us to expand the dataset to include similar tidal elevations which could have experienced hazardous wave and wind conditions due to the passage of a weather system. Only the conditions when the water level exceeds the elevation of the structure toe (2.582 m ODN, the lowest beach level from all surveys between 1996 and 2017) were considered for further analysis (input into BayonetGPE). In total 1244 combinations of waves and water levels (representing 15 minute intervals) were used to calculate wave overtopping estimates, of which 465 combinations were confidently estimated to cause overtopping of some level. Of these 32 of the combinations had an offshore significant wave height exceeding the 0.25 Return Period used by CCO to define winter storms. Together these overtopping discharges (l/s/m), water levels and wave heights were used to plan field deployments and design the WireWall system.

To transform the offshore information to the toe of the structure the 3rd generation shallow water wave model, SWAN version 41.20, was applied. Beach profiles for Hall Road (ref no. 11A02250) were obtained from 1996 to 2017 (Figure 3.1). Four profiles were selected (Table 3.1). The 3 recent surveys capture seasonal variability of the upper beach and the earliest profile represent an unusually low beach level, which had the potential to allow greater wave impact at the land-sea interface. The beach surveys were extended offshore to the WaveNet site using Seazone bathymetry from 05/12/2014, originally collected by the UK Hydrographic Office at 1 arcsecond. They were also extended landward onto the grass inland of the parking spaces using the longer transect taken 1st September 1996. The other transects used stopped at the sand-structure interface. The model settings were calibrated using the 2017 profiles with an AWAC positioned close to the low water mark just south of our beach survey line as part of the Cell Eleven Regional Monitoring programme. The past events closest in time to the beach surveys were used in the calibrations (25/02/2017 10:15; 04/04/2017 17:15; 04/10/2017 22:15). The AWAC data are hourly, which limits the number of validation points for the three profiles considered. The model was run in a computationally efficient 1DH (1 dimensional horizontal) profile approach (as is common practice in industry, especially when offshore data are limited) using 3rd generation mode to propagate the onshore directed component of the wave energy towards the structure. Where values for parameter settings in the model were not specified by an earlier storm modelling application to Liverpool Bay by Brown (2010), or are not known through available observations, default settings have been applied. The horizontal grid resolution was 10 m to allow an efficient run time. Ideally a 2DH domain would have been used to capture wave refraction and wave-current interactions, but our focus was on the development of new observational techniques so the simplest approach using readily available boundary conditions was used as is standard practice in initial scoping studies to develop a business case for the funding of coastal works.

The nearest grid point to the structure toe was approximately 3.5 m offshore and was used to extract information ($H_{m0,t}$ $T_{m-1,0,t}$ where subscript t denotes at the toe) for input to BayontGPE. The use of bulk wave parameters from the wave buoy to force the offshore boundary were compared with the use of spectral input. Minimal differences in results and a large computational time saving meant bulk values were applied (H_{m0} and T_p data as a time series). The bottom friction was set to use bed ripples and a sediment size of 0.23 mm (D_{50} for the upper beach at Crosby, Pye et al., 2010). The wave breaker parameter for a flat near-horizontal bathymetry, a value of 0.55, was used to match the industry standard assumption built into the design of the physical modelling. The model was calibrated using observations on the 25/2/17 and then checked using the later surveys (Table 3.3). The AWAC was only deployed from February 2017, limiting the number of validation points as this project started January 2018.

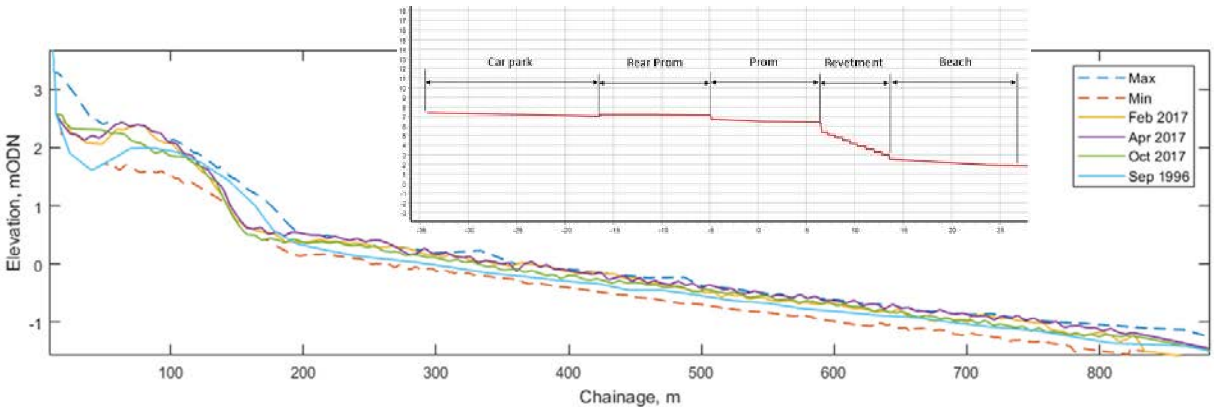


Figure 3.1. Beach survey data used in model calibration and sensitivity analysis of beach level. The max/min values represent the upper and lower bounds of variability in the beach levels between 1996 and 2017. The insert shows the beach-structure-car park profile, provided by Sefton Council.

Table 3.1: Beach profiles applied in the numerical overtopping estimates.

Date (DD/MM/YYYY)	Description
24/02/2017	A relatively high upper beach ridge with scour close to the toe.
04/04/2017	A similar profile to 24/02/2017, but with less scour close to the toe and the ridge has migrated slightly higher up the beach to the structure.
04/10/2017	A low wide upper beach ridge.
01/09/1996	The lowest beach levels at the structure toe within the survey data.

Table 3.3: SWAN (v41.20) wave validation using the AWAC positioned close to the LW mark. The model data are extracted at the point on the lower beach profile where the water depths are representative of those measured by the AWAC.

Survey date	Wave-Water level-wind forcing	%error depth	%error Hs	%error Tp	%error Tm02	%error Direction
24/02/2017	25/02/17 10:15	-0.82	0.33	-3.00	-6.64	-7.33
04/04/2017	4/04/17 17:15	-1.02	5.66	-7.08	-13.13	-0.35
04/10/2017	4/10/17 22:15	-0.1	-15.76	4.07	56.05	6.59

The empirical rules in EurOtop for a smooth dike slope, wall and bullnose structure were applied with the addition of variable friction to account for the steps on the sloped revetment at Crosby. The friction was set depending on the water level. An influence factor for the permeability and roughness of, or on, the slope (Υ_f) of 1 represents smooth concrete and 0.75 represents the influence of ribs. As the steps have a greater relative roughness at low water levels (i.e. the wave has to travel over a number of steps so the friction is greater) and at high water the steps are less effective at retarding the run up, we apply a roughness factor of 0.9 when the water reaches the top step and 0.75 when the water levels are near the toe, linearly interpolating between these values for intermediate water levels. Due to the limited research into oblique wave attack for longcrested waves, wave angle was not considered for the short-crested conditions at Crosby, where the wave approach is from an acute angle.

Each data point was run through the SWAN-BayonetGPE approach (Figure 3.2) and those events with a high confidence (i.e., a Mahalanobis distance (md) < 2) of the wave overtopping discharge estimate were kept. The conditions input into SWAN could then be analysed to identify monitoring thresholds in the offshore wave conditions (at Liverpool Wave Buoy), coastal water levels (at Liverpool Gladstone dock tide gauge) and coastal wind conditions (at the Hall Road Coastguard station weather station) for wave overtopping. The initial analysis indicated wave overtopping became more severe once mean spring high water was exceeded, i.e. 4.46 m ODN at Liverpool Gladstone dock tide gauge – NTSLF predictions for the years 2008 and 2026, which is approximately two steps down from the vertical sea wall. All winter spring tides larger than the mean were thus identified as potentially hazardous days for fieldwork.

For the physical modelling (Section 4.6 and 4.7) only water levels higher than mean spring tide (around 2 steps down the revetment) were applied to focus on conditions when overtopping could occur. BayonetGPE was applied using measurements from the flume experiment without the need for the SWAN model to transform the waves to the structure toe. These input flume data were obtained during the wave calibration tests, and were collected at the structure toe position prior to the structure being installed.

After successful field deployments (Section 4.10) the same SWAN-BayonetGPE approach as used for the past photographic evidence was applied. Available monitoring data were obtained and the overtopping window was simulated to generate numerical estimates to compare with the observed data.

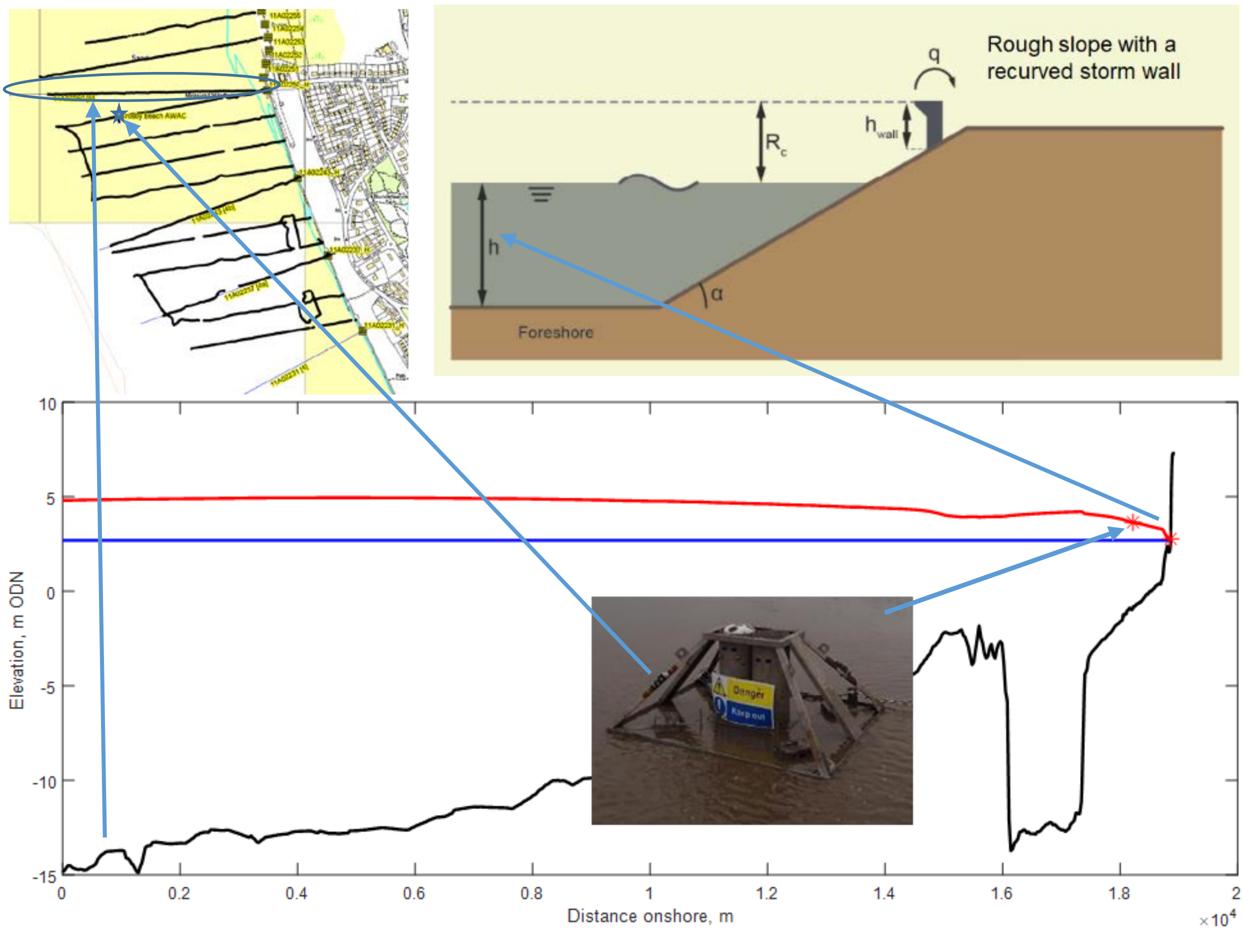


Figure 3.2: The profile line used in this study (top left). The SWAN model bathymetry (bottom) clearly including the Mersey channel, with an example output showing the H_{m0} values (red line) on top of the still water level (blue line). The stars indicate where information is extracted for validation against the AWAC (blue star) and for input into BayonetGPE (red stars), using the closest rules from the EurOtop guidance (top right).

Key information about the numerical approach

Following the update of the EurOtop manual and the BayonetGPE tool (Pullen et al., 2018) behind the guidance in 2018, all BayonetGPE estimates (for photographic evidence, flume and field analysis) used in the WireWall project were reproduced. Hereafter '(O19)' is used to indicate the values were re-estimated in October 2019 using the most recent version of BayonetGPE within the project. These updated data are presented in the results section to capture the latest developments in numerical prediction capability and prevent any discrepancy between numerical estimates generated at different stages of the WireWall project. It is this version of SWAN-BayonetGPE that is also applied to the 15 min field data to compare with the WireWall field measurements, the SC warning thresholds and the EA's warning system based on guidance in EurOtop (2007).

3.2 WireWall system design and laboratory testing

The mobile, battery-powered WireWall system was configured to record wave-by-wave overtopping volumes and horizontal speeds at Crosby using a 3D mesh of (cheap and easily replaceable) capacitance wires and accompanying electronics. It was designed to withstand high velocity (40 m/s) jets and incorporated redundancy to minimise the impact of data loss due to damage. A prototype system was developed, tested and calibrated at NOC in Southampton, then validated using tank data in the 2D wave flume at HRW. The wave overtopping discharge estimates for the existing structure at Crosby set the specification of requirements for WireWall's configuration (the estimated height and inland extent of overtopping guided the size of the rig and the mesh spacing), and also aided in planning field deployments.

3.2.1 Principles of operation

The WireWall system consisted of one or more units (Master unit plus Slave/s). Each unit had 6 capacitance wires arranged in a row, with each wire being next to an earth wire separated by about 1 cm: this gap was kept constant by tensioning the wires. When water forms a bridge between the capacitance and earth wires the output capacitance signal changes according to the wetted wire length. The signal is an integral of the wetted length. For example, 10 drops of 1 cm diameter each, hitting the wire in different places at the same time, would give the same signal as one body of water of 10 cm diameter. The data is output at 400 Hz and all 6 wires are time-syncronised at this level. The Master unit outputs a sync-signal (sample number) to the Slave unit(s), and this signal allows the data from multiple units to also be syncronised together at 400 Hz.

Prior to being installed on the WireWall rig, the wires themselves were calibrated by dipping them into known depths of water. This calibration allowed the conversion of the raw data (output in units of pico Farad) to wetted length/depth in mm. Once the system was installed in the flume, the calibrations were double-checked by raising the water level in the flume in known increments: the results showed that the slope of the fit used in the calibration was correct, but the additional cabling etc. added a constant "baseline" offset (which is automatically removed by the post-processing procedure). This is seen in the WireWall measured depths (Figure 3.3) as an offset of 5 to 8 cm (different for each wire) for the "dry" wire value. Other than this check, it should be noted that data from the WireWall system was ***not*** calibrated or tuned in any way to bring it into agreement with the tank data.

In the flume, the wires on each of the two WireWall units were located behind the modelled sea wall, spaced at 7 or 10 cm intervals along the sea-land axis, with the seaward-most wire (wire1) positioned at the seawards edge of the sea wall, and the second wire (wire2) positioned directly above the seaward edge of the most seaward tank with the remaining 4 wires spaced progressively further inland (Figure 3.5) over the seaward edges of the remaining tanks (or tank partitions). The lower ends of the wires were level with, or just below the top of the tanks which were themselves level with the top of the sea wall. This arrangement means that the volumes measured by the wires can be compared directly to those collected in the tanks. The time delay between overtopping water arriving at different wires allows the calculation of the horizontal velocity of the water between these wires. If the speed of the water is assumed to be constant (a reasonable assumption over short distances) then the volume (per linear meter) of water passing a wire for an overtopping event is given by:

volume (m^3/m) = speed (m/s) * mean wetted depth (m) * duration of event (s)

The data analysis depends on accurately detecting the time of arrival of water at each wire, and also determining the end of the event (i.e. when the water for an individual wave has passed the wire) to obtain the event duration. In the flume the start of an event was defined as the time at which the measured "depth" increased sharply, i.e. the rate of change of depth was above some threshold. The end of the event was determined as the time at which the measured depth returned close to the value recorded just before the start of the event (the "baseline" depth). The mean depth is calculated as the measured minus baseline value (thus removing any offset) averaged over the duration of the event. The flume results presented here all used the same thresholds. The threshold was set by examining one or two runs in detail, i.e. visually checking the time series of elevations and the resulting volumes to ensure that all events visible in the former are associated with a volume (Figure 3.3). If the threshold was set too high then events would be missed and return zero volume. Conversely, if the threshold was set too low then any noise in the signal could be interpreted as a (false) event start. See Figure 3.3, which shows a section of data from one of the flume runs carried out in September 2018. In this example, all events seen in the depth signal result in a volume, and there are no (noise) volumes which do not have a corresponding event clearly visible in the depth signal, i.e. the threshold are set correctly. It can be seen that very small volumes are detected, with the smallest in this example being just 2 cm^2 or 0.2 l/m (since 10 cm^2 = 1 l/m) from an event that had a maximum depth on wire5 (slave unit) of just 1 cm and a duration of only 0.1 second.

It should be noted that for a volume passing wire2, for example, the calculation uses the depth and duration measured on that wire along with the apparent speed derived from the time of the event starting on that wire minus the time the event arriving on its more seawards neighbour, i.e. wire1 in this case. The volume calculation thus depends on the accuracy of the measured speed. The accuracy of the measured speeds depends on the speed of the flow and the distance between wire pairs. For example, if the wire pair are separated by 10 cm, and the real speed of the flow is 10 m/s, then an event would take only 0.01 seconds, or 4 samples (at 400 Hz) to travel between one wire and the next: an error of +/- 1 sample would translate to a measured speed of 12.5 / 7.5 m/s or a volume error of +/- 25%. However, in the flume the flow speeds were usually much smaller than this, usually about 2 m/s, hence the expected velocity uncertainty would be about 5%. In the field trials at Crosby the wire spacing was increased to between 30 and 50 cm to reduce such errors. In addition, multiple measurements of the same body of water can be made by using different combinations of pairs of wires, e.g. the volume of water passing through wire6 can be measured using the speeds derived from pairs 1 and 6 (separated by 50 cm), 2 and 6 (separated by 40 cm) etc. The comparison of results from different wire pairs allows uncertainty in the measurements to be assessed. To denote the pairs of wires used in calculations we use the notation wires AB or wire pair AB from here on to mean the data collected from water passing between wire A to wire B.

These wave-by-wave measurements of volumes are converted into an overtopping discharge for a defined period, and the mean and standard deviation of the discharge can be compared with estimates from the numerical tools (typically based on 1000 waves), which assume the overtopping is uniform over a linear meter (m^3/s/m or l/s/m).

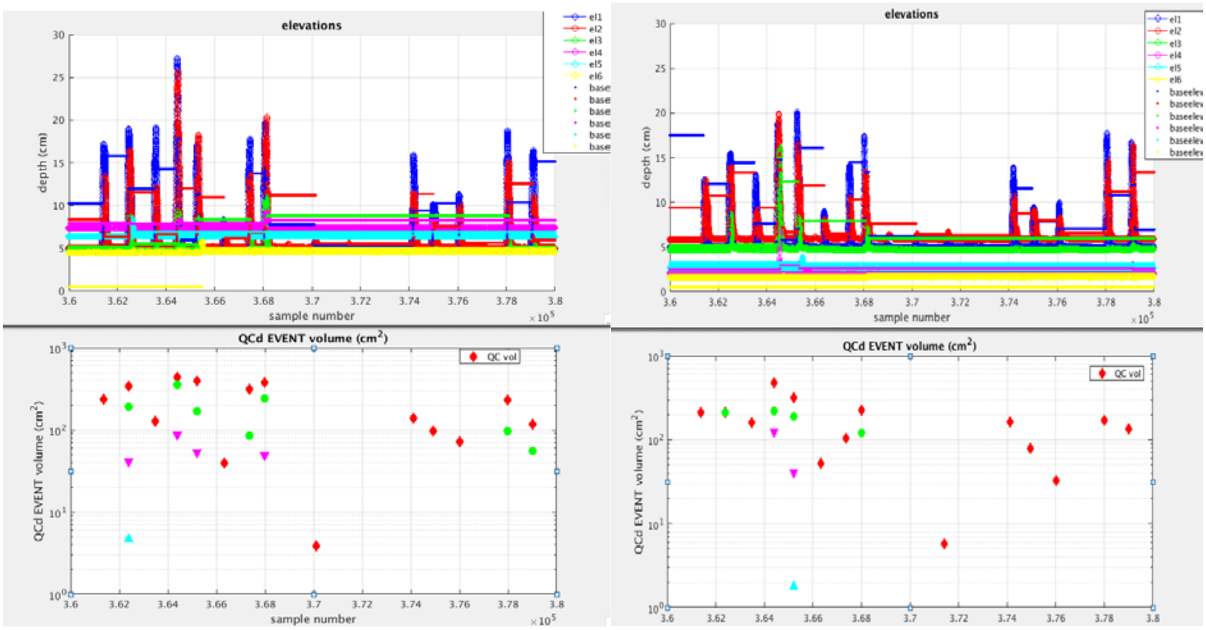


Figure 3.3. Top - time series of elevations (depths, or wetted length) as measured by the six wires on the Master unit (left) and the Slave unit (right). Wire1 (blue) is at the seawards edge of the wall, and wire6 (yellow) is furthest inland. The horizontal lines are artefacts of the processing and should be ignored. Bottom - volumes from the Master and Slave units. Colours as in key for top figure, i.e. red is volume passing wire2 (speed from wire pair 12), green is volume passing wire3 (speed from pair 23) etc. Note that the test (number 131, 18th September 2018) and the section of data were selected at random, rather than representing the best possible example. Also note that the elevations are not identical between Master and Slave: since the differences vary between one event and the next this is not caused by e.g. a calibration error, but is due to the actual overtopping in the flume not being completely constant across the width of the flume.

3.2.2. Validation of the measured apparent speed

Since the wires are oriented vertically in the flume tests and Crosby trials, only the horizontal component of the velocity is measured: this is the crucial velocity component for hazard impact assessments. It is thought that the absence of a vertical velocity measurement causes minimal error to the total volume calculation since, for a tube of water travelling on a diagonal trajectory (see Figure 3.4, top schematics), the resulting increase in measured wetted length (which increases with increasing vertical angle) is exactly offset by the underestimate in speed which results from using the horizontal component of velocity only.

There was no alternative system to measure overtopping speeds in the flume, hence no way to directly validate the speeds measured by WireWall in the flume. Instead, the wires were placed in a horizontal position and water filled balloons were burst at heights of 11 to 14 cm above the uppermost wire (Figure 3.4). The observations were compared with the expected speed of water falling under the influence of gravity (assuming that gravitational potential energy is converted to kinetic energy during the fall, using Newton's Law of Gravity: $Mgh = ½Mv^2$, *where M=mass, g=gravitational acceleration 9.81 m/s², h=fall distance and v=speed*). Data were also compared between different pairs of wires to give confidence in the results through cross-pair validation. For example the speed calculated between wires (a) 1 and 6 (b) 2 and 5 and (c) 3 and 4 should all be the same since they share the same central point. Comparing results (Figure 3.4) from widely spaced wires (e.g. 1 and 6, blue stars) with closely space wires (e.g. 3 and 4, downward green triangles) gave confidence that the sampling frequency of 400 Hz was adequate to capture the sorts of speeds measured in the flume trials, despite the close spacing of the wires (10 cm or less). In general the comparison with gravity, and the cross pair comparison, agreed extremely well.

In the field, the wire spacing was increased as far as practical (within the physical limits of the rig) in order to reduce errors in the measured velocity, and multiple cross-pair validation is used to identify potentially erroneous velocities.

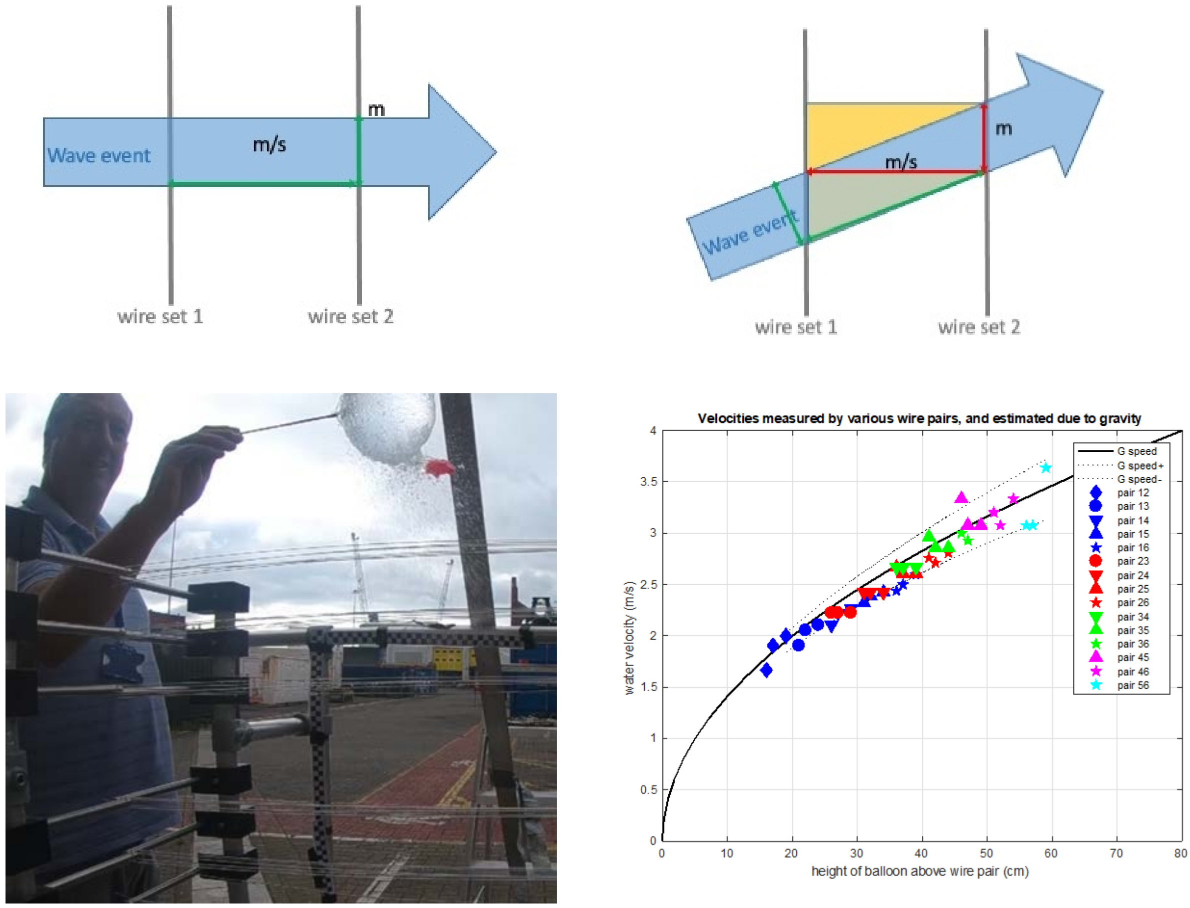


Figure 3.4: Top: schematic showing how the changes in measured depth and speed for a flow at an angle to the horizontal (red) offset each other and produce the same volume as the actual depth and speed of the flow (green). Bottom: balloon tests to validate speed measurements. The wires are now oriented

horizontally (left) rather than vertically (as in the flume and at Crosby). Right: the data points are the WireWall speeds measured at the centre point between pairs of wires (with wire 1 at the top and wire 6 at the bottom of the rig) from three balloon tests with wires 10 cm apart and a 400 Hz sampling rate. The solid black line is the expected water velocity calculated using the height of the balloon above the wires and the acceleration due to gravity. The dashed black lines show the error in the measured velocity if the water was detected late/early by +/- 1 sample.

3.2.3 Validation of volume measurements in the HRW flume

While velocity measurements were validated at the dockside at NOC as described in Section 3.2.2 above, the volume measurements were validated in HR Wallingford's flume facility. The wave flume (Figure 3.5), was 45 m long, 2 m deep and 1.2 m wide. It was equipped with a piston-type wave paddle controlled by HR Wallingford'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, e.g., JONSWAP, Pierson Moskowitz, or user-defined forms including bimodal spectra. Using traditional methods (collection tanks) of assessing wave overtopping in the flume, the WireWall measurements could be directly validated against the water volumes collected in overtopping tanks.

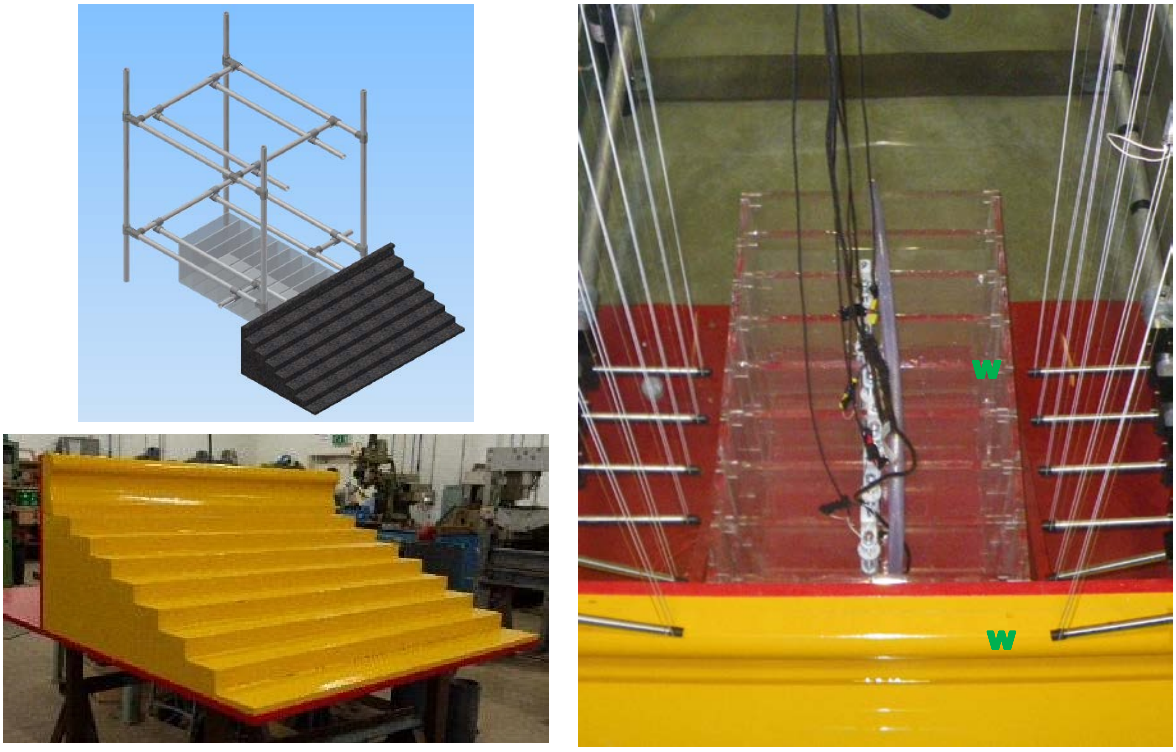


Figure 3.5: The WireWall rig design for the flume tests (top left) and the physical model of the sea wall structure (bottom left). Right, WireWall within HR Wallingford's flume (left) during the trial in August 2018 with the partitioned perspex tank. The WireWall Slave unit is to the left of the tank, and the Master unit to the right, with wire1 and wire6 indicated in green.

A prototype WireWall system was designed and engineered to fit within the flume in order to assess its capability under controlled wave conditions. Spring-loaded tensioning clamps were used to align 2 rows of 6 vertically tensioned wires. The capacitance wires were looped around the lower support (Figure 3.5) to double the sensitivity and prevent issues with sealing exposed ends that would be immersed in water during the overtopping events. Each of the 6 wires simultaneously logged high frequency (400 Hz) data to a single electronics unit, and the two units (Master and Slave) were also syncronized at 400 Hz. The rows were aligned with the oncoming wave direction to capture the speed of the overtopping jet. Two rows were used to: (a) capture spatial asymmetry in overtopping across the flume (which is not detectable by a single tank), (b) allow an assessment of uncertainty between the two units, and (c) to provide redundancy in case of damage or failure. The rig was made of 33.7 mm OD (outside diameter) aluminium tubing clamped to allow full adjustment of the wire positioning relative to the collection tanks. The flume rig was 1200 mm long, 800 mm wide and 1800 mm high (Figure 3.5). PTFE coated silver plated copper wire, with a 0.95mm outer diameter and a conductor diameter of 0.51 mm (24 AWG) was used for the capacitance wires. The earth wire was 0.9 mm diameter tinned copper wire. The wires were positioned to allow direct comparison of the WireWall volume data with that from the collection tanks. For example, during the trial beginning 20th August 2018 (Table 3.5) the wires were aligned with the partitions in the HRW perspex collection tank (Figure 3.5): the partitions were 78.5 mm long (in the sea-land direction) and 376 mm wide. In addition to WireWall itself, NOC converted the capacitance wire technology into a set of electronic rulers or "dipsticks" to obtain accurate wave-by-wave depth and volume changes within the tanks. The dipstick data were recorded at 1 Hz. The calibration of the dipsticks was double-checked by filling the tanks to various known depths. In addition, at the end of some tests the depths registered by the dipsticks were checked against the traditional method of manual depth measurements.

Starting with known wave conditions from the offshore wave buoy, and values from a joint probability wave and water level study at the same location, a representation of the coastal conditions for a 1:7.5 scale model of the Crosby sea wall were generated. A bathymetry representative of the Crosby beach and sea wall profile was built in the flume. The wooden structure was designed using a laser scan at the Hall Road survey transect collected 11th December 2013. The wave paddle conditions were calibrated using a four point reflection wave gauge array located where the structure toe would be positioned. Calibration was performed prior to the structure instalment to minimize corruption of incident waves by reflections. The procedure ensured the wave paddle conditions deliver the SWAN modelled conditions at the structure toe for the observed photographic events. These wave conditions were re-applied when the structure was installed and the flume filled to the required depth using the electronic readout at the flume tap. No further measurements of the water level conditions were made during the overtopping experiments. When scaled up to “real world” conditions the wave heights at the structure toe ($H_{m0,t}$) varied from 0.80 m to 0.94 m and peak wave periods at the structure toe, $T_{p,t}$, from 5.72 s to 7.65 s with different sea water levels.

The flume experiments took place over 4 week-long tests summarised in Table 3.5.

Week 1 (9th-13th July) was a preliminary trial to check the WireWall rig design and for NOC staff to familiarise themselves with the flume capabilities. The structure used was an existing one rather than the Crosby structure. Electronic problems meant that there were no usable WireWall data but the trial allowed NOC to make refinements to the rig (e.g. improving the supports for the wires by adding a tensioning system, resolving the electronic issues etc.) prior to the subsequent tests. It was also noted that when pumps were used to reduce the level of the pooled waters around the collection tanks this resulted in significant asymmetry in the overtopping, i.e. it was not uniform across the width of the flume. This was due to the pumped water being returned to the flume via a pipe that emptied into one side of the flume.

Week 2 (20th-24th August) was the first set of tests using the 1:7.5 scale model of the Crosby sea wall. The perspex collection tank used was 490 mm tall (the height of the sea wall), 400 mm wide (outer dimension) and separated into 8 lateral partitions designed to collect data to calculate the sea-land distribution of overtopping. The walls and partitions were 12 mm wide. The inner dimension of the partitions were 376 mm wide (across flume) and 66.5 mm long (land-sea axis). The more seawards partitions filled very quickly so small pumps (from a local chandlery) were installed in the seaward-most 3 partitions. This means that the accuracy of the volume data from the tanks will depend on the accuracy of the pump correction both in terms of the flow rate and the pump on/off times. Only short runs were performed since the flow rate of the pumps was insufficient to prevent partitions filling up. The WireWall Master and Slave units were arranged to either side of the tank, with the wires aligned with the partition walls. It was noted that the overtopping water skipped across the partition walls (like a stone skimmed across water, Figure 3.6, top) which meant that only total volumes could be used. In addition, water sometimes skipped sideways from the tank walls onto the WireWall wires: this was rectified by building up the side walls of the tank for the final six tests of that week.

Week 3 (3th-7th September). The effective width of the partitions was reduced from 376m to 63 mm by covering most of the tank (Figure 3.6, bottom left) in order to reduce the collection rate so that the pumps could cope with the wave conditions that produced large overtopping volumes. As before, the accuracy of the volume data from the tank will depend on the accuracy of the pump correction both in terms of the flow rate and the pump on/off times. All runs were long (~1000 waves) to add data on various wave and water level conditions to BayonetGPE (O19). *No WireWall system was installed.*

Week 4 (17th-21st September). The perspex tank was replaced with three large tanks designed and manufactured at NOC. These tanks were each 100 mm wide (cross flume) and 1000 mm long and were arranged longitudinally (Figure 3.6, bottom middle). For some tests the three tanks were all against the sea wall to investigate cross-flume non-uniformity in overtopping rates, whereas in others the two outer tanks were moved inland to collect information on overtopping distribution (Figure 3.6, bottom right). A pump was used in the middle tank to allow some long (~1000 wave) runs to be performed without the tanks overflowing.

Table 3.5: Physical modelling experiments carried out in HR Wallingford's wave flume.

Date	Experiment	Outcome
9-13 July 2018	Testing the initial rig design and flume set up with random waves and an existing (not Crosby) coastal structure.	Electronic problems meant that no usable WireWall were obtained. It was noticed that the addition of pumps to remove flood water from the land side caused significant cross-flume asymmetry in the overtopping.
20-24 August 2018	Short runs (a few wave conditions with different severities and different water levels) to validate the system against data from the HRW perspex tank with 8 partitions designed to collect a landward distribution of overtopping volumes. Only the final 6 runs could be used after the tank was modified.	Tank partitions filled very quickly so pumps were added to prevent them overflowing. Hence volume data from the tanks rely on the accuracy of the correction for the pumping out of the tanks. In addition, the thick partition walls meant that water skipped across their tops so only total volume data (not distribution) could be used.
3-7 September 2018	Long runs (1hr, 1000+ waves) to collect flume data to add to the EurOtop database. The small HRW perspex tank was largely covered to reduce the collection rate and prevent the tanks overflowing despite the use of pumps.	No WireWall system used. Volumes rely on the accuracy of the correction for the pumping out of the tanks.

17-21 September 2018	Some short and some long (~1000 wave) runs. NOC installed 3 large tanks, arranged longitudinally. Pumps used as required in some tanks during the longer runs.	WireWall installed and validated against the data from the large NOC tanks. In total 15 test were made: 8 long runs (3 different wave conditions) plus 7 short runs (to test repeatability of a single wave condition).

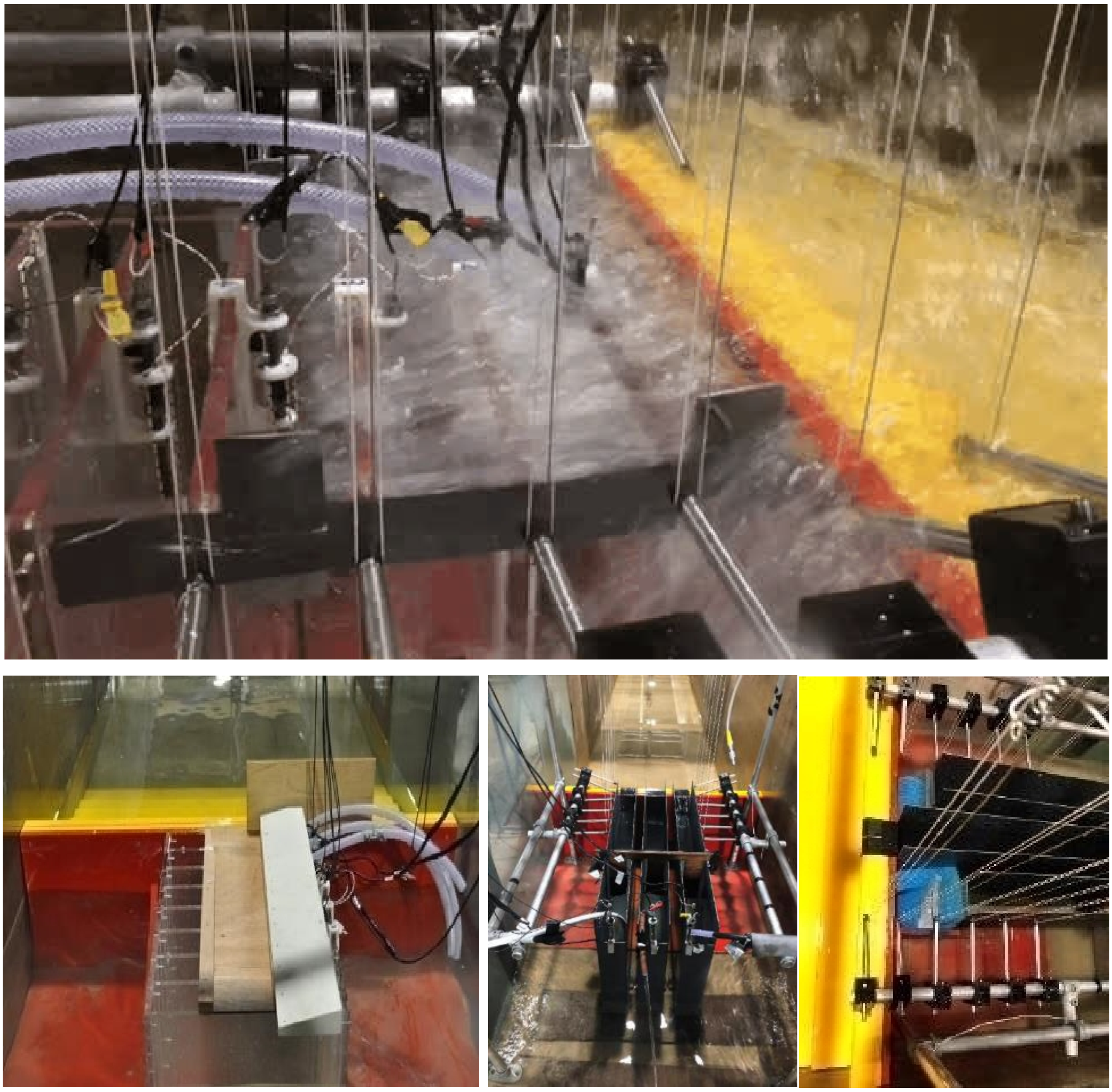


Figure 3.6: Top: the partitioned perspex tank as used during the final 6 runs during the tests in week 2 (20-24 August). Water can be seen skipping across the top of the partition walls, rather than dropping into the partitions. Outflow tubes for two pumps can be seen, along with the "dipsticks" attached to the rear wall of each partition. Clear plastic was taped along the side walls of the tanks to prevent water spilling sideways onto the WireWall wires. Bottom left: the perspex tank covered to reduce the surface area for week 3 (3-7 September) tests to expand the BayonetGPE training set (with no WireWall system deployed). Bottom centre: the 3 large NOC tanks arranged longitudinally, with pumps and dipsticks mounted at the landwards end, for the final week of tests (17-21 September). The middle tank was always against the sea wall to collect total overtopping data but the outer two tanks were moved inland for some tests, to try to collect overtopping distribution information - note the blue sponges (to absorb splash) in front of the tanks (bottom right).

All together the tank data comprises multiple runs of 7 wave-water level scenarios from runs of 1000 waves or more that were suitable to be incorporated into the next release of BayonetGPE. Three of these wave-water level scenarios from 1000-wave runs were performed when WireWall was installed. In addition, a number of short (<1000 wave) runs were performed to validate WireWall against tank data that did not require the use of pumps. Comparisons of the numerical BayonetGPE data with the observational (tank/WireWall) data were made using estimates of the total volume passing the crest. Observed total volumes from the tanks were obtained using the sum of the volumes in the partitions when the perspex tank was used, or the NOC longitudinal tanks (when they were against the sea wall) for week 4. For WireWall total volumes were obtained using data from wire pair 12, i.e. depths and durations from wire2 located immediately behind the crest, along with speed calculated using the time difference between that wire and wire1 (located on the seawards edge of the crest).

An aim of the flume tests was to investigate the land-sea distribution of overtopping behind the wall (along the sea-land axis). This was the motivation behind: (a) the partitions in the small perspex tank; (b) positioning the two outer large NOC tanks inland, 10 or 20 cm from the wall, during some of the tests in the final week; and, (c) positioning the 6 wires of each WireWall unit in a row along the sea-land axis. However, the recurve directed the majority of the overtopping plume upwards and/or offshore. During fieldwork it was clear that the wave overtopping hazard for typical winter spring tides is associated with waves up to 1 m running up the stepped revetment causing a vertical plume on impact with the vertical wall, which is driven over the crest by an onshore wind counteracting the momentum of some of the returned spray. Without wind influence in the flume these conditions did not overtop unless higher water levels were used, which enable the waves to overwash the defence crest as green water with spray (Figure 3.7), more typical of the conditions observed during the extreme storms in winter 2013/2014 (Figure 2.1). The collection tanks limited the wave size that could be simulated due to the speed at which they filled under the green water conditions. Finally the inland extent of overtopping in the absence of wind was very limited even in these more extreme conditions, and the attempt to measure the inland distribution was hampered by the skipping of water across partitions in the perspex tank as previously described, and, when the NOC tanks were moved inland, by water running up the front of tanks and/or splashing from the collected pool of water in front of the tanks, despite the use of absorbent sponges (Figure 3.6, bottom right).

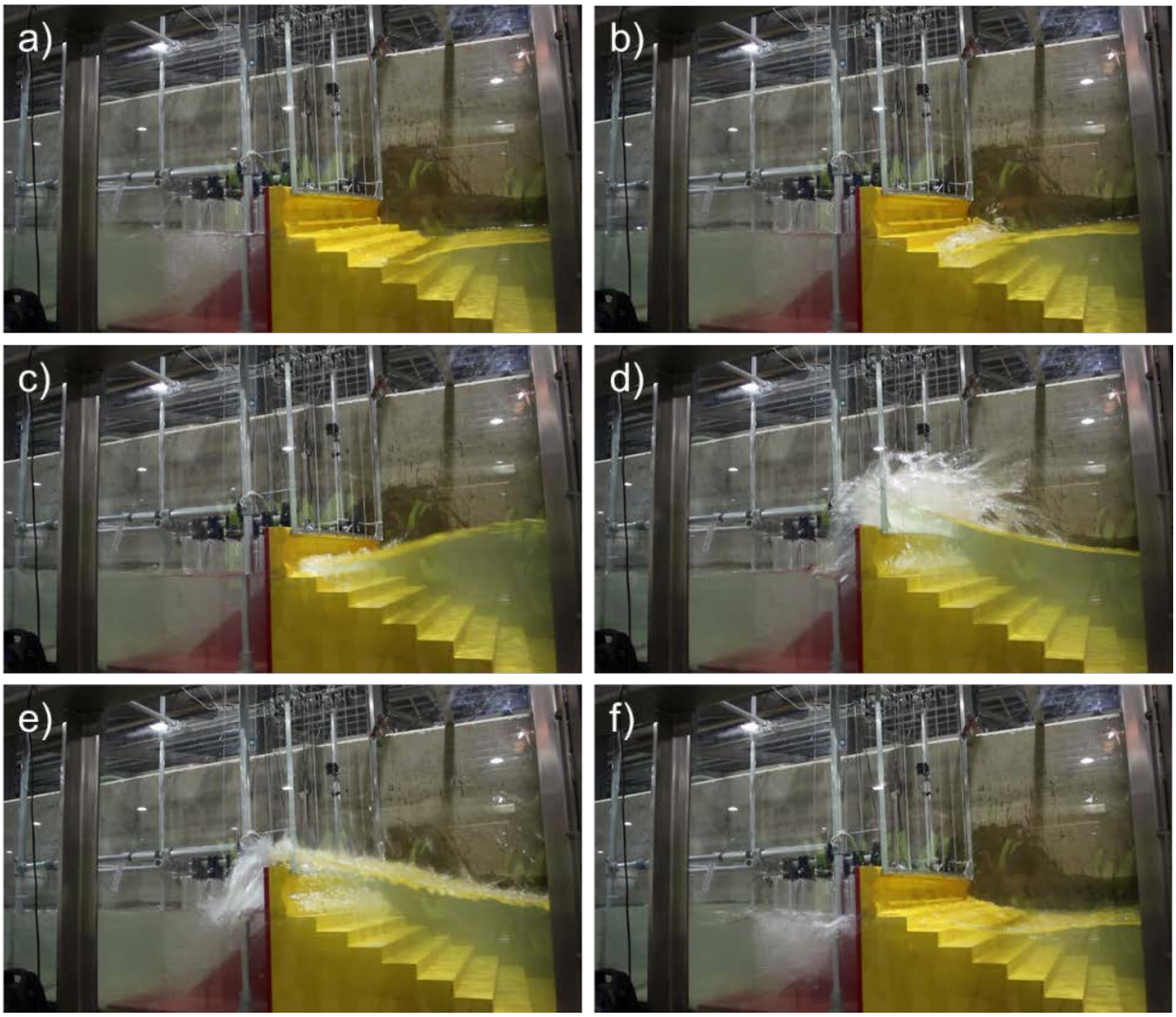


Figure 3.7: Example wave overtopping simulation taken 11:49 22/08/2018 at HRW.

3.3 Field deployments

Following flume tests the system was transferred to the NOC in Liverpool for deployment at Crosby. A site visit with the SC took place early in the project (27th June 2018) to identify the deployment site. Consideration was given to access, safety and position. A section of railing was identified to the north of the slipway area, close to an access gate, with a wide area of promenade, just to the side of the lifeguard observation window. This site was considered to be vulnerable to wave overtopping, but unaffected by the local influence of features within the existing structure (e.g., wave reflections off the slipway, or edge effects where the rock armour is positioned), and situated appropriately relative to the alongshore position of the defence crest. The slipway offering the potential of placing the rig further seaward of the defence line if there was a risk of no overtopping events during the winter period. While other locations experience greater overtopping due to localised effects the data collected would not have been appropriate for the calibration/validation of the numerical tools that do not resolve such small scale variability and localised wave interaction. During the site visit the railing dimensions, and the slope of the promenade were measured to design the deployment frame to position the base of the wires as close as possible to the surface of the sea wall and promenade. The location close to the RLNI station also offered places to mount video cameras to record the wave overtopping during field deployments. This site was just north of the Hall Road beach profile, which intersects the slipway, used in the numerical overtopping assessments. The data are therefore acceptable for comparison with the numerical estimates to assess the value of the WireWall data for the calibration of numerical tools and forecasting systems.

All spring tides exceeding mean high water spring (MHWS 4.46 m OD) were considered as potential deployment windows, as typical winter wave and wind conditions were likely to cause some overtopping, even if low impact, for a short period at high water. Spring tides on the weeks commencing 22/10/2018, 05/11/2018, 26/11/2018, 21/01/2019, 18/02/2019, 04/03/2019 and 18/03/2019 were all identified as potential windows to collect measurements. Relocating the deployments to the slipway was to be considered if typical wind conditions did not generate enough overtopping for a robust test of the WireWall system. This location would allow testing in lower impact conditions, but was not necessary as a brisk wind at spring tide was enough to generate notable overtopping. The numerical overtopping estimates for past events were used to identify thresholds to compare the long-range forecast against to prepare for a deployment or abort. Our target events were typical windy winter days, but the rig was designed to be flexible so the wire spacing could be adjusted (increased) if a storm were forecast to enable accurate measurement of faster moving water jets. While the data logging was identical to that in the flume the wire spacing was increased and the data analysis algorithms adjusted to measure denser plumes of water moving at greater speeds over larger distances. A thicker wire was also used to increase the system resilience, without comprising sensitivity.

For the deployments at Crosby a versatile field rig was designed so that it could be relocated to other locations along the sea wall if needed and the wire spacing could be adjusted for forecast conditions. The rig used readily available aluminium tubing of a standard 48.4 mm OD and galvanised steel fittings and clamps to allow adjustability. PTFE coated silver plated copper (600 Volt, 2.41 mm OD) was used for the capacitance wire and solid tinned copper (1.295 mm OD) was used for the earth wire. The wire tensioning system was designed to use a spring loaded approach that would allow the wires to be attached to the rig on site. This was critical to allow wire changes if damage was sustained and to simplify transportation logistics. Although the rig was designed to fit in a high top long wheel base transit van (Figure 3.8), to increase efficiency the outer frame was stored at the Coastguard station on site. The field rig dimensions were 2412 mm height, 1910 mm width and 2200 mm depth with ability to extend seaward by an extra 450 mm. The size allowed the frame to fit within the external 1800 mm OD railing spacing at Crosby to allow the system to be rigidly secured to the existing infrastructure in addition to being bolted to the floor at the four corners. The depth of the rig relative to the width of the promenade was chosen in order to maintain public assess (for pedestrians, cyclists, mobility scooters and the RLNI quad bike), even with the safety barriers in place. Although the wires were never spread across the full depth it allowed for adjustment in the spacing if an extreme event were to occur or future deployments were planned. For the typical winter conditions the wires were spaced relatively close to the defence crest so that the majority of the wires were in the overtopping zone and hence could provide information on the distribution of overtopping.

Three units were used (Master and two Slaves), each with 6 wires sampling at 400 Hz, and all units were synchronised together. The land-sea spacing of adjacent wires in each unit was set to 300 or 350 mm. The 6 wires of the unit located in the middle of the frame were aligned along the sea-land axis, whereas the wires in the outer two units were staggered to investigate the possible effects of flow separation around one wire sheltering the adjacent inland wire from the overtopping water (see Figure 3.8).

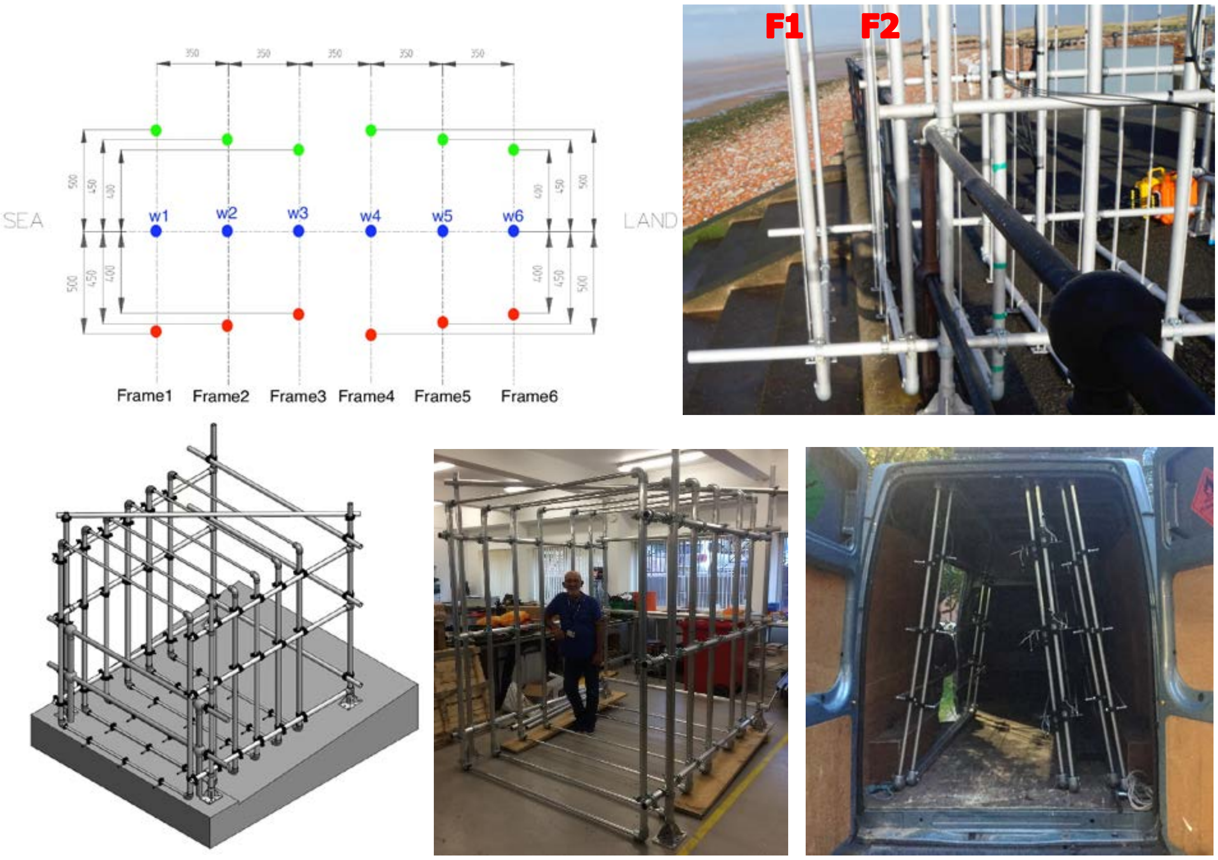


Figure 3.8: Top left - plan view of the nominal wire spacing (mm) for typical winter conditions at Crosby. The six wires for each unit (Master green, Slave1 blue, Slave2 red) are arranged along the sea (wire1) to inland (wire6) axis. Top right - side view of the rig in place, with frames 1 and 2 indicated by red F1 and F2. Bottom - the field rig.

Each of the three units were powered by, driven by and logged by its own set of electronics. The use of three units allowed for redundancy if one unit failed. If the Master unit failed entirely the slaves would continue with only the loss of the cross-unit synchronisation signal. Use of multiple units allows an assessment of alongshore variability in the overtopping. The use of six wires per unit allows multiple estimates of the speed of the overtopping from multiple pairs of wires (15 estimates in total if all 6 wires work) giving confidence in the speed and volume measurements and an estimate of uncertainty due to the complicated mix of spray and solid water travelling in various speeds and directions. Multiple wires again provides redundancy since only two are needed for a velocity estimate.

The system used a modular approach to allow flexibility in the configuration of the wires. The outer rig was bolted to the ground and fixed to the railings. Attached within the outer rig were six rectangular frames, mounted parallel with the sea wall and stacked one behind the other in the sea-land direction (Figure 3.8). Frame 1 projected seawards of the crest by about 30 cm and carried wire1 for all three units (Master, Slave1 and Slave2). Frame 2 was mounted next to the seaward face of the railings at the seawards edge of the crest, and carried wire2 for all three units. Frame 3 was just inland of the railings: water reaching frame 3 would therefore have the potential to impact pedestrians on the promenade. The other three frames were mounted progressively further inland. Hence the sea-land spacing of the wires for all three units could be adjusted by moving the frames in the land-sea direction, and the spacing between the three units and/or the degree of staggering, could be adjusted by moving the wires from side to side within the frame.

The top of the wires were attached to the frame using a tensioning system to keep the gap between capacitance and earth wires at about 1 cm: the actual size of the gap makes no difference to the signal, but just sets a lower limit to the size of droplet that can be detected. In high winds some wires vibrated so tape was added in one or two places along the 2 m length to ensure the capacitance and earth wires did not touch. At the lower end the earth wire was terminated, and the capacitance wire looped around a bespoke plastic fitting that allowed water to run off (rather than pool), whilst also providing protection to the wires from: (a) the ground while the frames were being maneuverer into place and (b) overtopping debris that washed along the promenade.

Our aim was to deploy the system in the field for 24 hour periods on the sea wall during conditions that were forecast to cause some level of overtopping. In reality the system was deployed for a few days at a time (Table 3.6) collecting data during the daytime tides when the research team were on site to operate the electronics (which were removed overnight) and observe the conditions being measured. This allowed some testing of the system's resilience to repeat overtopping and prolonged periods of weather (in particular rain). Prior to each field deployment, the wires were calibrated at the lab in Liverpool and the wires used during deployments were tested post-deployment to detect any damage, e.g. to the PTFE coating of the capacitance wires (Figure 3.9).

Alongside the WireWall data video camera footage was collected and available coastal monitoring obtained as detailed in Table 3.6. Cameras were mounted beside the rig looking alongshore or offshore either focused on the wires or providing a full view. The “site visits” provide footage of the conditions at different locations within Crosby Hall Road car park during tides when WireWall was not deployed. For the later field trials a weather station (borrowed from MMT) was fixed to the landward northern corner of the field rig to collect local wind velocity data. This was installed following discussions with the EA who were also partners on the concurrent project led by Manchester Metropolitan University (NERC grant NE/R009155/1: Quantitative Assessment Tool for Wind Effect on Wave Overtopping Seawalls). Wind is currently not considered in engineering tools to estimate overtopping so our aim was to capture data on the local wind for continued research into the influence of wind on overtopping and to validate their advances in the field.

Figure 3.9: WireWall field wire calibrations and damage assessments.

Table 3.6: Field data collection. * WireWall deployed, ** WireWall deployed and measurements collected, photos available in Section 4.9. The terms to describe the overtopping are defined as follows: 1) "Splashy" means some spray seen above the level of the crest. Any droplets that did manage to come through the rig were unlikely to have hit multiple wires. 2) "Good" means spray came over the promenade and through the rig. The spray density should have allowed multiple wires to have been wetted. 3) "Rig high" means a dense vertical plume of spray was observed with some of the overtopping plumes reaching 2 m tall. BayonetGPE (O19) durations are the period when estimates have high confidence (md<2).

Date *WireWall deployed **WireWall deployed and measurements collected	***BayonetGPE (O19), duration overtopping estimated to have occurred for, hrs:mins***	***Duration of visually observed overtopping when WireWall deployed, hrs:mins***	***Cameras***	***Wind***	***Beach profile***
03/08/2018					Test
04/10/2018					Pre (no event)
21/10/2018					Pre
24/10/2019*	00:00	A few splashes, 1:00			
25/10/2019**	00:30	Splashy, 01:40	2		
26/10/2019**	01:00	Good, 02:00	2		
05/11/2018					Pre/post
08/11/2018*	00:00 Not for use, rig test located south	Splashy, 01:20	2		
14/11/2018					Post
18/01/2019					Pre
22/01/2019**	02:15	Rig high, 03:05		30 min data	
23/01/2019*	02:00	Splashy, 02:10	2		
25/01/2019**	02:15	Rig high, 03.15	3	1 min data	Pre/post
26/01/2019					Post
19/02/2019	Site visit. Short notice forecast, WireWall not deployed		1		
07/03/2019	Site visit. Electronics needed repair, WireWall not deployed		1		
19/03/2019					Pre
20/03/2019*	Not simulated	No overtopping	0		
22/03/2019**	02:45	Good, 02:20	1	Visual notes	Step levels only (GPS failed)
23/03/2019					Post

Pre- and post- deployment beach profiles were collected using a Leica GNSS Rover (antenna), coupled with a Leica CS15 Viva Controller (handset), borrowed from SC. Data were collected using the same approach as the SC so that the profiles could be fed straight into the Cell Eleven Regional Monitoring Programme. The data were stored at 5 m intervals, with the additional collection of data on each step and of the beach level at the toe of the infrastructure. Data from the WaveNet buoy, UK tide gauge and Met Office weather station were also obtained for each deployment. Together these concurrent data provided input forcing to the numerical tools to validate the numerical overtopping estimates against the observed Crosby overtopping events.

The first deployment of WireWall at Crosby was October 2018 (Figure 3.10). Data for all events (Table 3.6) have been processed following the guidance of the projects Wider Interest Group (Appendix VI). Key examples have been made available through CCO and BODC. For information visit https://www.channelcoast.org/ccoresources/wirewall/ and see Appendices IV and V.

Figure 3.10: The first WireWall field deployment with overtopping examples taken during high tide on the 26th October 2019.

4. Results

The results are presented for: the numerical analysis using BayonetGPE (O19) (Sections 4.1, 4.8, 4.11), example validation tests in HRW's flume (Section 4.7) and example field observations (Sections 4.9 and 4.10). The numerical analysis of the Facebook and other photographic data provides a longer dataset covering a range of conditions to assess hazardous overtopping volumes (Section 4.2). These were used to design the WireWall system and plan deployments (Section 4.4). The return period curve data are used to estimate the overtopping volume for the existing structure for coastal conditions that meet the return period criteria (Section 4.5). These criteria will be used in scheme design, our data thus offers secondary information to the consultants doing the design work for validation of the tools they use. These estimates also give an idea of the volumes of overtopping that could be experienced for different severity storms for hazard management planning. To give confidence in our numerical estimates, BayonetGPE (O19) is compared with data obtained from the physical modelling of Crosby beach for the existing structure (Section 4.8). These flume data were also used to validate the WireWall technology and plan its configuration prior to field deployment.

For the long (≥1000 waves) runs when WireWall was also installed we compare the numerical, flume (tank) and WireWall results (Section 4.8). Once confident with the WireWall approach the system was deployed at Crosby – collecting the first ever field measurements of horizontal overtopping volumes and speeds on a wave-by-wave basis rather than just total volume per storm. We show two example events (Section 4.10) to demonstrate how these data can be used to validate numerical estimates of overtopping and flood hazard warning systems. The data in this report are available through both CCO and BODC (see Appendix IV for the DOIs).

4.1 Numerical overtopping estimates for past events based on photographic evidence from Facebook and Project Partners

The mean wave overtopping volumes from BayonetGPE (O19) were generated by HRW for all tides when there is a photographic record of some level of overtopping occurring during the period January 2013 to December 2017. The presented results use the offshore conditions on the day of the photograph and the beach survey from 24th February 2017. Data are available from the CCO website and BODC for all four profiles in Section 4.3 (see Appendix IV) to capture uncertainty in overtopping due to beach evolution.

A greater density of data occurs for the more typical windy spring tides than extreme events. In this section we present the estimates of mean overtopping volumes from BayonetGPE (O19) while the estimates of the upper and lower 1 s.d. and 2 s.d. are available in the data archived with BODC (see Appendix IV).

The mean overtopping discharges are plotted against the combined offshore wave and nearshore water level conditions (Figure 4.1), i.e. the parameters typically used by coastal managers to develop local warning systems. The plot shows BayonetGPE (O19) is less suitable for the low wave and water conditions, when overtopping is more likely to be a low density splash. Values that have a high uncertainty (md >2) are discarded in further analysis, however they indicate where new data are required to expand the application of BayonetGPE (O19). The estimates falling around the EA flood hazard thresholds have a high confidence (md<2), and thus can be used to assess the local hazard thresholds. The EA's overtopping warning accurately reflects the past storm events when waves were likely to be breaking directly onto the promenade and posing a flood hazard to the car park.

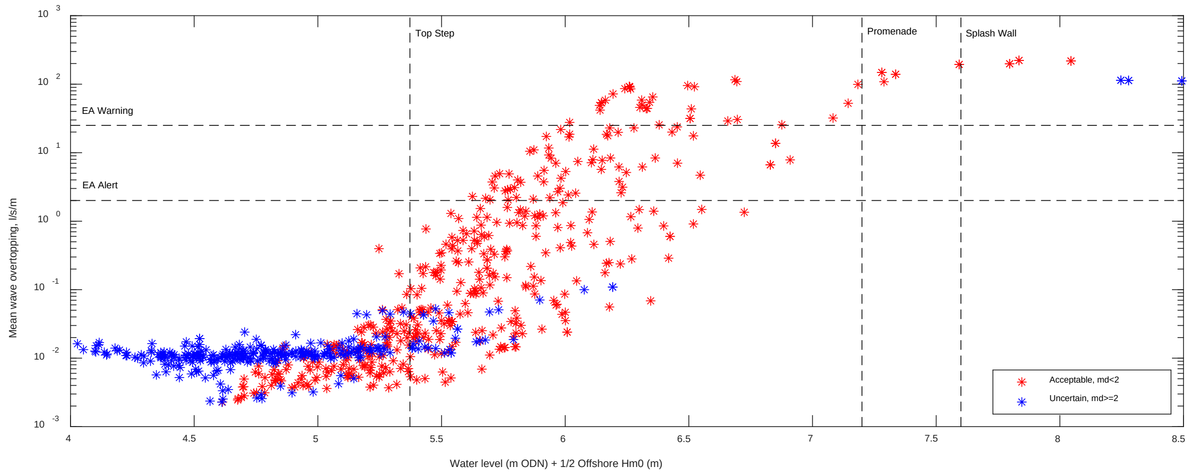


Figure 4.1: BayonetGPE (O19) mean overtopping predictions for the photographic evidence collected January 2013 – December 2017 using the beach survey collected 24th February 2017. The horizontal

dashed lines indicate the thresholds used in the EA's flood forecasting system. The vertical dashed lines indicate the SC's thresholds for flood hazard management. The dashed vertical lines indicate the wave and water levels relative to the structure (the top step of the revetment and the Promenade/Splash Wall hazard thresholds). The colour coding indicated the uncertainty in the overtopping estimates based on the Mahalanobis distance (md) value.

The mean overtopping estimates for conditions that are confidently represented within the database behind BayonetGPE (O19) are shown (Figure 4.2) relative to the operational overtopping hazard management thresholds applied by SC (see Section 2). The values are colour coded into "traffic light" warning categories for wind influence. They are presented against the combined water level and offshore wave height criteria relative to the Mean High Water Spring (MHWS) tidal level. The level of the Splash Wall (SW) fronting the car park and the Toilet Block Platform (TBP) at the inland boundary of the car park are shown by vertical lines. Figure 4.2a shows the flood hazard thresholds are rarely exceeded by these past events, however, wind blow spray overtopping could occur for a number of the events. It is seen that lower winds are associated with more overtopping for the same combined wave and water level conditions. This is a misleading artefact due to the linear relation between the wind and wave height (Figure 4.5) and shallow depths causing depth induced breaking, limiting the impact of the larger waves on the windier days: in other words, *for a given water level*, on windy days the offshore wave heights are larger (so the data in Figure 4.2 move to the right on the x axis) but these waves break as they enter shallow water and so do not result in greater overtopping than is seen on less windy days with the same water level. By plotting the mean overtopping discharge against water level alone, it is more clearly seen that in this tidally dominated location that higher wind speeds cause more overtopping (Figure 4.2b). It is suggested that for this location the warning system could be simplified to consider predicted water levels and forecast wind conditions alone. As an alternative, offshore wave height could be substituted for wind in the colour coding (as shown later in Figure 4.4a) to give a less noisy signal, but public wave forecasts are only available 48 hours in advance unlike 5 day weather forecasts.

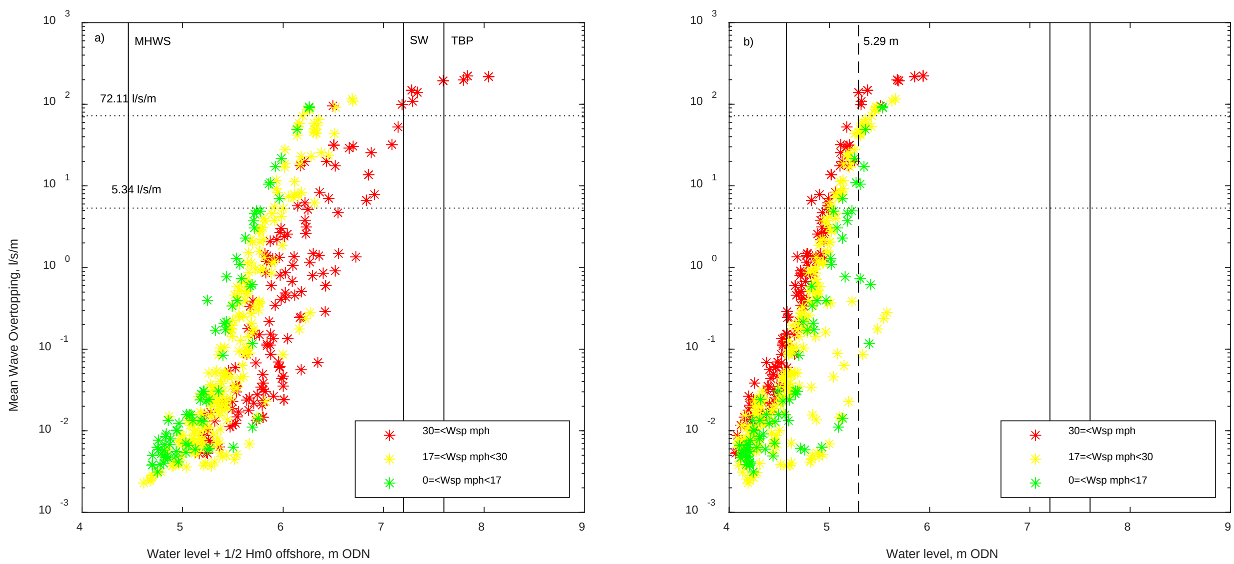


Figure 4.2: BayonetGPE (O19) mean overtopping predictions (md < 2) for the photographic evidence collected January 2013 – December 2017 using the beach survey collected 24th February 2017. The colour coding represents the wind speed (Wsp) thresholds used by Sefton Council for their early warning system. If the wind has a west to north west direction then the speed is considered to issue no hazard (green), an alert (amber) or a warning (red).

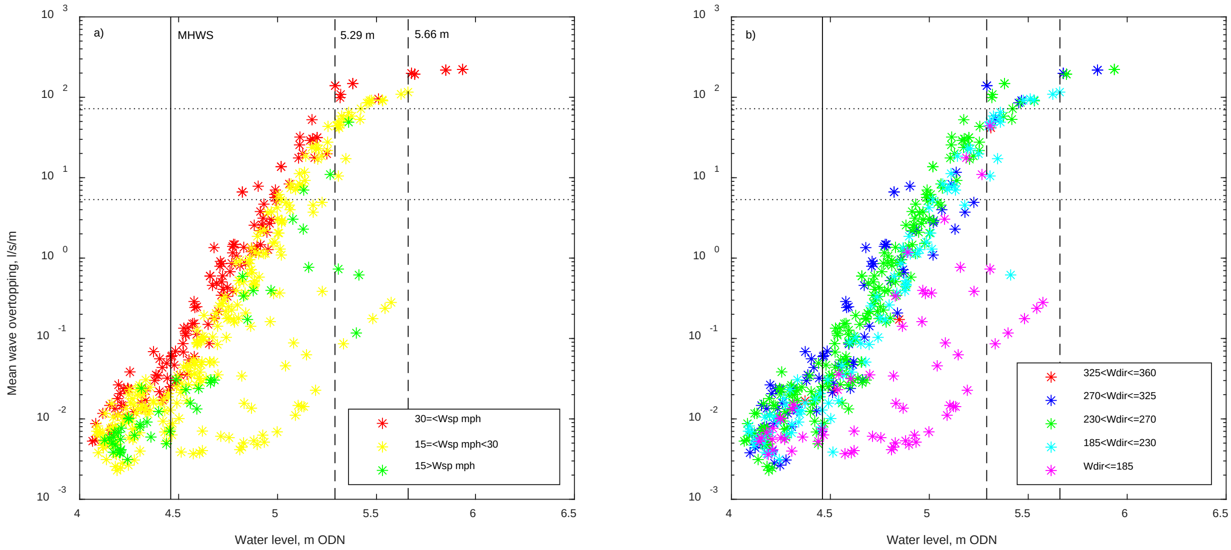


Figure 4.3: As in Figure 4.2 with a change in the x-axis scale for clarity and colour coding to show a) alternative wind speed thresholds and b) wind direction (Wdir).

From the past overtopping estimates a mean discharge of 72.11 l/s/m was identified as a lower threshold when water was expected to pass over the crest of the sea wall at Crosby (i.e., the promenade level, Figure 4.2a). However, events with lower wave and water level combinations were found to cause similar overtopping discharges although not considered as hazardous by the SC alert system. To capture all these events a water level threshold alone of 5.29 m ODN was identified as the level above which these more extreme overtopping discharges occur (Figure 4.2b). It is around this water level that the overtopping discharge starts to plateau with further increase in water levels. This suggests as water levels reach and exceed the top step of the revetment (~ 5.4 m OD) waves are able to break directly onto the vertical section of the wall or even over the promenade: the estimates for these conditions represent a possible upper overtopping limit when more green water (overwash) conditions occur. For these higher water levels the waves experience less depth limitations but remain fetch limited. A higher threshold of 5.66 m ODN was identified for conditions that pose a hazard to the car park (Figure 4.3a). Using these thresholds there is the potential that extreme tides with minimal wave activity could be considered as hazardous to promenade users. The highest astronomical tide at Liverpool Gladstone dock is 5.44 m ODN (National Tidal and Sea Level Facility (NTSLF)). We therefore revisit the wind criteria and find a more likely threshold to associate with wave overtopping is 15 mph or 6.7 m/s (Figure 4.3a) when winds have a westerly component (i.e. are between 185° and 325°, Figure 4.3b). When looking at the offshore wave conditions at the wave buoy there is a more clearly defined requirement that the significant wave height must exceed 1.4 m in addition to water levels exceeding 5.29 m ODN for hazardous overtopping to occur (Figure 4.4a). It was also found that overtopping is more likely to be associated with waves that have an offshore peak period exceeding 5 s.

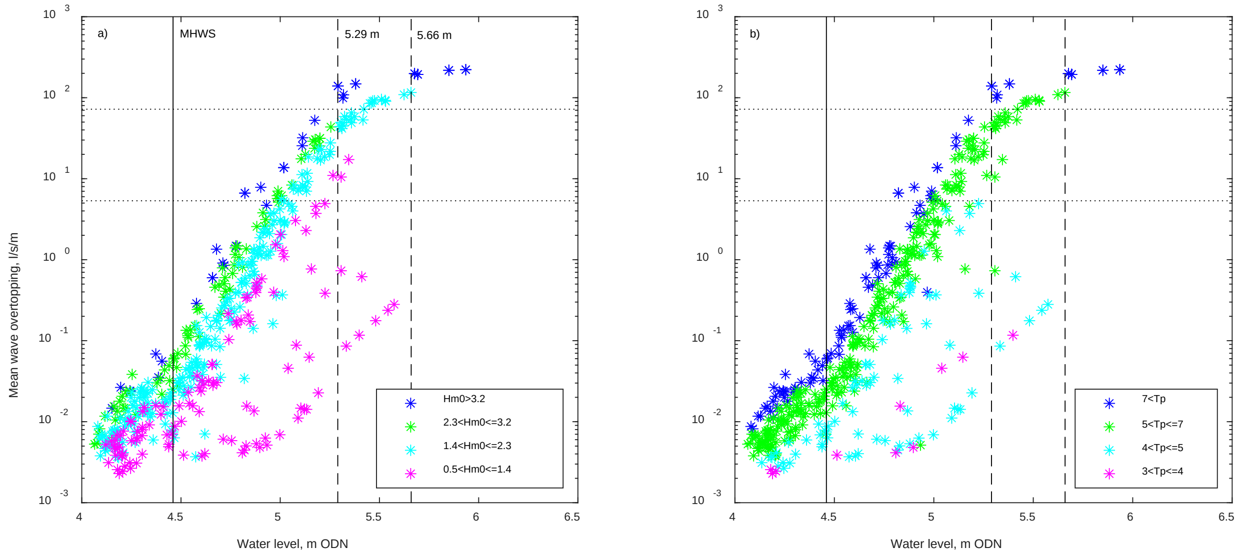


Figure 4.4: As in Figure 4.2 with a change colour coding to represent a) offshore wave heights (H_{m0}) and b) offshore peak Period (T_p) categories.

In Figure 4.5a the offshore wave height is found to have a roughly linear relation with the local wind speed (for wind directions with a westerly component). More scatter occurs once the wind exceeds 30 mph (13.4 m/s). Again we confirm that the largest waves (>2.5 m) are associated with wind directions between 185° (although more likely 230°) and 325°. Comparing the wave heights at the toe (from the SWAN model) to the water level (Figure 4.5b) we see a linear relation limiting the maximum wave heights at the toe due to depth induced breaking. Under the windier (higher wave) conditions the majority of wave height conditions at the toe are clustered along the limit with minimal scatter below it. For the past events, the majority of data points suggest the waves that cause an overtopping hazard are depth limited, while the scatter in the lower section of the plot indicates calmer wave and wind conditions, most likely during the highest spring tides, can also create overtopping. This suggests typical winter tides exceeding MHWS could be hazardous to pedestrians on the promenade if there is a westerly wind.

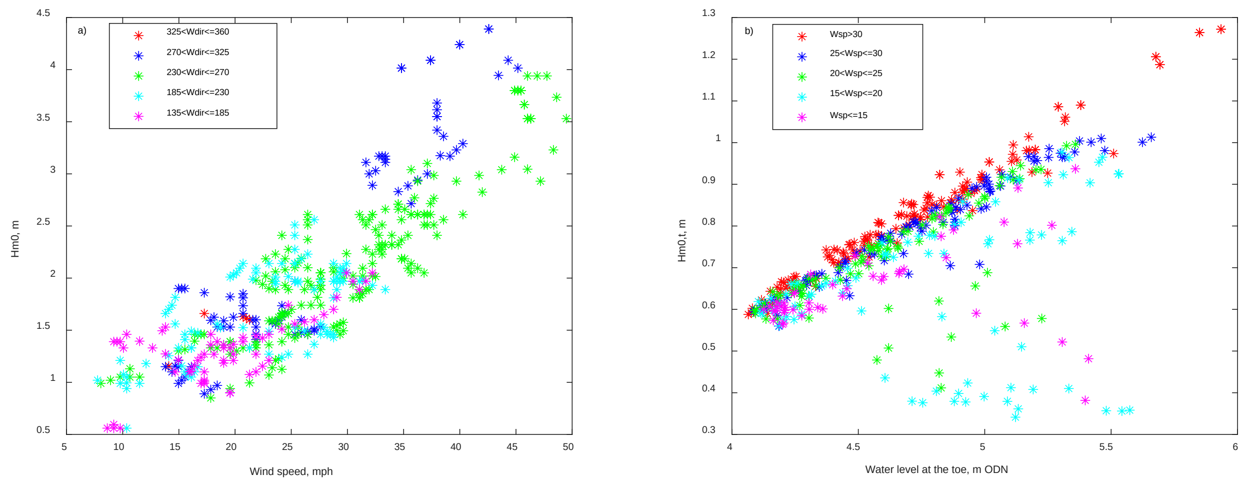


Figure 4.5: a) Offshore wave height (H_{m0}) relative to the wind speed measured in at Crosby Met Station, colour coded by wind direction (Wdir). b) The wave height at the toe relative to the water level, colour coded by wind speed (Wsp, mph).

Summary

Due to depth limited breaking a simple water level hazard threshold (of 5.3 m ODN) with either a wind or offshore wave height "traffic light" system would be effective.

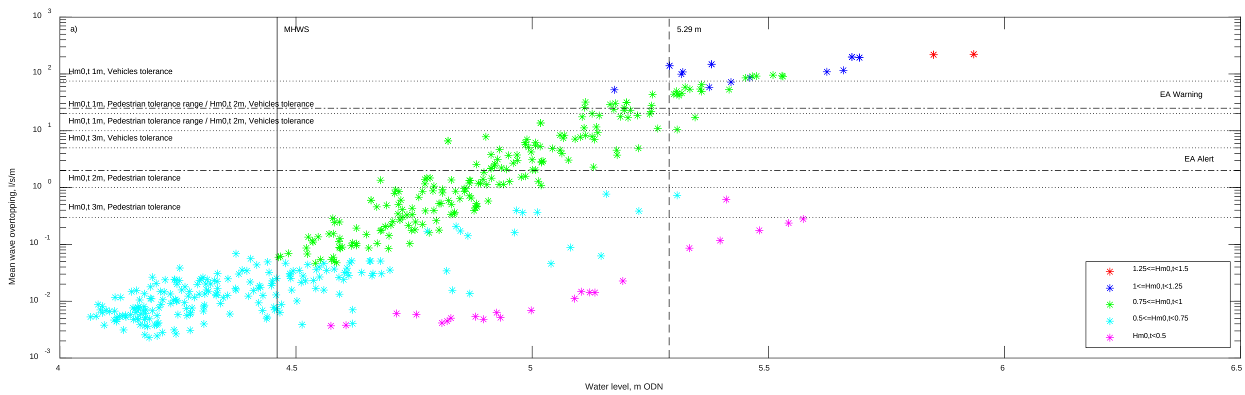
Any tides exceeding MHWS could be hazardous to pedestrians on the promenade if there is a westerly wind.

4.2 Numerical overtopping estimates for past events compared with industry standard hazard thresholds

The BayonetGPE (O19) mean overtopping discharges for past events are presented against the design thresholds from the EurOtop (2018) guidance and the existing EA warning thresholds for wave overtopping (Figure 4.6). These data set the current baseline in physical conditions against which any change in hazard can be assessed as part of new scheme design or for future defence performance assessments.

We do not show the EA still water level thresholds for tidal flooding as the alert (6.9 m ODN) is not exceeded in our data. The EA thresholds were refined after the winter 2013/2014 storms, which highlighted extreme events were not triggering a warning. The EA hazard warning is just above the EurOtop 1 m Hm0,t hazard threshold for pedestrians and 2 m Hm0,t hazard threshold for vehicles. These wave height thresholds seem appropriate for the fetch limited and depth limited conditions at Crosby and are in close agreement with each other. The EA warning threshold is only slightly lower than our suggested extreme overtopping threshold (72.11 l/s/m, Figure 4.2). The EA alert threshold differentiates between the high and low levels of overtopping that occur for water levels that exceed 5.25 m ODN.

Figure 4.6, for the existing structure, considers recent past conditions. For these data, which represent typical to extreme conditions, we find waves of at least 1 m at the structure toe can pose a hazard to both pedestrians and vehicles relative to the EurOtop (2018) guidelines when water levels exceed 5 m ODN (Figure 4.6a). Both small and large offshore waves can pose the same level of hazard as the wave height at the toe can be similar due to depth limited breaking of the larger waves. The EA thresholds are expected to be exceeded when the water level exceeds ~ 4.75 m ODN and offshore wave heights are at least 1 m. However, we know an alert is rarely issued although spring tides can reach this level with winter offshore waves often exceeding 1 m, suggesting the forecast underestimates the mean overtopping discharge. As the EA thresholds look suitable the following question is posed: *Does the EA forecast system underestimate the overtopping discharge and if so why?*



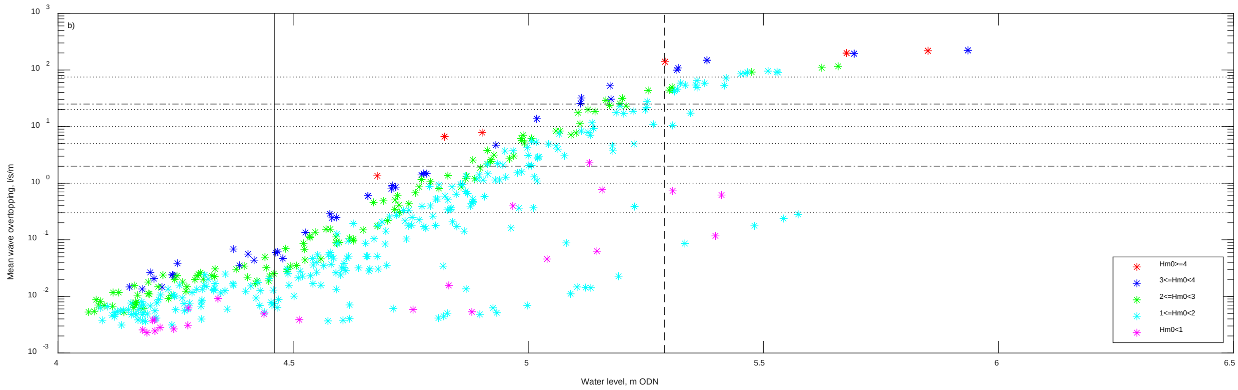


Figure 4.6: BayonetGPE (O19) mean overtopping predictions for the photographic evidence collected January 2013 – December 2017 using the beach survey collected 24th February 2017. The horizontal dotted lines are the guidance hazard safety thresholds provided in EurOtop (2018, Table 1.1) and horizontal dot-dash line indicates the thresholds used in the EA's flood forecasting system. The vertical dashed lines indicate our suggested threshold for hazardous overtopping. The solid vertical line indicate Mean High Water Spring (MHWS) tides. The colour coding indicates a) the wave height at the toe and b) the offshore wave height. Where a range in the tolerance to the overtopping hazard is suggested by EurOtop (2018), two thresholds bounding the hazard threshold are plotted.

The EA forecast system is based on a matrix of variables that include, water level, wind speed, wind direction, wave height at the structure toe, wave period at the structure toe and wave direction at the structure toe (Defra/Environment Agency, 2004). The wave variables at the structure toe are derived from SWAN modelling to propagate offshore wave conditions to the toe with consideration for the local wind and water level conditions. Using weather, surge and wave forecasts issued by the Met Office along with tidal predictions and wave transformations based on previous SWAN model output, the matrix is used as a look-up table to forecast the potential flood hazard. Figure 4.7a shows the water level conditions considered by the matrix cover the range of conditions experienced at Crosby and allow for rising sea level. However, our BayonetGPE (O19) data (red stars) representing typical conditions fall at the upper limit of or exceed the overtopping values within the EA matrix (black stars) for many of the water level categories. This suggests including updates to the empirical rules is critical for accurate estimates at this site or that the range of wind and wave conditions are not fully covered, or that the beach structure profile is different. We find that there is not a high enough range in wave conditions considered for wind speeds < 30 mph (Figure 4.7b), which can occur frequently in winter. The existing range in wave conditions may result in under predicted wave overtopping estimates by the matrix for typical conditions. This could have contributed to the need to lower the alert and warning thresholds in 2013/2014. When comparing our beach-structure profile with that used to populate the EA's forecast matrix in 2009, we notice that the beach level at the structure toe was ~1 m lower in the laser scan collected 11th December 2013 and that the beach level at the toe during our surveys in winter 2018/2019 could be just over 2 m lower. It should be noted that the EA's flood forecasting location is towards the southern end of the car park and our research is close to the north end of the car park. There is a trend in the beach level with increasing elevations to the south, suggesting spatial variability in the beach morphology is likely to cause the EA's beach level to be higher than ours. In the next Section 4.3, we show the sensitivity of the overtopping estimates to the beach level at the structure toe. The results suggest long-term change or seasonal variability will impact the overtopping estimate. If beach lowering has occurred since the initial set up of the EA's forecast system in 2009 overtopping estimates could be underestimated for present day. Relative to our estimates it is expected that the EA's estimates will be lower due to the more southerly position of the beach-structure transect.

We also notice there is a large amount of redundancy in the matrix for overtopping discharges less than 10^{-3} l/s/m for all water levels (Figure 4.7a). These lower overtopping discharges are associated with wind speeds of 6.7 mph (3 m/s) within the matrix, which do not consider a high enough range in wave height conditions (Figure 4.7b). For these low wind conditions larger remnant waves could still be present that are not in equilibrium with the instantaneous wind and could pose an overtopping hazard. When assessing the wave and wind conditions (Figure 4.7b) against past events the range in wind speeds looks adequate and allows for the possibility of increased wind speed in the future. However, while the range in wave conditions look adequate for high wind categories, when the waves will be fetch limited, they are inadequate for the low wind categories < 14 m/s (31.3 mph) and need expanding to consider waves of < 1. 25 m. It seems unnecessary to consider waves < 0.3 m.

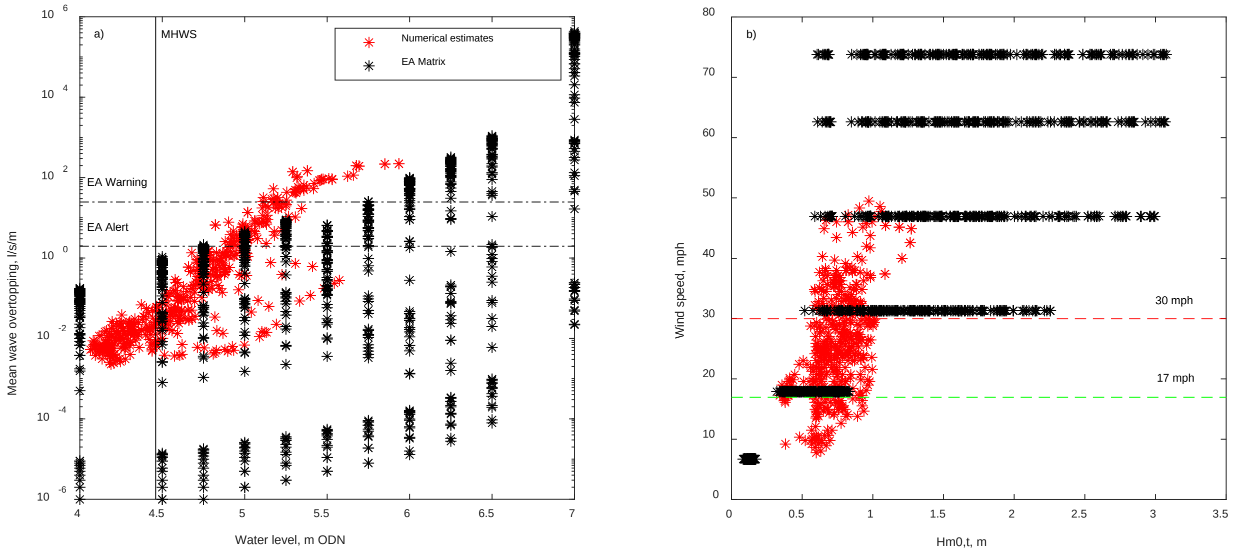


Figure 4.7: BayonetGPE (O19) mean overtopping predictions as in Figure 4.6 overlain by the range of conditions available within the EA's forecast matrix. a) Illustrates the water levels and associated mean overtopping values. The EA hazard threshold and MHWS is also indicated. b) Illustrates the wave height at the structure toe and the local wind conditions. The wind speed thresholds used by the SC are indicated.

From this comparison we suspect the mean wave overtopping discharge is under predicted for the north of the car park by the past configuration of SWAN-BayonetGPE used to generate the EA matrix. We suspect the more typical windy winter spring tides that could trigger an alert hazardous to pedestrians on the promenade may be missed due to a limited range in wave conditions for wind speeds < 30 mph. For a more accurate forecast of typical winter conditions (wind speeds < 30 mph) higher wave conditions need to be considered (and a way to capture beach level variability) in the matrix.

Summary

The photographic evidence from Facebook provides information on the baseline overtopping conditions at Crosby.

The EurOtop and EA wave overtopping hazard thresholds seem appropriate for the existing structure at Crosby.

The EA matrix is thought to under predict mean overtopping discharges when winds are < 30 mph.

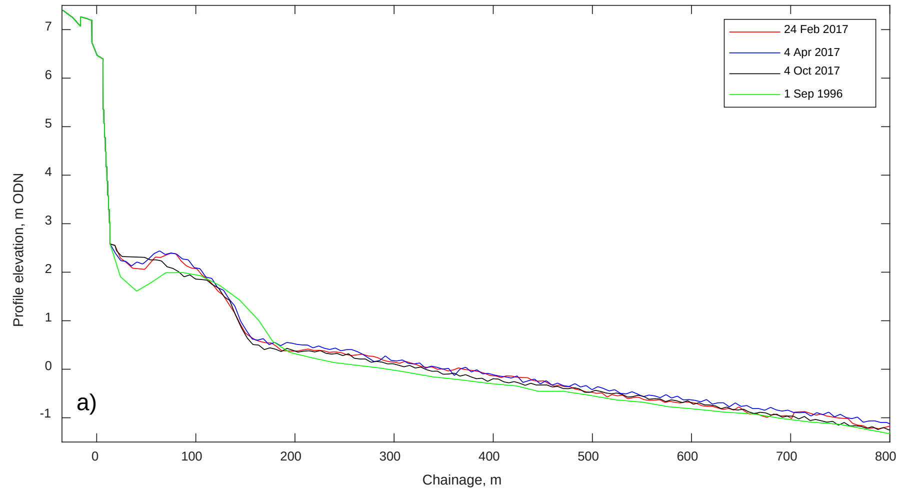
If any future refresh of the EA matrix is planned we would recommend that:

- The latest version of BayonetGPE is used to capture updates and include an upper and lower standard deviation to account for uncertainty in predictions.
- A larger range of wave conditions for wind speeds < 30 mph are considered.
- An approach to capture spatial and temporal variability in beach level is included within the condition combinations forming the matrix. At least a decadal refresh in the beach levels is required.

4.3 Sensitivity of numerical overtopping estimates to beach profile

At Crosby the stepped revetment causes broken waves to impact the vertical wall, unless the tidal levels are elevated noticeably higher than MHWS by surge. For each of the wave and water level combinations identified from photographic evidence we estimated the wave overtopping using a range of beach surveys to look at how the beach profile influences the wave overtopping hazard. Surveys on the 24th February 2017, 4th April 2017 and 4th October 2017 were used to represent seasonal variability. An earlier survey from the 1st September 1996 was used to capture longer term beach level change. Figure 4.8 shows the changes in the upper sand-bar over time. While the February and April profiles have a similar profile (Figure 4.8a) the beach level immediately fronting the structure (Figure 4.8b) is lower in April while the October profile is of a similar level to February. The September 1996 profile is much lower again. The actual level of the beach–structure interface is poorly resolved by the 5 m resolution survey data. However, the sand remains relatively low at this northern end of the sea wall, with most of the steps visible and beach scour/lowering temporarily exposing the sheet piling at the structure toe.

Figure 4.9 and Table 4.1 show the sensitivity in the overtopping values. The similarity in the overtopping estimates for February and October (red and black points) suggest it is the beach level at the toe of the structure (within the first 10 m) rather than the sand-bar morphology that is more important in mediating wave overtopping hazard. The lower the beach fronting the structure the greater the overtopping due to the deeper water levels allowing larger waves to reach the stepped revetment.



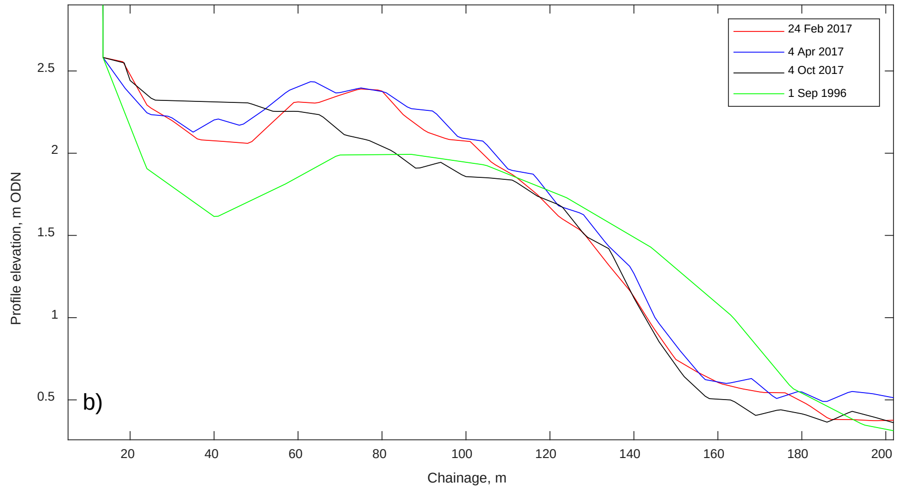


Figure 4.8: Beach surveys used to assess the impact of shoreline evolution on the numerical estimates of wave overtopping. a) The beach profile. b) The upper beach and interface with the structure.

While the overtopping estimates are similar for October and February (Figure 4.9), they are higher for April and September. There are also more data for April and September that meet the md < 2 criteria for certainty in the values. In April these additional data are mostly for the highest tides with lower wave activity (the scatter below the dense data points showing the increase in overtopping discharge with water level). In September these data are for lower water levels (< 4 m ODN). For the most extreme conditions the overtopping sensitivity to beach profile reduces, most probably as the small changes in depth have minimal influence on the waves that are already depth limited in the intertidal zone. The noticeably higher overtopping discharges in September are associated with a lower beach level of approximately 0.5 m. In Section 4.2 above, it was noted the beach profile in the EA's forecast system, which is up to a decade old relative to the surveys used here, is approximately 1.5 m higher than the 2017 beach profiles so is likely to estimate noticeably lower overtopping than presented here. Table 4.1 illustrates the variability in the percentile values of the data. In general the medians of the data are within a factor of two of each other while the 90th percentile values (representing the more extreme conditions) are within a factor of 3.

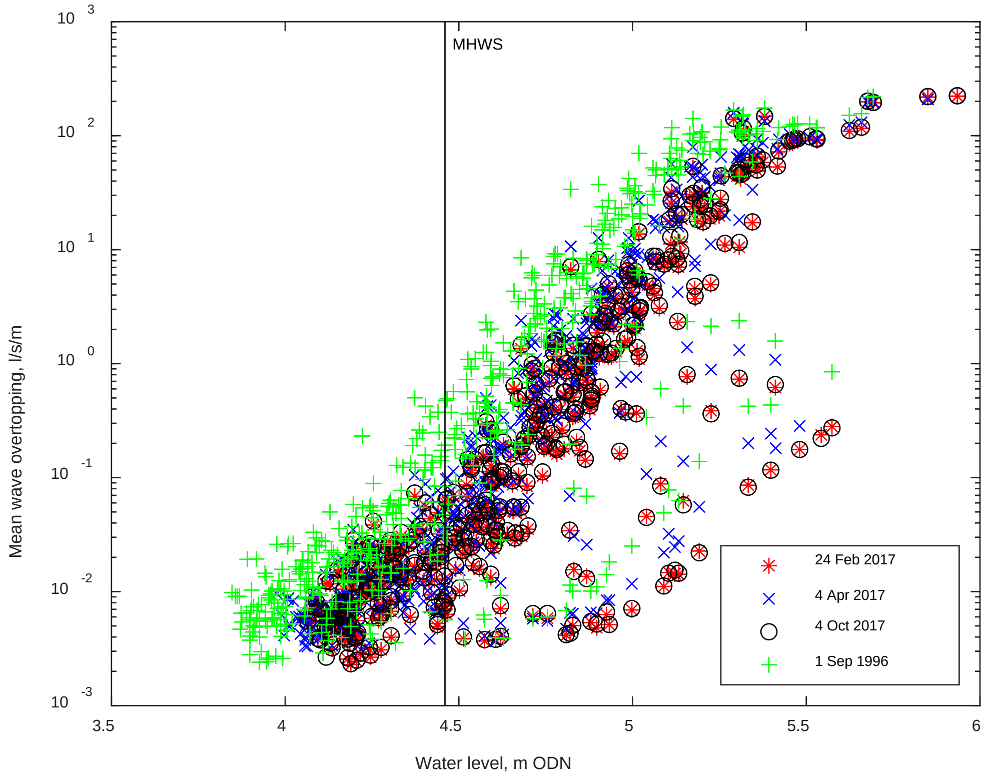


Figure 4.9: BayonetGPE (O19) mean overtopping predictions (md < 2) for the photographic evidence collected January 2013 – December 2017 using the beach survey collected in 2017 and September 1996. Numerical estimates generated October 2019. The solid vertical line indicates MHWS.

Table 4.1: Percentile values of the mean overtopping discharges (l/s/m) estimated for different beach profiles.

Beach Profile	10th	25th	50th	75th	90th
24th Feb 2017	0.0057	0.0133	0.0881	1.4775	23.7438
4th Apr 2017	0.0060	0.0119	0.1063	2.5075	41.5937
4th Oct 2017	0.0058	0.0136	0.0875	1.5343	24.8929
1st Sep 1996	0.0064	0.0158	0.1927	5.4200	60.1234

Summary

The beach level at the structure toe has more impact on overtopping discharge than the upper beach sand-bar morphology (ridge runnel evolution).

The percentile overtopping discharge estimates for the past events indicate that a high beach level within ~ 5 m of the toe result in lower discharge rates and that a lowering in beach level of ~ 0.5 m can cause noticeable increases in the overtopping estimates.

4.4 WireWall deployment thresholds

WireWall deployments were planned to capture typical wave overtopping conditions as well as any extreme events to maximise data collection within the limited deployment period (October 2018 – March 2019). Our aim was to record any measurable overtopping to demonstrate the data that could be collected by the WireWall technology. If a storm had occurred during our winter measurement period that would have been a bonus. Extreme waves (storm conditions) are classified by CCO as conditions that exceed the 0.25 year return period (i.e. events that are likely to occur 4 times a year).

Using the nearest available wave monitoring data to Crosby, CCO (Dhoop and Thompson, 2018) analysed the wave conditions to find the offshore storm threshold for Crosby is a H_{m0} of 3.44 m (Table 4.2). From the 465 conditions generated (that meet the md < 2 quality criteria for the BayonetGPE estimates) from the photographic evidence (Section 4.1), 32 exceed the CCO extreme wave threshold. These events occur for water levels ranging from 4.23 to 5.94 m ODN. This suggests there are plenty of wave overtopping events during non-storm, spring tide conditions.

Table 4.2: CCO extreme wave (storm thresholds) from Dhoop and Thompson (2018).

Return Period (years)	H_{m0} (m)
0.25	3.44
1	4.33
2	4.72
5	5.21
10	5.54
20	5.86
50	6.24

The WireWall deployments were planned based on tidal predictions. The long-range weather forecast was used to decide if winds were likely to be in the right direction (W to NW) and strong enough (> 10 mph) for wave overtopping to occur. If the forecast looked like there was the potential for overtopping to occur the equipment was prepared. In the last 48 hrs the available forecasts for waves, surge and wind were checked to make the final decision to deploy.

Summary

For Crosby the following thresholds to measure the minimum levels of overtopping were used to guide field deployments:

- Water levels > 4.46 m ODN (MSHW).
- Offshore wave heights > 0.5 m.
- Wind speed > 10 mph (4.5 m/s) with a westerly component during the rising tide or overnight prior to deployment (to sample decaying sea states that may affect the overtopping).

4.5 Numerical analysis of joint probability return period curve data

The SWAN (v41.20)-BayonetGPE (O19) approach was applied to the wave-water level conditions (no wind) for the joint probability return period curves previously generated at the Liverpool Wave Buoy location in a study commissioned by the North West Coastal Group in 2011 (Halcrow, 2011). We present both the mean overtopping estimates for the photographic evidence and for the points forming the return period curve data relative to the offshore wave-water level conditions. The information is shown for the beach survey 24th February 2017, but data are available from BODC for all four profiles in Section 4.3 (see Appendix IV).

The past photographic evidence data (Section 4.1) are plotted against the return period curves (Figure 4.10) to identify the region of the curves where overtopping conditions are most likely to occur and to classify the severity of these events in terms of overtopping hazard. The plots also include a shaded box highlighting the conditions typically used in the design of a new scheme. Our data, although mainly low severity (i.e., more likely than a 1 in 5 year storm event) covers all storm severity categories used in coastal scheme design, from less than a 1 in 1 year joint probability event to just over a 1 in 200 year joint probability event. Due to the macro-tidal, fetch limited nature of this location, past events show that overtopping is restricted to the section of the joint probability return period curves where water levels exceed 4.1 m ODN and offshore wave heights exceed 0.5 m. It also shows that the conditions used in the planning of new coastal schemes for flood management of local properties does not assess the annually occurring overtopping hazards to those visiting the site, which is important for public safety management.

There are two types of joint wave-water level combinations that generate extreme conditions at Crosby (Figure 4.10a). The first are associated with storms (wind speeds > 30 mph) causing both the water levels and waves to be high (water levels > 5 m ODN and waves > 4 m). The second type occur when moderate wave activity (< 2 m) under lower wind conditions (< 30 mph) occurs during the highest tides (> 5 m ODN), i.e., tides exceeding MHWS with an onshore wind or remnant waves from a previous storm. The first type are positioned in the right corner of the curves and are associated with winds from 230° to 325°. The second type are positioned on the lower vertical section of the curves and can be associated with any wind direction (Figure 4.10b). The first type represent the most extreme events and are also associates with longer period waves (Figure 4.10c).

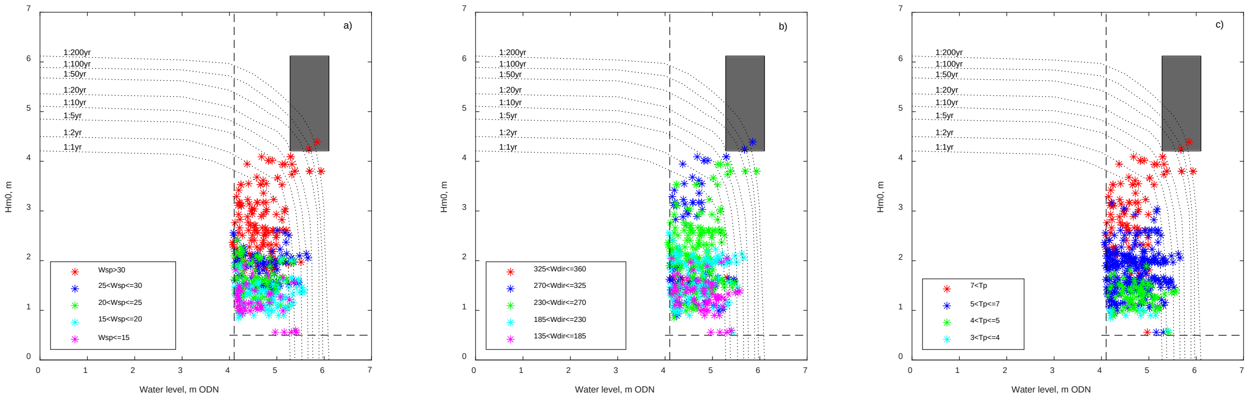


Figure 4.10: The wave and water level combinations for the photographic evidence collected January 2013 – December 2017. The data are categorised by a) wind speed (mph), b) wind direction (degrees) and c) wave period (s). The dashed curves represent the different severity events forming the return period curves. The shaded box represents the likely combinations of return period events considered in scheme design. The dashed vertical line and horizontal lines indicate the section of the curves where overtopping conditions have occurred from our analysis.

Information on the expected mean overtopping discharges for different joint probability conditions are shown in Figure 4.11. No data are provided for water depth less than 4 m ODN because the depth limited wave conditions at the toe either produce no overtopping or are uncertain (md > 2). This figure can be used to quantify the expected mean overtopping discharge for events of different severity to: 1) identify the joint conditions to consider when assessing new scheme designs, 2) identify the joint conditions certain to cause overtopping and/or 3) assess changing trends in the overtopping discharges and conditions that cause overtopping. The colour coding is related to the safety thresholds in EurOtop (2018, Table 1.1). The validity of the numerical estimates is assessed in Section 4.11. The most hazardous conditions (qm > 75 l/s/m) occur for conditions less probable than a 1 in 5 year event for the first type of overtopping (storms) and a 1 in 2 year events when associated with the second type of overtopping (caused by extreme tides and typical waves). Higher levels of hazard to the public are thus associated with the more frequent typical wave conditions that occur during the highest tides. For the existing sea wall a hazard to people can occur for most 1 in 1 year wave and water level combination, while a hazard to vehicles is more likely when waves > 1 m.

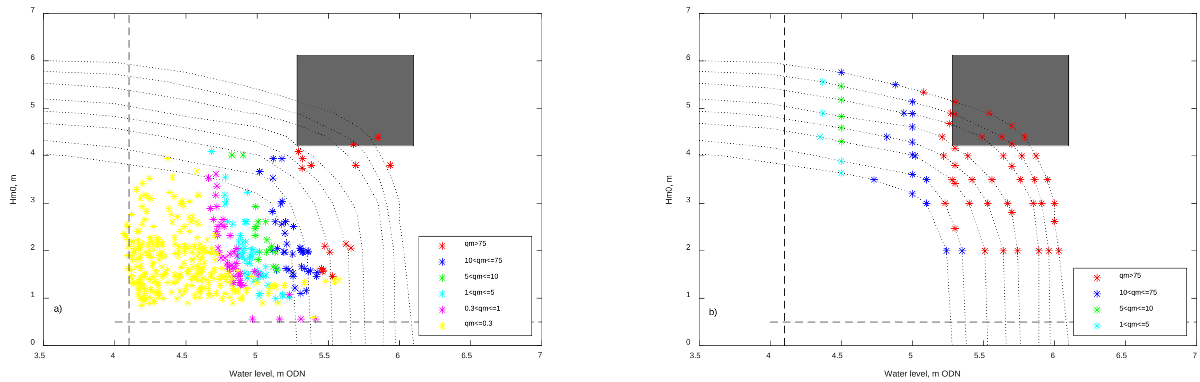


Figure 4.11: BayonetGPE (O19) mean overtopping predictions (md < 2) for the wave and water level combinations: a) for the photographic evidence collected January 2013 – December 2017, b) joint probability combinations creating the return period curves. The data are for the beach survey collected in February 2017. The lines and shaded area are as in Figure 4.10.

When we compare the BayonetGPE (O19) mean overtopping estimates for the return period curve data to that of the photographic evidence (Figure 4.12) we see there is overlap for the extreme water level conditions. For lower water levels the return period curve data are associated with higher overtopping discharges as the offshore conditions cover higher wave conditions than those identified from the past events (January 2013 – December 2017). It is therefore suggested that lower wave conditions than identified from the joint probability return period analysis should be considered when assessing the typical winter hazard for new scheme designs and in early warning systems (as previously found for the EA matrix, Section 4.3).

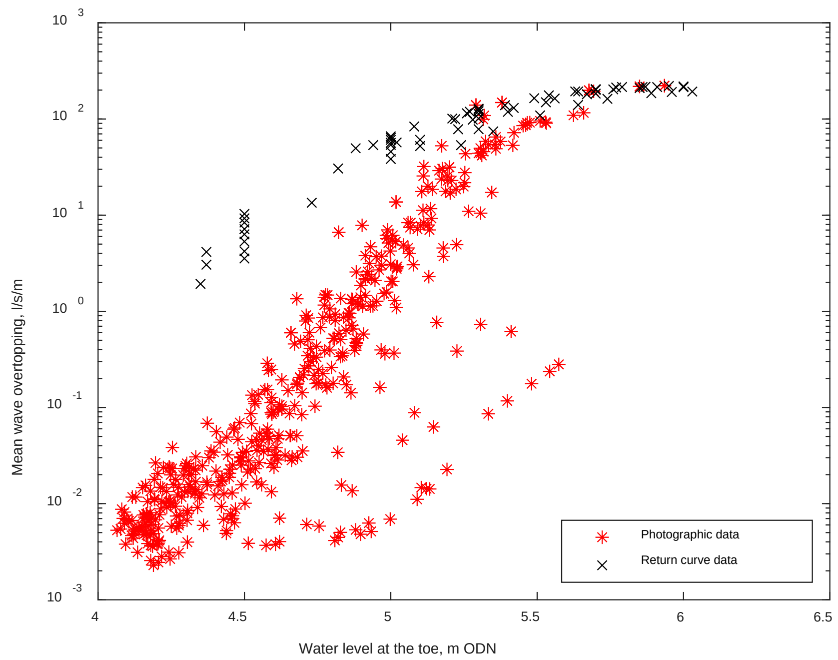


Figure 4.12: Comparison of the BayonetGPE (O19) mean overtopping predictions (md < 2) for the water level combinations for: 1) the photographic evidence collected January 2013 – December 2017, 2) joint probability combinations creating the return period curves. The data are for the beach survey collected in February 2017.

Summary

Wave overtopping hazard at Crosby occurs during spring tides when there is an onshore wind or background wave activity, as well as during storms.

The overtopping during spring tides can pose a similar level of hazard to pedestrians as that during storms, but can occur more frequently.

If joint probability analysis is used to define the wave and water level combinations for new scheme and early warning system design, more frequent low wave conditions could be missed.

4.6 Comparison of the physical modelling to the past events from photographic evidence

The physical modelling facility at HRW was used to run simulations (each of over 1000 waves) for 7 different wave-water level conditions to validate the BayonetGPE (O19) estimates for Crosby and later be incorporated into future releases of the BayonetGPE database: the results are summarised in Table 4.3 (Section 4.8). The simulations for the 5 higher water level conditions were repeated to give confidence in the consistency of the results from the physical model. Validation of BayonetGPE (O19) is given in Section 4.8.

Figure 4.13 shows the tank results for all 21 experiments (13 using the covered perspex HRW tank in the 3-7 September trial and 8 using the NOC tanks in the 17-21 September trial) compared to the BayonetGPE (O19) results for the past events (2013-2017) identified from the photographic evidence. It can be seen that the wave-water level conditions used in the flume experiments differ from those that were seen in the past events. At Crosby, the highest still water level (i.e. the highest predicted astronomical tide) is 5.44 m ODN and any mean water levels higher than that are due to the effects of storm surges. In such storm-driven cases with very high water levels, the wave heights at the structure toe are larger than those generated in the flume experiments (see Figure 4.14). The use of this unrepresentative combination, of very high water levels with lower wave heights, is the reason that the overtopping from the flume experiments is much smaller than that from the past events as shown in Figure 4.13. The decision to use exceptionally high water levels in the flume was made in order to ensure that measurable (large) overtopping volumes were collected by the tanks and also in an attempt to produce overtopping that penetrated further inland. To achieve this green water (over wash) conditions were required due to the effectiveness of the recurved sea wall on dense vertical plumes of spray. The tank measurements cannot therefore be used in a direct comparison against past events. They simply expand the data set to cover conditions that differ from those that occurred during past events captured by the public photographic record.

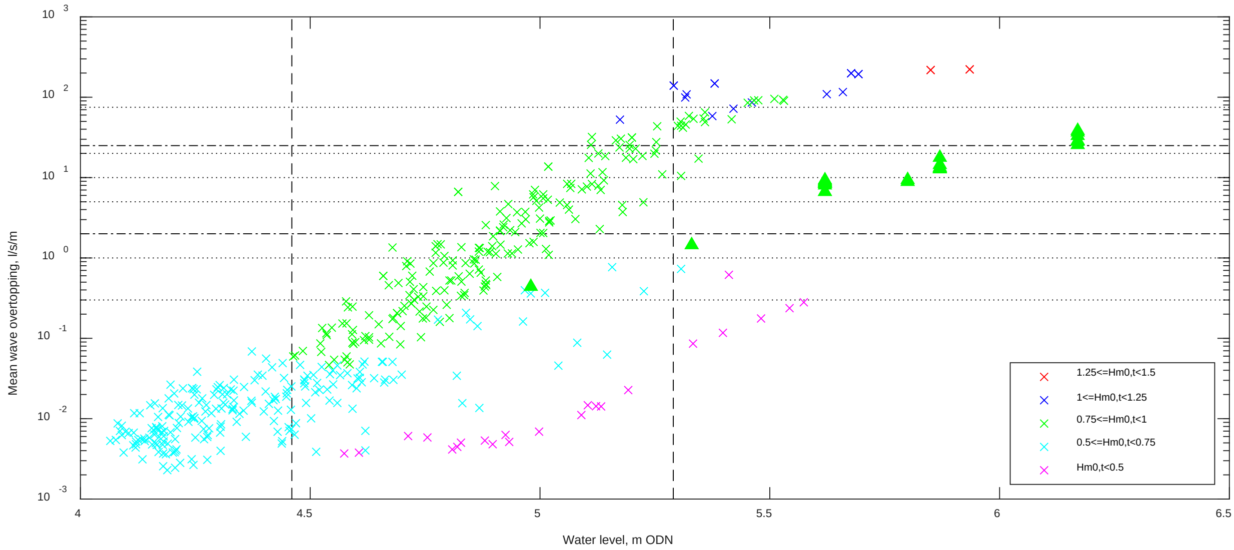


Figure 4.13: Comparison of the tank measurements collected in HRW's flume (triangles) compared to the BayonetGPE (O19) estimates (crosses) for the photographic evidence shown in Figure 4.6a. The colours indicate wave heights at the structure toe, as estimated by the SWAN model (for the past events) and by the wave gauges (for the flume data).

The same data are presented against the waves and water level conditions at the toe of the defence (Figure 4.14). The format is similar to the return period curve data plotted for Liverpool Bay (Figure 4.11a), but focus on the conditions at the toe of the structure since a range of offshore wave conditions can have the same height at the structure toe due to the influence of the concurrent wind, water level and currents causing wave breaking and refraction. For example, depth induced breaking means a large offshore wave can have the same height at the structure toe as smaller waves that have not experienced any breaking (see Gouldby et al., 2017). The flume experiments were designed to cover a range of wave conditions experienced at the structure toe, identified from the numerical results representing the photographic evidence, and are therefore difficult to relate back to a specific offshore wave condition.

Figure 4.14 shows the clear (near linear) depth limitation on the waves heights at the structure toe. The dense clustering of data around the upper limit shows that for overtopping events the larger waves coincide with higher water levels. The scatter of points below the main band of data represent smaller waves, which are not depth limited, coinciding with the highest spring tides. These data represent "nuisance" flood hazards that will occur more frequently as sea level rises. It is suggested that the more "exciting" overtopping events shared through social media are typically associated with depth limited conditions, whereas the smaller waves that are not depth limited during high spring tides either create less wave overtopping or less eye-catching wave overtopping. At this site a flood alert is not generally issued if offshore wave conditions are low (< 2.5 m during our field deployments) and are depth limited because it is assumed that the broken waves will only cause run-up on the stepped revetment and will not overtop the vertical wall. However, our video and social media images show that wave run up can cause a dense plume of water with a height that exceeds the crest level of the promenade (See Figure 4.21, Section 4.9). An increase in overtopping discharge can clearly be associated with higher water levels, which firstly allow waves to reach the structure and secondly allow larger waves to reach the structure once the toe is inundated by the tide.

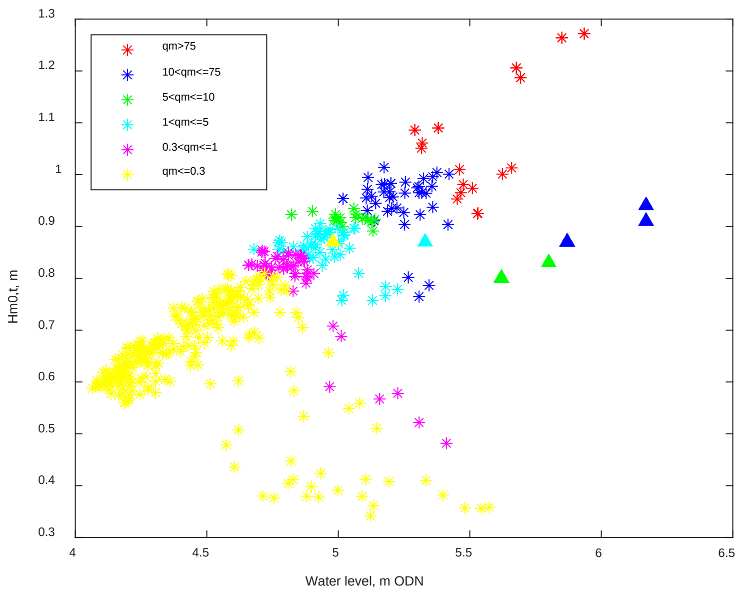


Figure 4.14: Comparison of the tank measurements collected in HRW's flume (triangles) for the long (1000 wave) runs compared with the BayonetGPE (O19) estimates (stars) for the photographic evidence.

Summary

Due to the onshore wind being a critical factor in causing wave overtopping at Crosby it was challenging to replicate overtopping conditions within a laboratory environment. The physical modelling data therefore represent overtopping under higher water level conditions than those recoded in the past photographic record collected by the public.

The depth limited nature of the waves at Crosby causes the overtopping to be very sensitive to the water level as this controls when the waves can impact the structure and the wave height on impact. This makes the conditions at the toe of the structure more important than the offshore conditions when assessing overtopping hazard.

4.7 Physical modelling to validate WireWall

The HRW flume experiments provided a range of wave-water level conditions to assess WireWall's measurement capability against the traditional method of collecting overtopping water in tanks situated inland of the sea wall structure. The 7 different wave-water level combinations are given in Table 4.3 (Section 4.8). The data for all 21 runs where WireWall was deployed (the 6 runs for condition WC01 with the perspex tank performed during the August trails, and the 15 runs during 17-21 September with the NOC tanks for WC01, WC07 and WC15) are available from the CCO website and BODC (see Appendix IV).

4.7.1 WireWall comparison against the perspex tank data from the 20-24 August flume trial

As described in Section 3.2.3 the perspex tank used for the initial trials of the WireWall system required the use of pumps in the three seaward-most partitions and even then the runs were time limited to prevent the water overflowing into the more landward partitions. In addition, water spilled sideways from the thick walls of the tank onto the WireWall wires until the tank walls were built up for the final 6 tests of the week. Figure 4.15 shows the results from those final 6 tests, all of which used wave condition WC01 and were terminated after 500 to 600 seconds (rather than the ~2000 seconds required for a full run of >1000 waves). It can be seen that the Master unit of the WireWall system agrees very closely with the results of the tank data (summed over all partitions) for 5 of the runs, with the 6th (test 40) being biased high. The high bias was due to a single event (about 270 seconds into the run), which was associated with an unusually (erroneous) high speed value. The results from the Slave unit are more scattered but agree well with the tank data on average. During this week of trials the Slave unit suffered from noise due to an unknown source of electrical interference: this is probably the cause of the increased variability in the Slave results.

WireWall was absent for the following week of flume tests (3-7 September), during which full length (>1000 waves) runs were performed for the seven different wave-water level conditions (Table 4.3, Section 4.8). During this week about 80% of the surface area of the perspex tank was covered over to reduce the rate at which it filled.

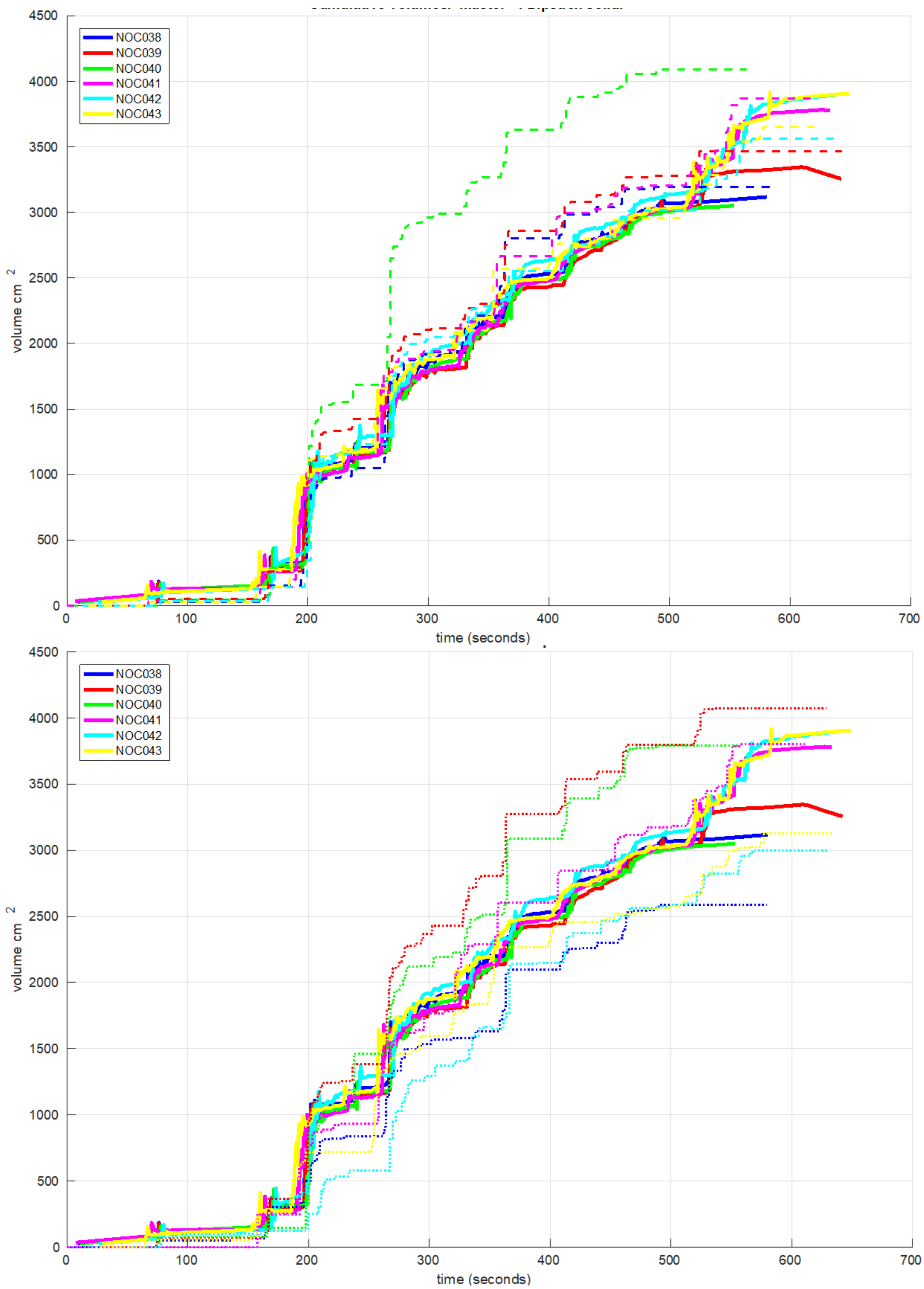


Figure 4.15: Cumulative volumes (cm[2]) for flume tests 38 to 43 inclusive that took place on the 20-24 August 2018. Colours indicate the test number. The wave paddle was turned off between 500 and 600 seconds into the run, hence the divergence of the results after 500 seconds. Note that the volumes are as measured, i.e. not scaled up to real world values. Volumes from the perspex tank are shown by the solid lines, and the WireWall volumes are given by the dashed lines. Left - volumes from the WireWall Master unit on one side of the tank. Right - volumes from the WireWall Slave unit on the other side of the tank.

4.7.2 WireWall comparison against the NOC tanks during the 17-21 September flume trial

For the final week of tests (17-21 September) the 3 large metal NOC tanks were used (Section 3.2.3, Figure 3.6). They were numbered tank4 (under the WireWall Slave unit), tank5 (middle) and tank6 (under the WireWall master unit) to reflect the channel number that the data feeds were logged to. Use of 3 tanks arranged side-by-side allowed us to investigate any cross-flume variation in overtopping. It had been noticed in the preliminary trial in July (Section 3.2.3) that use of a large "land" pump (as distinct from the small pumps used inside the tanks to prevent them overflowing) to reduce flood-water on the landward side of the sea wall caused significant cross-flume variation. For that reason the "land" pump was not used during the final week of tests. Despite this, cross-flume variation in overtopping was still present. This is evident from the time series of depth measurements from the 2 WireWall units: Figure 3.3 (Section 3.2.1) shows a short section of data which illustrates that the size of individual wave overtopping events seen by the Slave and Master units differ. There is not a constant offset or bias between the two units which means that this is not a calibration issue, rather it is a reflection of the actual size of overtopping differing between the different locations of the Master and Slave units: the two units were located to either side of the tank and were separated by a distance of 40 to 45 cm (c.f. flume width of 120 cm). For some tests all three tanks were against the sea wall to measure total volume. For five of the repeat runs of WC01 the outer tanks measured between 5 and 25% *more* overtopping than the middle tank, whereas for two of the other repeat runs of WC15 the two outer tanks measured between 10 and 30% *less* overtopping than the middle tank. This indicates that the actual overtopping varied between one run and another by up to 50%, as well as varying across the width of the flume. The centre-line of the outer tanks were offset by only 15 cm compared to the centre-line of the middle tank. Measurement errors (due to potential calibration drifts or shifts in the dipstick sensor used to measure the depth of water in the tanks, combined with a 2% variation in tank capacity) is at most 5% so these differences between the middle and outer tanks volumes of between +25 and -30% are therefore due to real differences in the overtopping across the flume. It should be noted that these results were obtained for short runs (800 seconds or less) so that **no** pumps were needed inside the tanks.

For the full length (>1000 wave) runs, it was necessary to use pumps inside the tanks (as done for the perspex tank) in order to prevent them overflowing. A correction for the pumps was applied based on (a) the pump flow rate and (b) the times during which the pump was operating. The pump flow rate was measured on a number of occasions and varied between 500 and 630 Litres/hour. The flow rate differed from one pump to another, and also varied in time, possibly due to different voltage setting on the power supplies used for each pump, so all data were corrected using a flow rate of 550 L/hr. The pumps were usually turned on around 1000 seconds into the run and were then left on. However, the pump correction was not applied when the water level in the tank fell below about 1 cm and the pumps stopped working. The on/off aspect of the pump correction can introduce errors if (i) the pump continued to work for water levels below 1 cm and/or (ii) failed to re-start again immediately when the water level rose due to a temporary air blockage. For the full length runs, these various pump uncertainties combine to produce an uncertainty of up to 20% in addition to the cross-flume uncertainty of up to 30% discussed above.

Figure 4.16 compares total volume results from the WireWall units against the tank results for the short runs, the long runs (final value) and the long runs at the point

BEFORE the pumps were used. Note that "as measured" values are used, i.e. they are not scaled up to real-world values. It can be seen that the agreement of the WireWall units with the tank data is very good, usually within 20% which is excellent considering the uncertainties in the tank volumes as described above (up to 30% uncertainty for the short runs without pumps, and potentially more than that for the long runs due to the use of pumps). The main exception (circled in green) is one of the long runs for WC15, where both Master and Slave units show volumes that are significantly larger than those from the middle tank. However, it was noticed that in this case the pump was turned on at least 300 seconds later than for the other two runs of the WC15, and that the tank volume registered as full, so it is extremely likely that in this case the tank overflowed and therefore that the volume in the middle tank is an underestimate and it is the WireWall volumes that are correct.

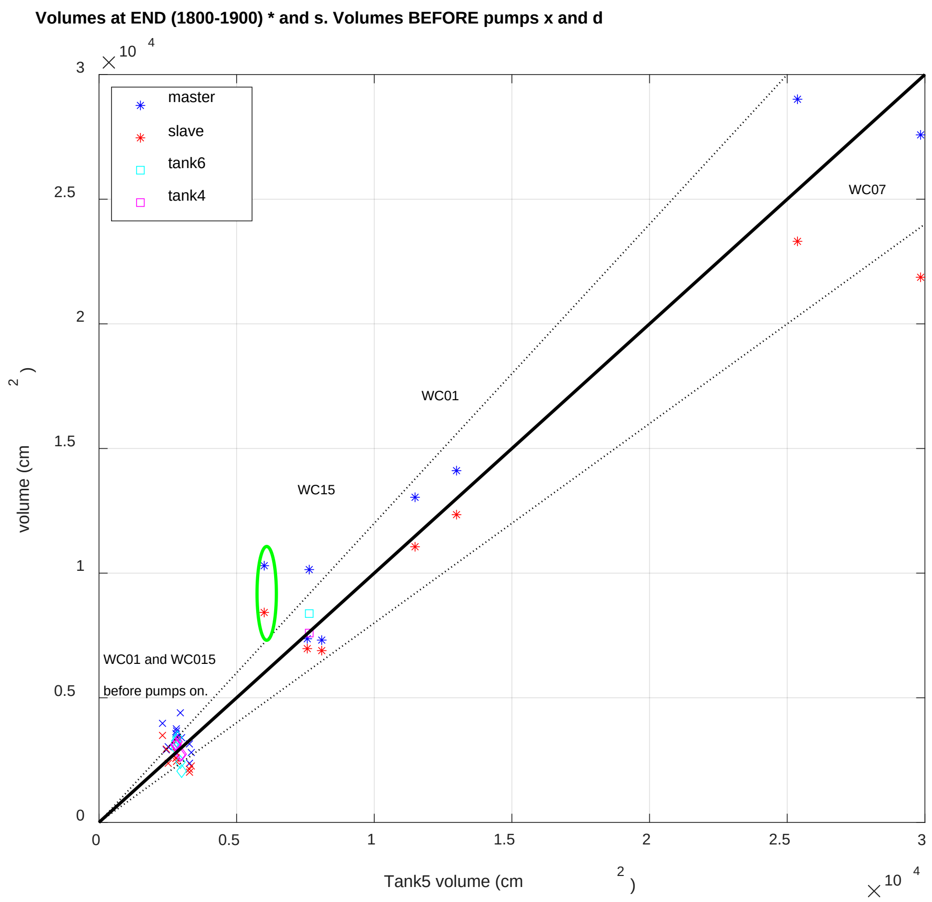


Figure 4.16. Volumes from WireWall Master and Slave units, plus volumes from the outer NOC tanks ("tank6" was nearest Master, "tank4" nearest Slave) when they were against the sea wall, against the middle tank ("tank5") which was always against the sea wall. Volumes towards the end of long runs are shown by * (WireWall) and open squares (tanks): these volumes are all > 5,000 cm^2. Those obtained during short runs or longer runs BEFORE pumps were turned on are shown by open diamond (WireWall) and are all < 5,000 cm^2. Green circle highlights the WireWall values for run 148 when the pump was turned on late. The black line indicates 1:1 agreement, and dotted black lines show +/-20% uncertainty in the volumes from the middle tank. NOTE the volumes are "as measured", i.e. are not scaled up to real-world values. The volumes are given in cm^2, where 10 cm^2 = 1 L/m. Scaled up to real world, $1x10^4$ cm^2 as measured = $5.625x10^4$ L/m or 56.25 m^3/m.

4.7.3 Distribution of overtopping inland

As discussed in Section 3.2.3 it was not possible to obtain the inland distribution of overtopping using the perspex tank since the water skipped across the tops of the thick partition walls from one partition into the adjacent ones (Figure 3.6 top). During the final week of trials with the larger NOC tanks that were arranged longitudinally, various attempts were made to obtain distribution data by moving one or both of the two outer tanks inland away from the sea wall, while leaving the middle tank against the sea wall to collect total overtopping. Figure 3.6 (bottom right) shows such an arrangement where tank4 (next to the WireWall Slave unit) was moved inland by 10 cm, and tank6 (nearest the WireWall Master unit) was moved inland by 20 cm. In this arrangement, the front (seawards) edge of tank5 (middle) was aligned with wires2, the front edge of tank4 was aligned with wires3 and the front of tank6 was aligned with wires4. This allowed the volumes collected by the tanks in different positions to be compared directly with the WireWall data on different pairs of wires.

Sponges (blue, visible in Figure 3.6 bottom right) were placed in front of tanks 4 and 6 to reduce the amount of overtopping water that landed in front of the tanks but then splashed up into the tank, and/or caused waves in the "flood" water in front of the tanks to run up and into them. However, this was not completely effective, particularly in wave-water level conditions with high water levels (WC01 and WC07, Table 4.3) and hence high "flood" water levels since the land pumps were not employed (in order to minimise cross-flume variations in overtopping, Section 4.7.2). Of the three wave-water level combinations that were run using the NOC tanks, WC15 had the lowest water level.

Figure 4.17 shows the cumulative (as measured) volumes from one of the long runs (>1000 waves) carried out for WC15. The pump in tank5 was turned on about 1200 seconds in to the run, but there was no need for pumps in the two outer tanks that were further inland. It can be seen that the total volume from the middle tank5 agree closely with total volumes from both Master and Slave units (calculated from wire pair 12, blue). Tank4 was 10 cm inland and shows reduced volumes, as expected, but the tank volumes are larger than those obtained by the WireWall units using wire pairs 23 (red) despite close alignment of the wires with the tank. Tank6 was 20 cm inland and overestimates slightly compared to WireWall data from the Master unit pair 34 (green). The agreement between tank6 and the slave unit is less good, but the Slave unit was on the opposite side of the flume to tank6 and the cross-flume variation in overtopping means the reduced volumes seen by Slave 2 may well be real. Given the problem of splashing/runup into the two inland tanks the values from tanks4 and 6 will be biased high to some unknown extent. Hence the only conclusion to be drawn is that the inland distributions from the WireWall units look realistic, and that the slight difference in results between the two WireWall units may well be due, at least in part, to real variations in overtopping across the flume.

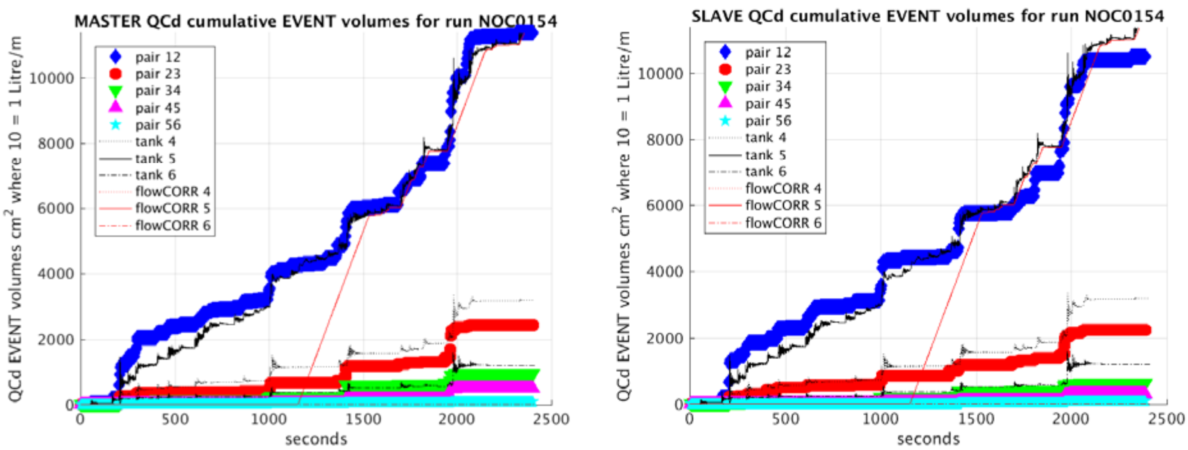


Figure 4.17: Cumulative volumes for run 154, WC15. Left: results from the Master unit (next to tank6). Right: results from the Slave unit (next to tank4). The colours indicate which pair of wires were used in the

WireWall data. The solid black line shows volumes for tank5 (middle), dotted black tank4, and dashed black tank6. The red line shows the pump correction applied to obtain the tank5 volumes.

Summary

The results from the collection tanks have an uncertainty of at least +/-20% due to real variations in overtopping. When pumps are used in the tanks, this can cause an additional uncertainty of +/- 20%.

The results from WireWall agree well with those from the tanks, and are within the limits of the tank uncertainties.

Benefits of WireWall over traditional tank approach are: the ability to measure cross-flume variability, no capacity limitations and minimal interference with the distribution of overtopping water as it travels inland.

Elevated water levels for the representative wave conditions were applied to produce measureable overtopping.

4.8 Physical model tank-BayonetGPE-WireWall comparison

The physical modelling in HRW's flume enables comparison of the numerical estimates from BayonetGPE (O19) with the physical data collected in the flume using two approaches (the traditional tank collection method and the new WireWall measurement system). The results for individual flume runs are available on the CCO website and via BODC (see Appendix IV) and are summarised here. Table 4.3 shows the mean and standard deviation of discharge rates (scaled up to real-world values) for each wave condition along with the number of runs performed for that wave condition. The tabulated WireWall data are from the long (>1000 wave) runs performed during the final week (17-21 September) of flume trials during which the large NOC tanks were used. The tabulated tank data are a mix of the same runs from the final week plus the long runs performed during 3-7 September using the covered perspex tank (with no WireWall system present). Where repeat simulations were performed for a given wave-water level combination the mean and standard deviation are given. The shorter runs discussed above (Section 4.7) are not presented here.

Table 4.3: Flume tests used to compare measured and BayondetGPE (O19) estimated overtopping data. The waves (at the toe of the structure) and water level condition are real-world values, i.e. scaled up from the waves and water levels in the flume. The number of repeat runs for which tank (T no.) and/or WireWall (W no) data were collected are provided. Tank data are the mean of all data available (from the HRW tank and/or one or more of the three NOC tanks). WireWall values are averaged using values from both the Master and Slave units. Mean and +/- s.d. are given for discharge rates. * indicates only 1 run. ** indicates there were 6 runs for WC15 but one run had estimates from all three NOC tanks providing 8 tank values in total.

				Tanks	**T**	**WireWall**	**W**	**BayonetGPE (O19)**		
Flume Test	WL m ODN	Hm0, t m	Tp,t s	qm, l/s/m	no.	qm, l/s/m	no.	qm, l/s/m	-1 S.D.	+1 S.D.
WC01	5.87	0.87	6.27	14.2 ± 2.1	5	14.0 ± 1.4	2	13.4	4.0	147.6
WC06	6.17	0.91	5.72	27.2 ± 2.3	2	-		71.8	14.4	1793.6
WC07	6.17	0.94	6.6	34.1± 4.5	4	28.3 ± 3.8	2	96.1	16.2	3382.4
WC12*	4.98	0.87	6.27	0.4	1	-		0.3	0.1	6.4
WC13*	5.33	0.87	6.27	1.5	1	-		0.5	0.1	9.5
WC14	5.80	0.83	6.42	9.1 ± 0.3	2	-		7.6	2.1	100.8
WC15	5.62	0.8	7.65	8.4 ± 0.8	6**	9.1 ± 1.6	4	3.1	0.6	88.6

The data are presented (Figure 4.18) in terms of overtopping discharge against water level to enable qualitative comparison with the photographic evidence (Sections 4.1 – 4.5), although, as discussed in Section 4.6 the combination of high water levels (> 5.4 m ODN) with low wave heights does not occur at Crosby. For the 3rd series of tests (3rd September 2018, Table 3.5) WireWall was not installed. Only the long (1hr, > 1000 wave) flume tests are plotted in this section, of which WireWall was installed during only 3 of the wave conditions (WC01, 07 and 15). As previously shown in Section 4.7.2, the WireWall results agreed extremely well with the tank data (generally within the 20% or more uncertainty estimated for the tank data). The BayonetGPE (O19) results differ more widely from the tank and Wirewall data. However, the BayonetGPE (O19) captures the trend in overtopping discharges, and the tank measurements fall within +/- 1 standard deviation about the mean BayonetGPE (O19) value. For water levels of less than 5.8 m ODN BayonetGPE (O19) is biased low and for water levels over 5.8 m ODN it is biased slightly high. There is no consistent bias between BayonetGPE (O19) and WireWall for the three wave-water level conditions where both methods can be compared: for the lower water level case of WC15, the Bayonet mean discharge estimate is a factor of 3 lower than that from WireWall (and tank) data; for the intermediate WC01 the Bayonet mean is in good agreement with the WireWall/tank data; for the very highest water level case of WC07, the mean BayonetGPE (O19) estimate is a factor of 3 higher than the WireWall/tank data. This demonstrates the sort of agreement that may be achieved in the field if both methods are robust.

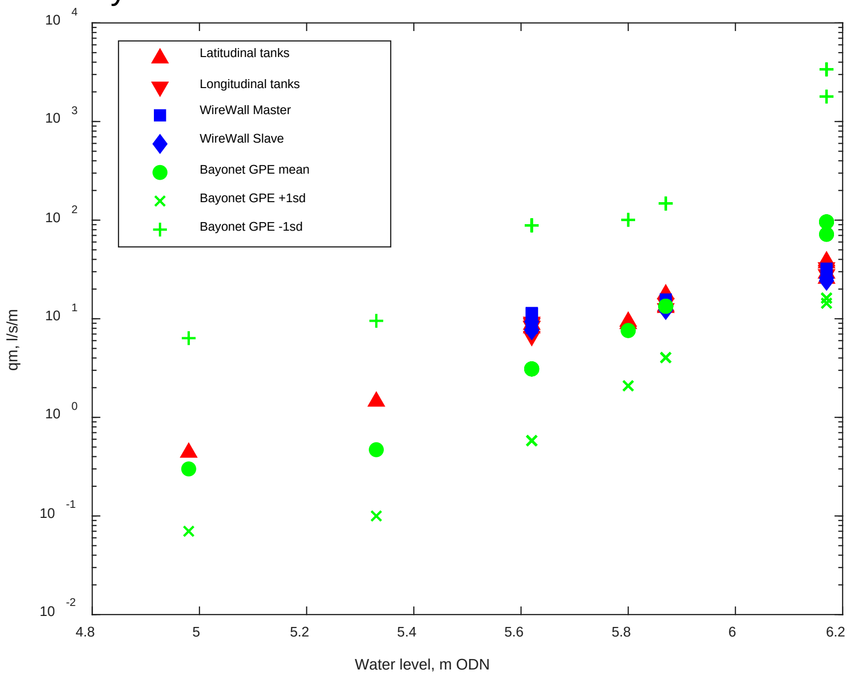


Figure 4.18: BayonetGPE (O19) validation using data from the tanks (red, both NOC and HRW) and from the WireWall system (blue). The +/- 1 s.d. estimates for BayonetGPE (O19) are shown along with the mean values. The discharge rates and water levels are scaled up to real-world values.

While the mean BayonetGPE (O19) and measured tank/WireWall data have acceptable agreement (within a factor of +/-3) in the flume, wider differences may be expected in the field. This is due to: (a) the laboratory conditions being idealised, e.g. in the flume the wave direction is always perpendicular to the structure, but in the field the wave direction can vary and more than one wave direction may exist at one time; and (b) the flume conditions do not capture events that cause a vertical plume of dense spray or a single fine jet of spray due to wave runup on the stepped revetment. In addition, in the field the wind has a key influence on the transport of the spray over the crest of the sea wall. Considering that the majority of our field data are for low energy (spray) conditions (Table 3.6) under the influence of an onshore wind the BayonetGPE (O19) overtopping estimates for the field measurements could be biased low since BayonetGPE does not include the influence of wind.

Summary

WireWall measurements were in good agreement with the tank data for long flume runs (> 1000 waves). The results were generally within the +/-20% or more uncertainty estimated for the tank data.

BayonetGPE (O19) captures the trend in overtopping discharges, and the tank measurements fall within +/- 1 s.d. about the mean BayonetGPE (O19) value.

There is no consistent bias between WireWall data and BayonetGPE (O19) estimates. The difference in values can be up to a factor of 3. The same level of agreement can thus be expected in the field tests

4.9 Visual observations during WireWall field deployments

Images from each field deployment are available in Appendix III. From visual observations made during all the deployments, the WireWall field rig seemed to be an appropriate height to collect data for typical winter (windy spring tide) overtopping conditions, while also allowing ease of transportation (Figure 3.8). It is these conditions for which the alert threshold for hazardous overtopping conditions to promenade users could be usefully refined. During many of the events people may have got a little wet, but the overtopping was not considered hazardous to pedestrians. However, for the events when the vertical plume exceeded the top railing there was potentially a hazard as water and debris (including house bricks) were carried landward by the overtopping water. These conditions caused a higher volume of water to flow onto the promenade and created a return flow. Figures 4.19 and 4.20 show examples of what the conditions looked like as they passed through the field rig from the rear and side view cameras. Figure 4.19 shows dense spray comes through the rig lower down as the vertical plume collapses under gravity, eventually causing an inland rush of water on the promenade. Having the wires as close to the tarmac as possible is therefore critical to capture this overtopping flow. Figure 4.20 shows how a flow on the promenade develops and returns after being reflected by the splash wall. The momentum of the flow under this event enables some of the water to flow up and over the splash wall. In some cases the return flow had not fully drained before the next wave started to overtop. For this event the wave sequence often meant only the largest wave caused such a return flow and the next wave was often smaller not adding to the flow. In a higher energy storm more waves would cause flow on the promenade, which may not have time to drain between waves.

Figure 4.19: Example photos from the rear rig mounted GoPro collected during the January 2019 deployment.

Figure 4.20: Example photos from the side mounted GoPro (south of the rig) collected during the January 2019 deployment.

The camera footage allows us to identify the processes that occur that are not captured by the EA’s flood forecasting service. Figure 4.21 illustrates how a sea state that is not particularly rough results in a forecast of low waves that are, under normal spring tide conditions, depth limited and break on the toe of the defence, and are therefore forecast to result in runup on the stepped revetment and not overtopping. The photos show that while this is the case the runup still causes a (< ~ 2.4m) vertical plume of dense spray after impacting the vertical sea wall. The recurve works well deflecting the spray seaward. However, when an onshore wind is present some of this plume is carried over the crest of the defence before it collapses under gravity. The influence of wind on overtopping has been incorporated into a new engineering tool developed by Manchester Metropolitan University. To enable future collaborative research we added a weather station on to the rear of the rig for some of the field deployments to collect an initial dataset of wave overtopping and wind conditions. Although quite limited, the data are the first wave overtopping and wind data to be collected simultaneously at exactly the same location in the field.

At Crosby waves propagating from the west arrive at Crosby seafront with a slight angle due to the coastal orientation causing a southerly component to the wave direction that often carried the overtopping plume along the sea wall from north to south. During this period of travel the wind continually acted on the plume carrying more water over as the plume travelled along the sea wall. A clear example is available on YouTube, https://youtu.be/dd6QHjHuHYc.

The camera footage collected as part of the project was vital to understand the behaviour and characteristics of the overtopping water in order to develop the data analysis techniques. By knowing the direction of travel through the rig we could identify when water coming in from the side (perpendicular to the expected land-sea direction) appeared to result in unrealistically high speeds (along the land-sea direction). We could identify when a flow of water along the promenade was coming under the rig from waves overtopping to the north of the rig. Under some conditions, water passed underneath the front row of wires (that projected seawards of the wall) and appeared first in the second row of wires: such events may have gone undetected if we had assumed that all overtopping would appear first on the seawards most wires. There were also events where a violent jet went vertically upwards and was seen at almost the same time on both the first and second row of wires (resulting in the speeds calculated between the first and second row to approach infinity!). However, in the majority of such cases the water returns vertically downwards back into the sea and was not detected on any of the other rows of wires further inland: in the cases when the water was detected on inland wires, then the speed of travel at the inland wire was assumed to be the correct speed. We have taken both concerns into consideration in the data analysis (Section 4.10) and captured uncertainty by presenting the data for different wire pair combinations. It is thought that using wire pair 13 is most accurate at calculating the volume of water that passes over the crest of the Crosby sea defence (see Section 4.10 for more details).

Figure 4.21: Example photo sequence to explain the site-specific processes during a typical windy spring tide that potentially require an alert to be issued for pedestrian safety, but are not represented within generic hazard warning tools. The position of the weather station is also shown (bottom right).

Summary

The size of the WireWall field rig seemed appropriate to collect data for typical winter (windy spring tide) overtopping conditions and allowed it to be transported in a long wheelbase high-top van.

The camera footage shows windy spring tides can pose a hazard to pedestrians on the promenade, even though hazard alert thresholds are not met.

Small waves breaking onto the stepped revetment run-up and on impact with the sea wall create a dense vertical plume of water, which can exceed 2.4 m and overtop the defence crest when an onshore wind counteracts the effect of the recurve of the sea wall.

4.10 WireWall field measurements

Section 3.3 above describes the configuration of the WireWall system used during the 9 deployment days in winter 2018/2019 (Table 3.6). In this section we focus on the preliminary results for 2 contrasting deployments. The 26th October 2018 (Appendix II, Figure AII.2) deployment represents wave overtopping conditions that were well below the height of the field rig, whereas the 25th January 2019 (Appendix II, Figure AII.6) deployment represents more energetic conditions that produced overtopping that was occasionally a little higher than the field rig. On both days there was at least some overtopping that would pose a hazard to pedestrians on the promenade, but not to the cars parked inland of the promenade. Data from these two deployments are available through the CCO website and BODC (see Appendix IV) for the seaward wires (1 to 3) that experienced the most overtopping and measure the overtopping at the sea defence crest. It is these overtopping discharges that are most valuable to validate numerical tools and hazard management thresholds.

An example of the wave-by-wave data from the deployment on the 25th January is shown in Figure 4.22. For this single overtopping plume the height of the signal represents the length ("depth" in the figures) of the wire that is wet, and it can be seen that less water reaches the wires further inland (wire1 projects forwards of the sea wall, and wire6 is furthest inland). The horizontal speed of the plume compared to its rate of collapse under gravity influences the amount of water that reaches further inland. Once the plume has collapsed the signal slowly returns to zero as the water drains off the promenade. Noise in the signal is due to the spray nature of the water and sometimes also spray with a southerly component of travel entering the rig after travelling alongshore. The processing algorithm uses the gradient of the signal to detect the start and end of (wave-by-wave) overtopping events and the large signal from the initial overtopping plume can be separated from water pooling, or running along, the promenade. Here we focus on the overtopping hazard from the plume but there is the potential in future to also assess the depth of the pooled water and possibly the speed of the flow on the promenade to assess any hazard from the return flow. For the more extreme January events (Table 3.6) the wave-by-wave data were checked to identify if the overtopping plume signal had a “flat top” suggesting the rig was fully immersed and the overtopping water was exceeding the height of the rig. However, despite a few plumes being visibly taller than the rig (Figure 4.23), the maximum wire depth of 2.4 m was rarely seen because the plumes were made up of spray (air and water mixed) rather than solid water. In general, the rig was an optimal size for Crosby to measure typical conditions on the highest spring tides when a moderate wind blows from a west to north west direction.

Figure 4.22 shows that the size and shape of the plume varies at each of the three units which indicates the variability of the overtopping over a very short (alongshore) distance (the three units were separated by 40 to 50 cm from each other). In addition, it can be seen that the event starts fractionally earlier on the Master unit (located on the north side of the rig) compared to Slave 1 (in the middle of the rig) and Slave2 (on the south). The time difference of the arrival of the water on the Master compared to Slave2 is less than 0.1 seconds, and indicates that the wave direction had a very slight northerly component compared to the face of the sea wall.

Another potential use for information such as in Figure 4.22, is the possibility to identify where and when the overtopping plume breaks up into a less dense (more noisy) spray signal. This could be of value for infrastructure planning to position equipment or facility buildings on top of sea wall or dockside infrastructure or in ports and harbours.

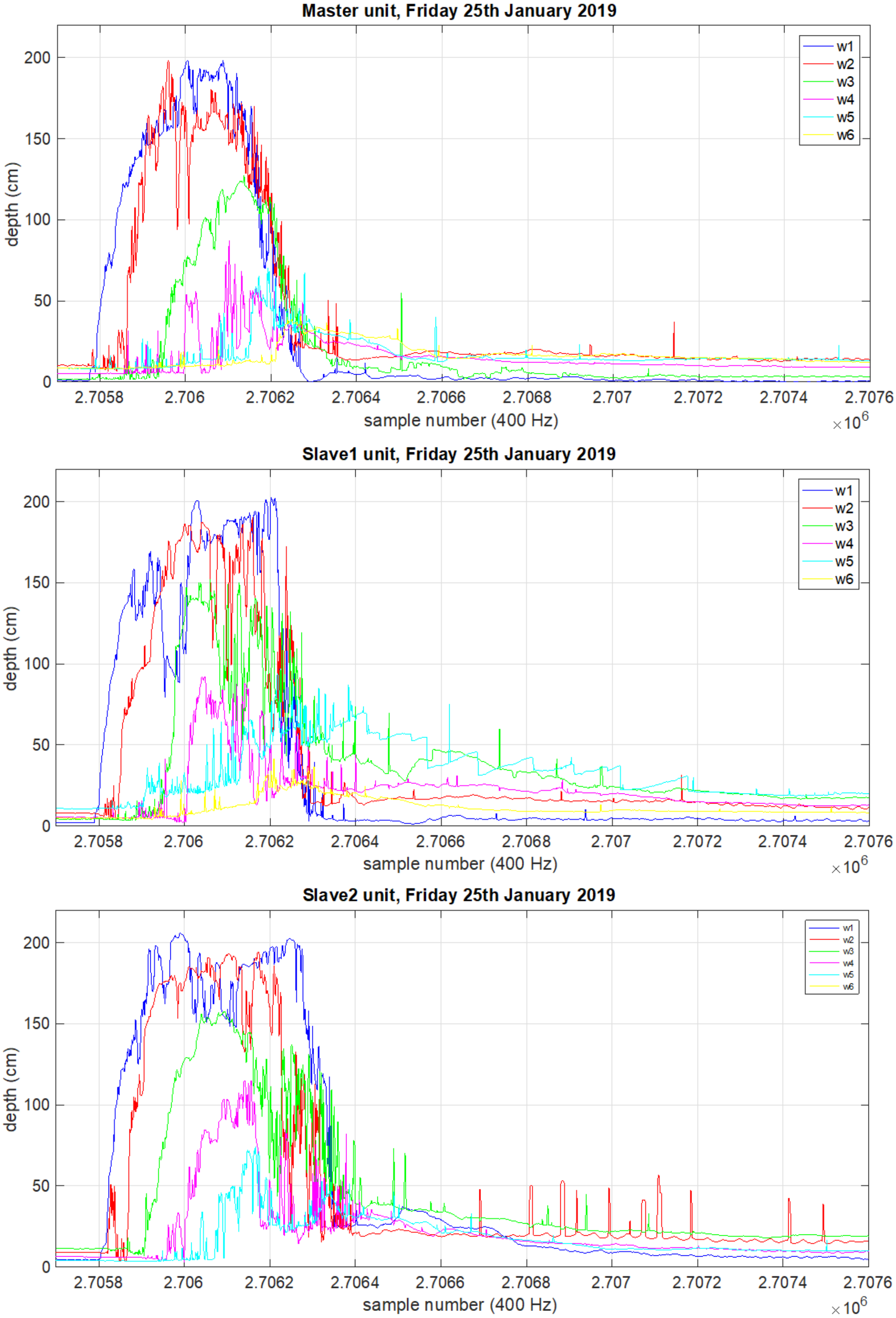


Figure 4.22: An example of one of the larger wave plumes on the 25th January 2019, showing time series data from each of the three WireWall units: the Master (top plot, north row of wires), Slave 1 (middle plot, middle row of wires) and Slave 2 (bottom plot, south row of wires). The lines represent each of the 6 wires in the row (wire1 to wire6) and show the wave passing from the sea (wire1 left) towards land (wire6 right) with time. The data were collected at 400 Hz: the plots show 4.75 seconds of data and the plume lasted for about 1.5 seconds. Note that wire3 and wire5 on the Slave1 unit were not working well (as indicated by their very slow and erratic decrease after the plume has passed). Similarly, wire6 on Slave2 failed

completely. Wires with issues such as these are identified during processing and are ignored by the processing algorithm.

Figure 4.23: Still image of one of the very largest plumes observed during the deployment on Friday 25th January 2019. It can be seen that the seawards part of the plume is taller than the rig. However, the upper part of the flume is made up of quite fine spray compared to the much denser spray/solid water lower down. In addition, the height of the plume reduces as it travels through the rig.

Depths, speeds and volumes are calculated from multiple wire pairs AB, where wireB is inland of wireA. In each case, the volume of water passing through B is calculated from the depth on B, along with the speed derived from the time lag of the event as seen on wireA compared to wireB. In this way, five estimates can be made of the speed and volume of the water reaching the most inland wire6, for example, using data from pairs 16, 26, 36, 46 and 56. This provides a method to assess uncertainty in the measurements at each wire inland of wire2. For water reaching wire3, located next to the railing, only two estimates are available, i.e. from pair 13 and pair 23. If all 6 wires in a unit are working then there will be up to fifteen estimates of the speed of the flow for each plume event, depending on how far inland it reaches. As can be seen in Figure 4.22, the time taken between the event being seen on one wire and the next may vary between different pairs because small volumes of spray (not associated with the main plume) may be detected first (e.g. wire2 in red, on the Slave2 unit in Figure 4.22). This can result in the calculated speed being much higher on one pair compared to the other pairs. Similarly, the direction of the flow of the plume can affect the calculated speed, and hence the resulting volume, for any given pair. Figure 4.24 shows a case where a near-vertical plume is generated at the face of the sea wall and is therefore seen on wire1 and wire2 almost simultaneously (resulting in an overestimate of the horizontal speed) before it travels inland to wire3 and wire4. Further inland, wire5 and wire6 see water very soon after wire4: in this case it is due to a body of water arriving from further north on the promenade.

Figure 4.25 shows the speeds calculated for a section of data (about 40 minute long) from the Master unit during the same deployment. It can be seen that most pairs register speeds of only a few m/s, but some pairs (often pair12) show speeds that are very much higher (occasionally up to 70 m/s but these are off scale in this figure). Such erroneously high speeds would lead to erroneously large volumes to be calculated for that pair. For this reason a cut-off speed of 6 m/s was chosen and for each overtopping plume the speed of the flow in the sea-land direction is estimated using the median value of all pair speeds which are below the cut-off value. It should be noted that this is done on a wave-by-wave basis so that each plume is assigned a speed based on the data from that plume. This approach is reasonable since it is assumed that the horizontal speed of the flow will not vary significantly over short distances (1.75 m between wire1 and wire6).

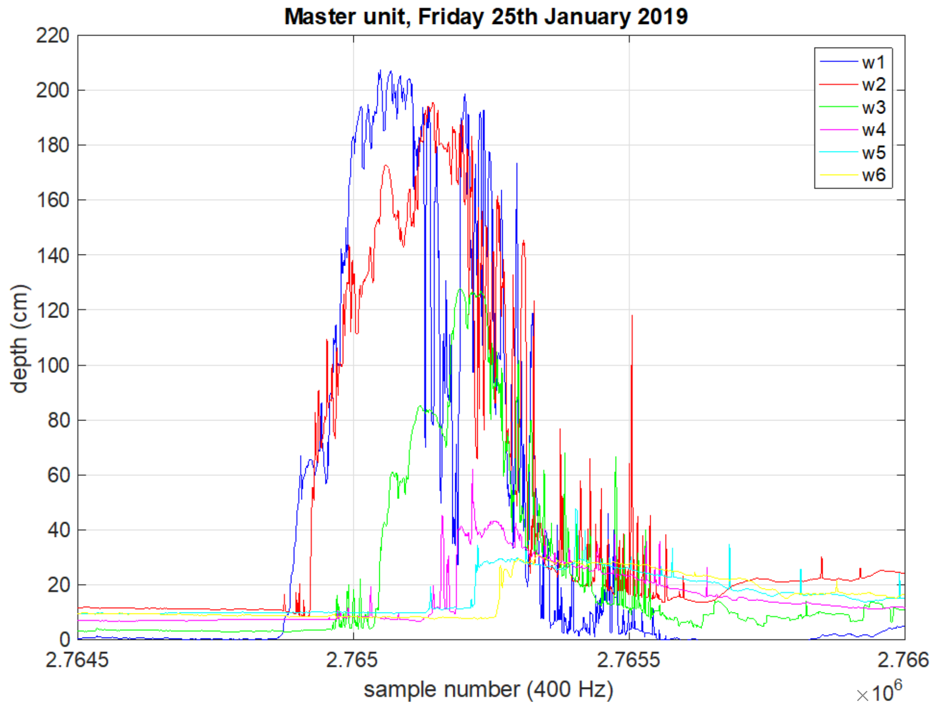


Figure 4.24: A plume event from Friday 25th January as recorded by the WireWall Master unit.

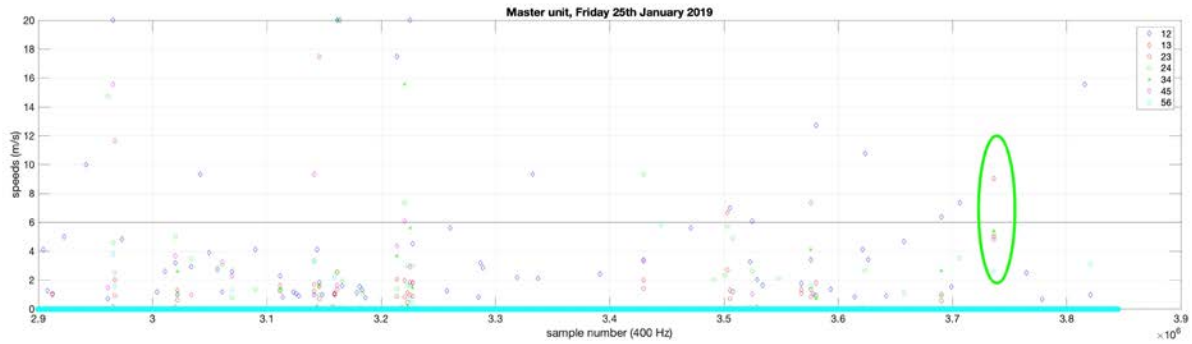


Figure 4.25: Speeds from different wire pairs for a section of data (about 40 minutes long) from the Master unit on Friday 25th January. Not all pair speeds are shown for clarity. The green circle highlights an overtopping plume when the majority of pairs give a speed of about 5 m/s. The horizontal black line shows the choice of "cut off" speed of 6 m/s for this deployment.

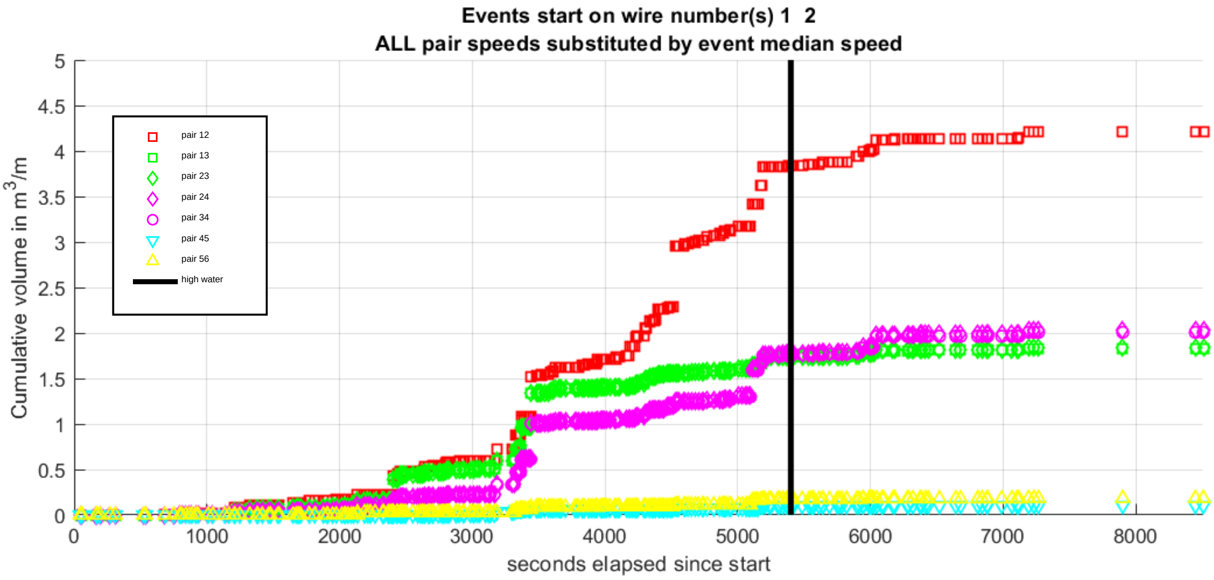


Figure 4.26: The cumulative volumes from the deployment on Friday 26th October 2018, calculated from various wire pairs from the Slave2 unit. High water is indicated by the vertical black line. Colours denote which wireB is used for the depth measurement in the calculation of the volume.

Figure 4.26 shows the cumulative volumes calculated from the WireWall unit Slave2 during the deployment on Friday 26th October 2018. It can be seen that the volumes decrease in size with inland distance. It can also be seen that wire4 (pink) is damaged by a large event that occurs at about 5000 seconds (i.e. it exceeds the wire3 (green) seaward measurements), and after that point the volumes on wire4 are biased high (higher than the volumes calculated on wire 3 which is nearer the sea). Otherwise, sudden jumps in the cumulative values are the result of larger overtopping plumes or a short sequence of small overtopping plumes occurring close together. By analysing the overtopping on the flood and ebb tide (over a 90 minute period centred on high water) it is found that much more overtopping occurs on the flood tide than the ebb tide. This is seen in Figure 4.26 by the steeper increase in the cumulative overtopping occurring on the flood tide than on the ebb. Before HW the total overtopping volume on pair12 is nearly 4 m^3/m and after HW the volume is much less than 1 m^3/m. The wind was fairly consistent fluctuating from 11 m/s at the start to 7 m/s at HW and back to 11 m/s towards the end. This flood-ebb asymmetry is present in the other deployments and is thought to be related to the turn of the local tidal current. For example, the top plot in Figure 4.27 shows the cumulative volumes from the much more energetic overtopping event on Friday 25th January 2019. The flood asymmetry is seen again, with volume on pair12 of more than 50 m^3/m by the time of high water, and only about 10 m^3/m after high water.

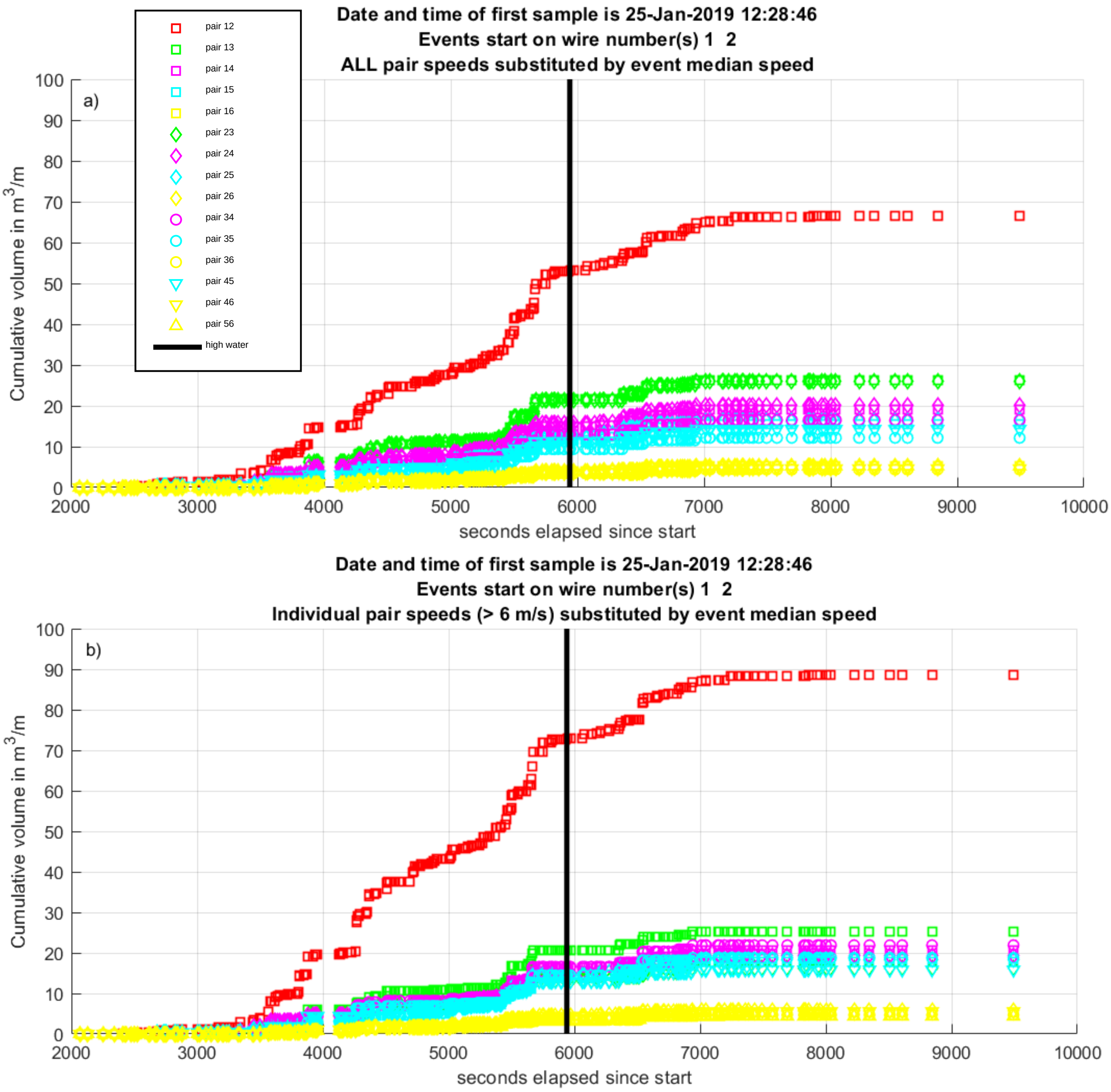


Figure 4.27: Cumulative volumes from the Master unit on Friday 25th January 2019. All possible combinations of wire pairs AB are plotted, as indicated in the key. Colours denote which wireB is used for the depth measurement in the calculation of the volume. a) The standard method of assigning each overtopping plume a single speed, calculated from the median of measured speeds (below the threshold of 6 m/s) for that plume. b) An alternative approach where only speeds that are above the threshold of 6 m/s are substituted by the median. The results from this approach only differ noticeably for pair 12, since this pair often register erroneously high speeds due to the up/down nature of the plume at the face of the sea wall.

As described above, the standard method to calculate the volume of an individual plume is to use the depth on wireB combined with the median of the speeds calculated from all wire pairs for that plume (excluding any speeds which were higher than a threshold of 6 m/s). This approach is taken to avoid erroneously large volumes resulting from erroneously large speed estimates that occur when, for example, a plume of water rises vertically upwards at the sea wall and impacts wires 1 and 2 almost simultaneously, or if water arrives diagonally through the side of the rig and is again seen almost simultaneously by the more inland wires. An alternative approach would be to only substitute those speeds that are over the 6 m/s threshold. This is shown in Figure 4.27b, and it can be seen that on average there is very little difference in the results, but the agreement between wire pairs XB is slightly less good, as would be expected.

An important question to consider is which is the most appropriate volume to use for model validation? All the deployments were carried out with the rig arranged so that wire1 projected seawards of the face of the sea wall, in order to detect the speed of the water as it approached the wall. Wire2 was set immediately above the face of the sea wall, and wire3 was about 30 cm inland, on the landward side of the railing that runs along the promenade. See photo in the top right of Figure 3.8. Water that is registered on pair12 will significantly overestimate the volumes reaching the promenade, since many of the plumes travelled vertically up the face of the sea wall and the majority of the water fell back into the sea. In contrast, water reaching wire3 has arrived inland on the railing that protects pedestrians on the promenade from falling into the water. **Thus it is thought that volumes reaching wire3 (shown green the cumulative volume plots above) best represent overtopping that could pose a hazard to pedestrians.**

To produce a time-series of overtopping discharge rates, the data are averaged over 5 minute intervals (see Figure 4.28), and also as 15 minute running means produced every 5 minutes in order to smooth out some of the variability. The averaging interval can be selected to suit the required frequency of data, while removing the noise due to individual wave variability. A 5 minute minimum interval is suggested due to the large temporal variability in overtopping, while 15 minutes is suitable for the comparison with overtopping tools that typically use offshore wave and nearshore water level observations recorded at this lower frequency. Figure 4.28 shows results for the deployment on the 26th October 2018 and the WireWall time-series data highlights the asymmetry in the tidal phases. The peak in overtopping occurs approximately 15 minutes before HW and overtopping decreases in volume and duration on the falling tide. The data shows that at high water there is over 2 orders of magnitude difference in the overtopping discharge distribution through the rig (< 2 m inland distance).

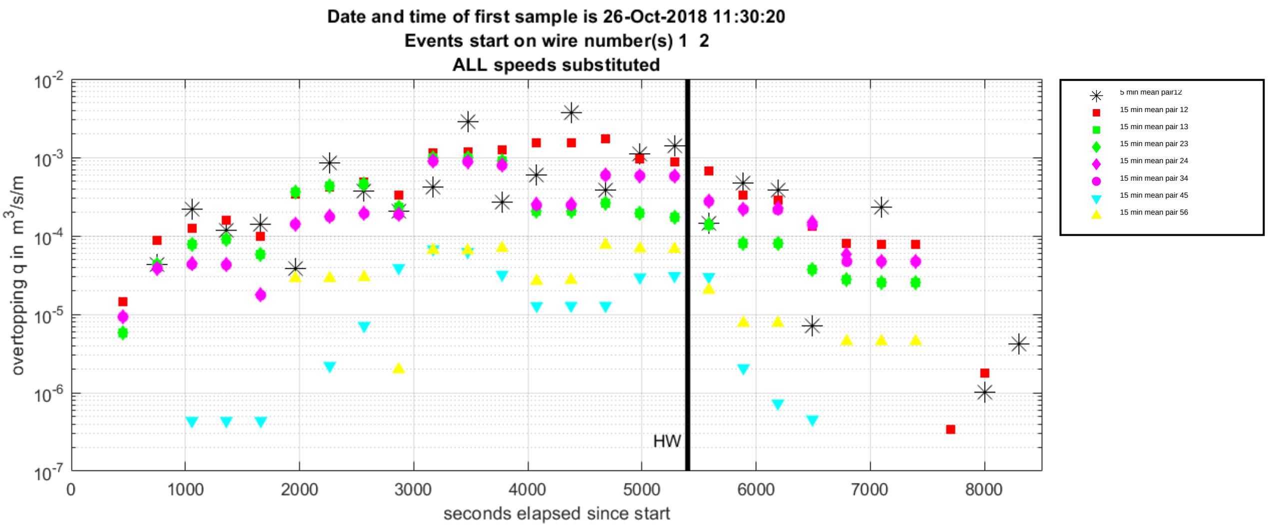


Figure 4.28: An example time series of overtopping discharge rate ($m^3/s/m$) for the 26th October 2018. The 15 minute running mean values are presented at 5 minute intervals. Note that wire4 (pink) is damaged part-way through the deployment and the volumes from that wire are biased high from 5000 about seconds onwards.

We use existing available data from the AWAC and local Meteorological Station to investigate the cause of the asymmetry in the overtopping time-series data. We assume it is related to the change in tide as greater overtopping is seen on the flood tide (about 4 or 5 times the amount compared to the ebb tide for the two deployments discussed here) for all WireWall deployments and the variability in wind and offshore wave conditions is minimal during the overtopping windows. Figure 4.29 clearly shows the change in tidal current at the AWAC positioned close to the low water mark slightly south of our model transect. The data are only available hourly, so cannot resolve the processes that cause a peak in overtopping discharge 15 minutes prior to high water. However, the data can help explain why there is about 4 or 5 times more overtopping on flood-tide than on the ebb. It is clear fast currents are directed onshore in a direction that would refract the waves towards the sea wall prior to high water. The tidal flow then rapidly decreases at high water and turns to oppose wave propagation.

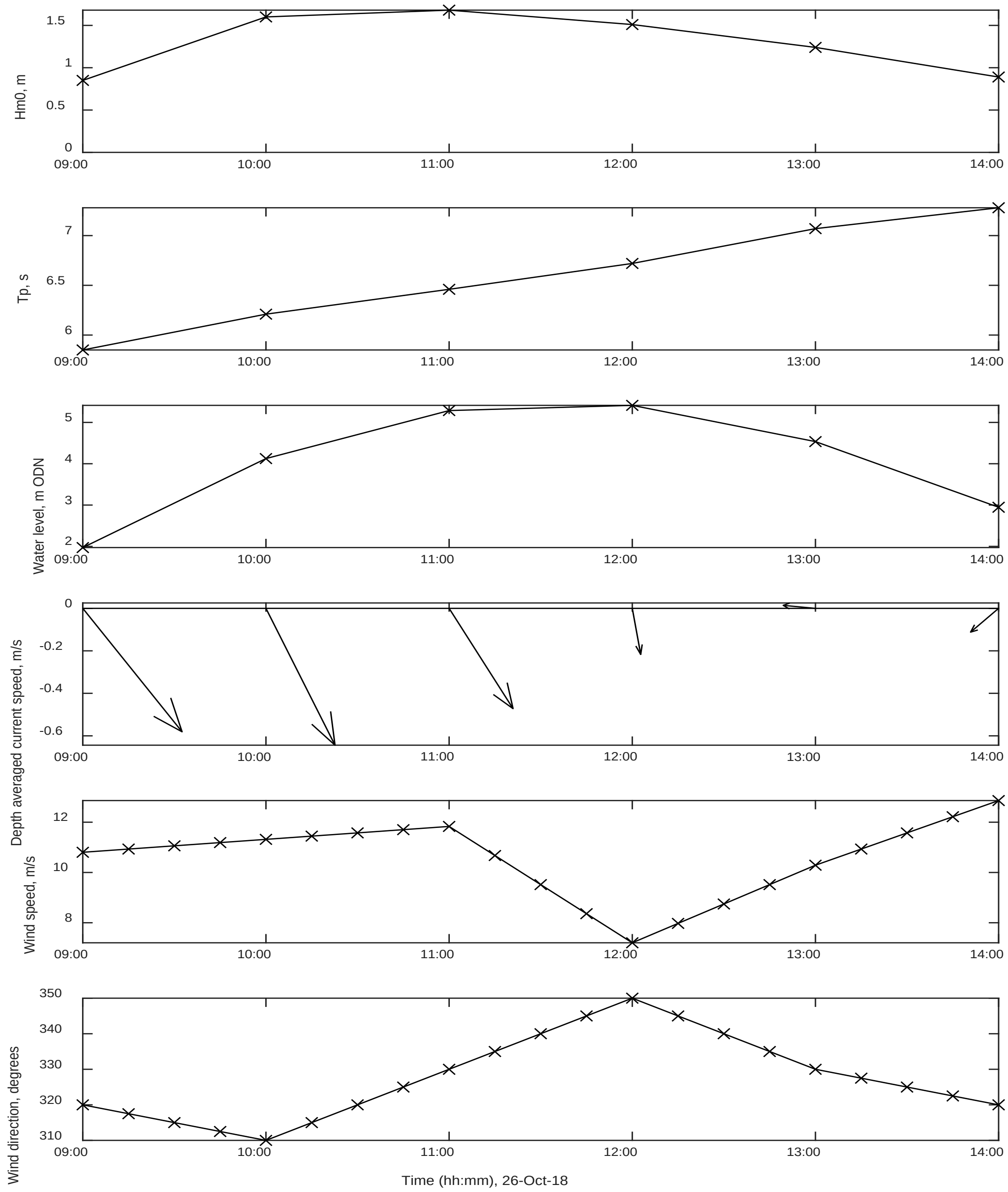


Figure 4.29: Observations from the AWAC close to the low water mark and the Met Station at the Coastguard station for the overtopping window 26th October 2018.

While it is appreciated BayonetGPE (O19) might under predict the field conditions for Crosby due to the influence of wind, there are also uncertainties relating to the WireWall measurements. These also need to be considered prior to numerical-observation comparisons. The biggest factor is the alongshore variability in overtopping: the rig carried three units spanning an alongshore distance of about 90 cm and Figure 4.22 shows that significant variability exists even in this small spatial scale. In addition, the overtopping plumes often travelled at an angle to the sea-land axis, so for some plumes the water seen on the inland wires actually arrived through the side of the rig: however over a full event duration this would average out due to other events where the water was not registered by the inland wires since it had already exited the rig through the side. The main measurement uncertainty is in the estimate of the speed of the overtopping water, since the speed is used to calculate the volume. However, the results are quite robust to the choice of threshold speed, and to the method of either using individual speeds or a single median speed for each plume (Section 4.10). Use of a single median speed for the whole of a deployment also has very little impact (not shown). Hence although the estimate of speed for a given single plume may have high uncertainty, over a whole event deployment these uncertainties tend to average out. Use of multiple wire pairs gives confidence in the estimate of speed used to calculate the volume results, as does the realistic distribution of water volumes with inland distance. Finally, the video cameras provide qualitative support for the WireWall measurement: the duration of events passing through the rig is consistent with the typical median measured speeds of just a few m/s and the height of the water compared to the rig is consistent with the measured heights/depths. There is the potential that WireWall under-predicts a few of the very largest plumes that were taller than the height of the rig (Figure 4.22, bottom), but these were very rarely seen during the 2018/2019 deployments (Table 3.6). In general, most of the uncertainties in the measurement method would tend to lead to the results being biased low rather than high. For example: if the threshold speed is set too low then the volumes will be underestimated (if it is set too high this should not be an issue for the bigger events since the median speed should be reliable); if plumes are taller than the rig then their volumes will be underestimated; if water arrives at an angle and is not seen on the seawards-most wires (wire1 and wire2) then the plume is not registered; if water arrives diagonally and is seen on only the most seawards wires (wire1 and wire2) before leaving through the side of the rig then the inland part of the plume will not be measured.

Summary

The 26th October 2018 represents moderate-energy conditions.

WireWall successfully measured wave-by-wave overtopping volume distribution inland from the crest of a sea defence in the field.

The use of measurements from all available wire pairs gives confidence in the speed estimated for each individual wave-by-wave event, and hence in the resulting volume.

The highest frequency of post-processed measurements useful for flood risk management is a time-series of overtopping information at 5 minute intervals, but the data can also be presented as cumulative overtopping volumes.

We have identified asymmetries in the overtopping during the tidal cycle, with total overtopping volumes prior to high water being 4 or 5 times greater than those after high water.

4.11 Field BayonetGPE-WireWall comparison

4.11.1 SWAN validation

The accuracy of the BayonetGPE (O19) estimates will depend on the accuracy of the wave conditions transformed to the structure toe using SWAN. Ideally a SWAN model from the AWAC to the structure toe would have been used to capture the nearshore wave refraction. However, this would have required the AWAC data to be available more readily at a higher frequency to resolve the time variability seen during the (~ 2 hour) overtopping window at high water. Here we first use the data from the AWAC during the field deployments to initially validate the SWAN wave transformations, and then we compare the WireWall measurements to BayonetGPE (O19) estimates. The AWAC data are provided at an hourly frequency and during some tides have missing data during the overtopping window. Figure 4.30 qualitatively validates the numerical wave transformation from the WaveNet buoy to the AWAC for the two events described in detail in this report, i.e. 26th October 2018 and 25th January 2019.

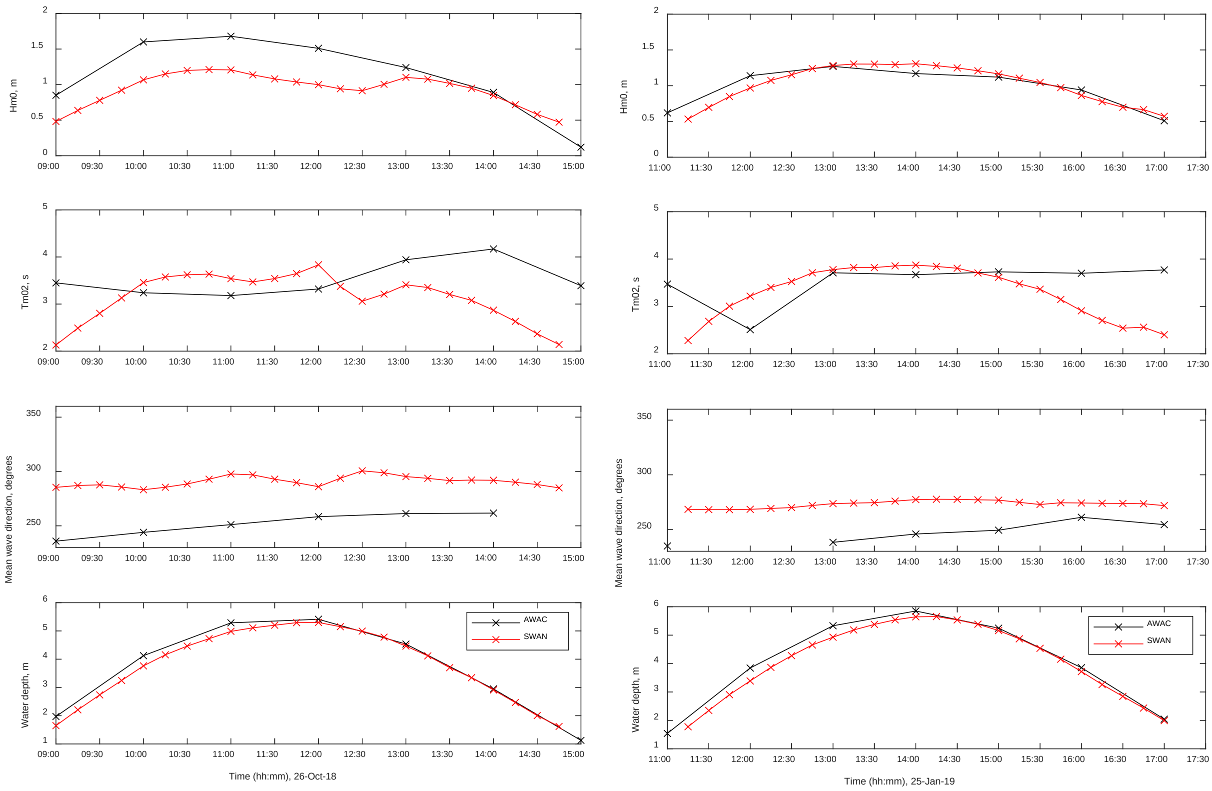


Figure 4.30: Time-series data from SWAN (extracted at the closets grid point to the AWAC position across shore and just to the north alongshore, see Figure 3.2) and the AWAC over the overtopping windows on (a) the 26th October 2018 and (b) 25th January 2019.

While the wave conditions at the AWAC position are acceptable, there are discrepancies. The key parameters at the structure toe for input in to BayonetGPE are wave height, wave period and depth, which are more accurately modelled than the wave direction. However, the discrepancies in conditions offshore will have limited impact on the overtopping as it is the errors in values at the structure toe that have most impact, and these errors are largely due to the resolution of the upper beach profile. The error in wave direction highlights the limitation of using a cross-shore profile model without the consideration of currents, an approach often used due to the lack of existing current data. Our transect is complicated by 1) the Mersey channel and strong tides both of which will influence wave refraction, and 2) alongshore wave driven currents during more extreme wave conditions, that can prevent flow reversal of the tide. The transect follows the survey line which is normal to the shore and positioned for long-term monitoring of the beach levels (including the ridge runnel system). It was not adjusted to align with the prevailing offshore wave direction, which would be the ideal set up for a 1DH profile model application. However, variability in wave direction for each individual event will always cause issues and easily cannot be accounted for if forecasting or modelling in near-real time. From the AWAC data the wave heights are found to peak before high water in our examples and the water levels are slightly higher on the flood tide. These local impacts might have caused asymmetries in the overtopping as measured by WireWall (see above) and illustrate the very high value of having wave and water level data close to the toe of the structure. The error metrics for the events are shown in Tables 4.4 and 4.5. The 8th November 2018 has lowest skill, mainly due to the small waves propagating from a more southerly direction (Table 4.6), which is not ideal for this 1DH modelling approach.

Table 4.4: The bias in the maximum value of conditions modelled by SWAN relative to the AWAC. Corresponding offshore and overtopping conditions are given later in Table 4.6.

Date	Hm0, m	Tm02, s	Wave direction, deg	Depth, m
24/10/2018	0.08	-0.05	30.60	-0.05
25/10/2018	0.04	-0.36	25.40	-0.11
26/10/2018	-0.47	-0.34	38.90	-0.11
08/11/2018	0.04	-1.18	-22.90	-0.07
22/01/2019	-0.56	-0.43	20.90	-0.09
23/01/2019	-0.25	-0.43	13.90	0.06
25/01/2019	0.04	0.10	16.50	-0.19
22/03/2019	0.15	0.50	2.30	-0.12

Table 4.5: The bias in the range of conditions modelled by SWAN relative to the AWAC. Corresponding offshore and overtopping conditions are given later in Table 4.6.

Date	Hm0, m	Tm02, s	Wave direction, deg	Depth, m
24/10/2018	0.52	0.42	-1.00	-0.63
25/10/2018	-0.07	0.85	-9.00	-0.54
26/10/2018	-0.09	0.71	-8.40	0.24
08/11/2018	0.02	-0.33	-61.3	-0.51
22/01/2019	-0.44	0.12	-17.30	0.40
23/01/2019	-0.33	-1.19	-60.90	-1.00
25/01/2019	0.01	0.33	-16.80	-0.43
22/03/2019	0.24	1.05	-5.80	-0.12

Summary

The SWAN modelling approach was acceptable for this study.

Wave refraction due to the complex bathymetry and strong currents should ideally be captured in a study of this site.

To improve the accuracy of the modelled wave conditions at the structure toe it would be preferable to use either 1) a 2DH or 3D modelling approach to at least provide conditions at the offshore point of the beach survey or 2) AWAC data, preferably at a higher frequency, at the offshore end of the beach survey.

4.11.2 BayonetGPE setup using the 1st field deployment 26th October 2018

Initial comparison between the WireWall field measurements and the BayonetGPE (O19) estimates were made for 26th October 2018 (Figure 4.31). We can see that WireWall is able to measure over the complete overtopping window, while BayonetGPE

(O19) can only confidently estimate conditions for approximately 1 hour before high water when overtopping is at its maximum. This demonstrates the value in the WireWall observations in capturing information for the full duration of an event, which is critical for assessing the cumulative volumes for hazard management, issuing timely hazard alerts and understanding the time variability in the overtopping hazard as conditions change (e.g., the tide). When compared with the EA alert threshold (Figure 4.31) the 5 minute averaged WireWall data collected on the seaward side of the handrail (wire2) and the upper uncertainty bound (+2 s.d.) associated with the mean BayonetGPE (O19) estimate would have triggered an alert for approximately 15 minutes about 30 minutes prior to high water.

The inland overtopping distribution passing through different pairs of wires is shown alongside the mean BayonetGPE (O19) estimate and the upper and lower bounds representing 1st and 2nd standard deviations (s.d.) from the mean value for the 26th October 2018 (Figure 4.31). These bounds are used to capture uncertainty in the tool. As discussed in Section 4.10, the best estimate of the overtopping water that presents a hazard to pedestrians is that which reaches wire3 since this is located immediately inland of the railing or handrail on the promenade, just 30 cm inland of the crest. In contrast, a large fraction of the water that reaches wire2 (immediately above the crest) may not reach the railing and will either fall vertically downwards directly back into the sea, or only reaches the crest of the wall and then drains back into the sea without reaching wire3. For this reason the volumes on wire2 represent an extreme upper limit to the WireWall overtopping measurements. Since the potential measurement issues discussed in Section 4.10 would tend to lead to the WireWall volumes being underestimated, rather than overestimated, we believe that the volumes from wire3 can be considered representative of the likely overtopping, with those on wire2 representing the extreme upper limit.

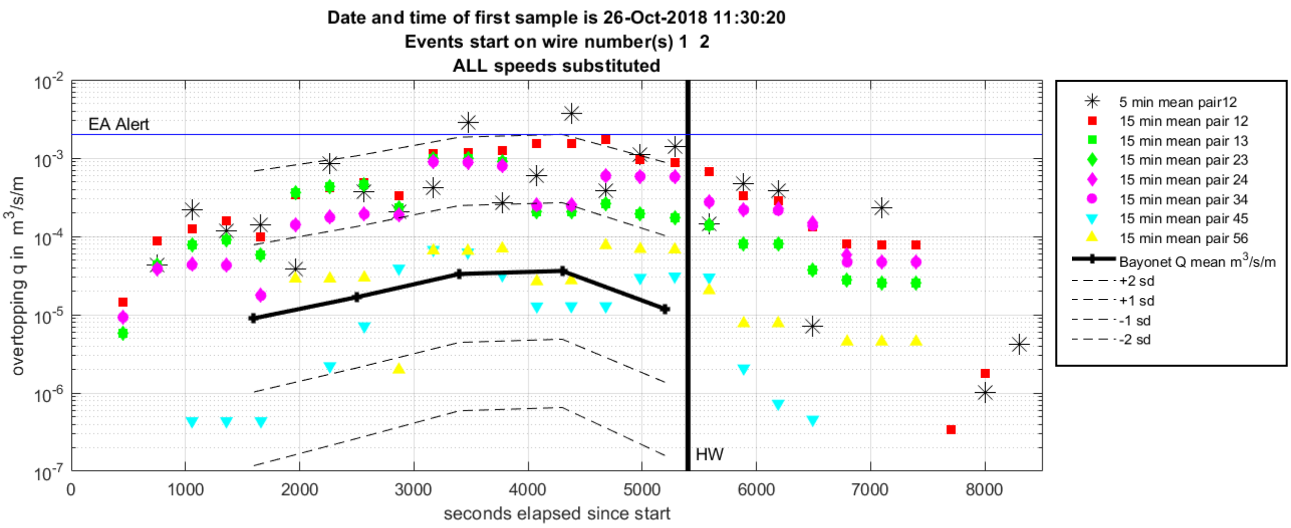


Figure 4.31: Overtopping measured by WireWall and estimated by SWAN-BayonetGPE (O19) 26th October 2018. The WireWall data are presented as 5 minute averages and 15 minute running means at 5 minute intervals. The SWAN-Bayonet (O19) data are calculated using 15 minute interval input data from the local tide gauge, wave buoy and weather station and shown as a thick and dashed lines. Note that wire4 (magenta) is damaged before high water (vertical line) and is biased very high thereafter. The EA alert threshold is given (blue line) for comparison.

Considering wire pairs A2 and A3 for the 26th October 2018 we find there is over an order of magnitude discrepancy between WireWall and BayonetGPE (O19), with WireWall showing peak overtopping discharges of more than 10^{-3} m^3/s/m on wire3, whereas the mean estimate from BayontGPE predicts a maximum of about $2.5\text{x}10^{-5}$

$m^3/s/m$. Initial comparisons had indicated a discrepancy of over two orders of magnitude, but further investigation showed that this was due to an issue in the input parameters for BayonetGPE (<O19). When these were corrected (BayonetGPE October 2019 data presented here) the comparison showed good agreement given the observations (pair A3) were within the +2 s.d. uncertainty bound (and sometimes close to +1 s.d.) of the numerical estimates.

Summary

WireWall measures over the full overtopping window to collect data that are out of range in the BayonetGPE (O19) database.

There is over an order of magnitude discrepancy between WireWall and BayonetGPE (O19), but BayonetGPE does not incorporate wind influence, which is critical at Crosby and was the key driver of the wave overtopping during our deployments.

4.11.3 BayonetGPE comparison with the overtopping 25th January 2019

The BayonetGPE input parameters for the Crosby sea wall structure fall outside the standard options within the EurOtop (2018) manual. Following appropriate set up of the input parameters using the 26th October 2018 (Section 4.11.2), overtopping estimates for all other field deployments were generated using BayonetGPE (O19). The 25th January 2019 provides an example of more extreme conditions that pose a hazard to pedestrians (Figure 4.32).

BayonetGPE (O19) is expected to perform better for these higher-energy events as it was developed for structure design purposes (extreme event estimates) rather than for estimating everyday acceptable levels of overtopping. Figure 4.32 illustrates that the WireWall data and mean estimate from BayonetGPE (O19) agree within an order of magnitude for the peak of the overtopping period on 25th January 2019, but that BayonetGPE (O19) underestimates by two orders of magnitude at the start of the overtopping window. In general, the Bayonet estimates are closer to the WireWall data on pair A5, which is about 1 m inland from the crest. For this event BayonetGPE (O19) captures the majority of the overtopping window, but the numerical results are more symmetric around high water than those measured by WireWall. WireWall again captures an asymmetry in the overtopping with more overtopping occurring on flood tide than ebb and with the peak in overtopping conditions occurring about 15 minutes before high water. This asymmetric pattern was observed during all field deployments. For this event the conditions exceed the EA hazard alert and $H_{m0,t,}$ = 1 m EurOtop hazard threshold for pedestrians during both the flood and ebb tide. The duration and magnitude by which the alert thresholds are exceeded is greater on the flood tide.

The magnitude of the 25th January 2019 provides a useful case to assess the EurOtop pedestrian hazard threshold for Crosby (Figure 4.32). The measured discharge rate at the hand railing (wire13) exceeded the lower limit for about 15 minutes before high water, and it was exceeded at the crest (wire12) during the hour before high water. SWAN estimated $H_{m0,t} \leq 0.87$ m during the overtopping window. Although the seaward wire measurements exceed this threshold, the mean BayonetGPE (O19) values remain well below the threshold. No hazard alert was issued by the EA's flood forecasting system, while both the WireWall and BayonetGPE (O19) data exceed the EA's hazard alert threshold. The camera footage confirms the WireWall data that shows an alert **should** have been issued for pedestrian safety reasons. This suggests that a 10 l/s/m overtopping discharge rate seems appropriate as a lower limit to any hazard threshold for promenade users at Crosby and if the < 2 s.d. of uncertainty is taken into account (rather than just relying on the mean) in the numerical estimates this is likely to be triggered more frequently by the latest version of BayonetGPE since future releases should incorporate field data from Crosby to expand the database.

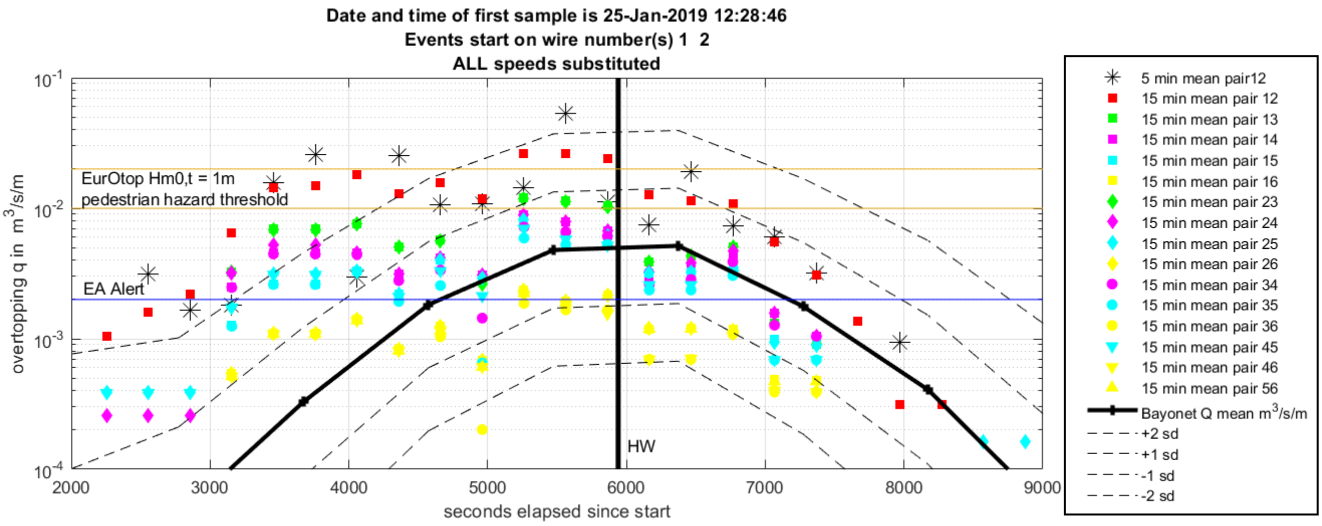


Figure 4.32: Overtopping measured by WireWall and estimated by SWAN-Bayonet (O19) for 25th January 2019. The WireWall data are presented as 15 minute running means at 5 minute intervals. The SWAN-Bayonet (O19) data are calculated using 15 minute interval input data from the local tide gauge, wave buoy and weather station and the mean values are shown as a thick line. The EA alert threshold (blue line) and EurOtop pedestrian hazard threshold range (gold lines) are given for comparison.

The low bias in BayonetGPE (O19) results compared with WireWall is expected as wind influence is not considered within the tool, and the onshore wind carries the plume inland. In the absence of an onshore wind the recurve on the wall works well. The EurOtop (2018) guidance suggests ±2 s.d. around the mean overtopping discharge should be considered to account for local uncertainty: Figure 4.31 shows that the BayonetGPE (O19) +/- 2 s.d. estimates can span more than three orders of magnitude.

When comparing the cumulative overtopping volumes from WireWall and BayonetGPE (O19) we see how the impact of uncertainty in the latter grows over an overtopping window of a few hours (Figure 4.33). The BayonetGEP (O19) mean overtopping volume aligns most closely with that measured to reach the 5th inland wire (about 90 cm inland) within the WireWall rig, and are about 50% smaller than the volumes reaching the 3rd wire located very close to the railing. When considering < 2 s.d. to account for uncertainty the full sea to land distribution of WireWall measurements are within the uncertainty bounds. This demonstrates how improved understanding of the uncertainty in overtopping estimates is critical to refine these bounds for structure design purposes. Designing to capture the worst case scenario could result in significantly higher build and maintenance costs for a coastal scheme. However, some uncertainty must be accounted for around the mean as there is potential for underestimation of the total overtopping at the crest due to processes not captured within the numerical approach, e.g. wind blow spray and, in this case, a representation of the oblique wave propagation.

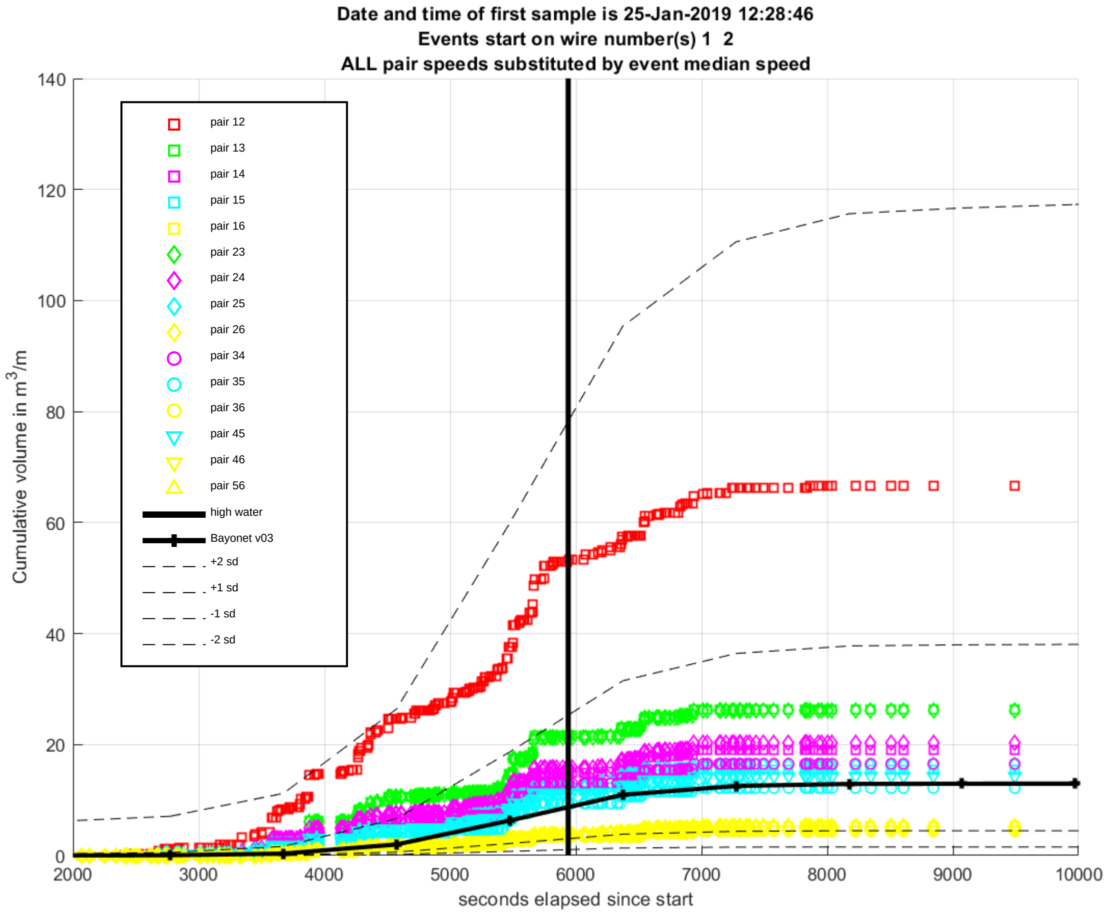


Figure 4.33: Cumulative overtopping measured by WireWall and estimated by SWAN-Bayonet (O19) 25th January 2019. The SWAN-Bayonet (O19) data are calculated using 15 minute interval input data from the local tide gauge, wave buoy and weather station and shown as different lines in grey scale.

Summary

The 25th January 2019 represents high-energy conditions.

WireWall and BayonetGPE (O19) agree within an order of magnitude for the peak of the overtopping period, but Bayonet underestimates by two orders of magnitude at the start of the overtopping window.

The WireWall data fall within the BayonetGPE (O19) uncertainty bounds (+/- 2 s.d. of the mean), but when assessing the cumulating overtopping volume these bounds grow to be extremely large. Having more confidence in the mean value at a site is critical.

When there is a large vertical component to the overtopping plume wire1 and wire2 (just seaward and at the crest of the sea wall) can both be wet to a high elevation in the uprush of water. Measurements of overtopping discharge from wires12 can be 50% higher than values from wires13 or wires 23, suggesting the plume falls back to sea and does not travel inland past the handrail. For hazard management we suggest using overtopping data measured at wire3 when setting hazard thresholds and validating numerical tools.

4.11.4 WireWall-BayonetGPE comparison for the eight overtopping conditions with both data available

The Crosby field conditions were potentially out of range for the SWAN-BayonetGPE (O19) approach. During winter 2018/2019 no green water overtopping events were observed during WireWall deployments. The spray conditions encountered during these deployments are a challenge to estimate numerically. In the field a vertical plume of spray was generated and overtopping was caused by the onshore wind counteracting the effect of the recurve. We therefore expect the mean numerical estimates to be biased low at this site during typical winter conditions, where the recurve works well.

The total volume (m^3/m) measured by WireWall and estimated by BayonetGPE (O19) over the duration of the overtopping window for the eight deployments where both data are available (Table 3.6) are given in Table 4.6 and shown in Figure 4.34. For deployments where more than one of the three WireWall units worked an estimate of the variability between the units is given as an uncertainty. Total overtopping from wire3 (next to the railing, about 30 cm inland of the crest) is the best estimate of the measured overtopping that could cause a hazard to pedestrians. Overtopping at wire2 will be biased considerably high since a large fraction of the measured water will fall vertically back down into the sea: these values are given in the table since they represent the extreme upper limit to the measured overtopping, i.e. water which may have passed the crest of the wall but flowed back into the sea without being registered at all just 30 cm inland. A modified upper limit is created by using volumes at wire2 ONLY if some of the plume water was detected on wire3: this is termed the "sensible" upper limit. It is clear that there is no consistent over- or under-estimate between WireWall measurements and the BayonetGPE (O19) estimates, which indicates that the difference between the WireWall measurements and BayonetGPE (O19) is not due to a calibration issue, for example, but is due to factors (e.g. the onshore component of the wind speed and/or the wave direction and/or changes in tidal currents) that are not currently included in the SWAN-BayonetGPE (O19) approach. Of the 9 deployments there were 3 when no overtopping was measured and of the 8 deployments simulated by BayonetGPE (O19) 6 estimated overtopping. Bayonet predicted overtopping on the 23rd January whereas none was measured. For the 4 deployments where overtopping was detected at wire3 on WireWall, the BayonetGPE estimates agreed with the WireWall data (to within the +/- 1 s.d. bounds of the tool) on two occasions, but underestimated by more than 1 s.d. on the other two occasions (26th October 2018 and 22nd January 2019).

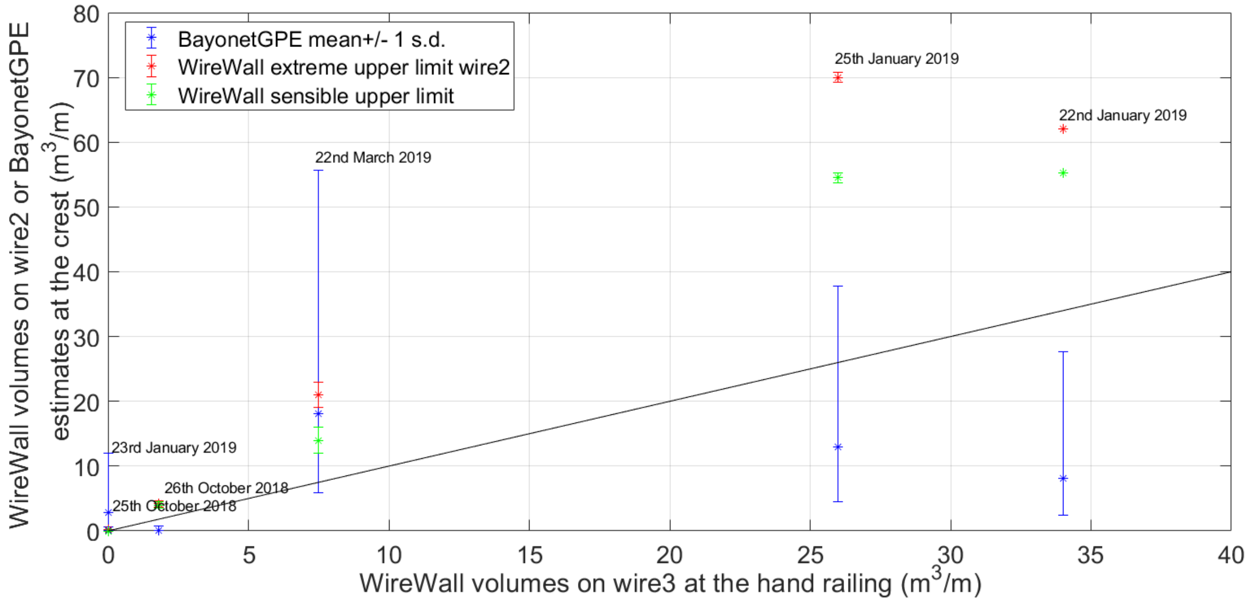


Figure 4.34 Comparison of WireWall data with the mean volume estimated from BayonetGPE (O19). The dates of the four most-energetic deployments are shown. Error bars indicate the +/- 1 s.d. estimate for the

BayonetGPE (O19) results (blue points). Error bars on the WireWall results are from measurements made from more than one of the three units (Master, Slave1, Slave2). The x-axis shows the WireWall volumes on wire pairs A3, i.e. at the railing. The y-axis is the corresponding volume from one of the following: BayonetGPE (O19), WireWall wires12 or WireWall wires12 when overtopping is also detected on wire3 (“sensible”), as indicated by the legend symbols. The black line indicates 1:1 agreement (i.e., the overtopping volume passing the railing is the same as the overtopping volume at the crest). Red points show the extreme upper limit, i.e. all volumes detected on Wire2 at the crest, whereas the green points show the "sensible" upper limit which is only the A2 volumes where at least some of the plume water has reached Wire3. See Table 4.6 for values.

The two largest overtopping events occurred on the 22nd and 25th of January 2019. On those two days conditions were generally very similar, except that on the 25th the mean wind speed was much stronger, at 10.5 m/s (compared to 6 m/s on the 22nd). Despite this, the overtopping measured by WireWall was larger on the 22nd than the 25th. However, it should be noted that wire3 on the Master unit on the 22nd January occasionally showed a high bias after rig-high plumes were encountered (believed to be due to slight water ingress in the connector at the top of the rig) so the wire3 results may be reduced somewhat when the data are investigated in more detail. Data from the two slave units have yet to be analysed due to an issue with the calibrations applied to the raw data by the logging system. Once this has been rectified, and the data from the slave units are re-processed, the results for the 22nd January will be more reliable. If the results from the slave units confirm that overtopping was greater on the 22nd than the 25th, this could be due either to the slightly longer wave period, the more southerly wind direction, and/or the misalignment of the wind and wave directions causing slightly increased wave spreading and perhaps slightly more confused seas (wave heights offshore and at the toe, wave direction and water levels were all almost identical on the two days). The mean estimates from BayonetGPE (O19) underestimated the overtopping on both days, by a factor of 2 on the 25th (and, currently, a factor of 4 on the 22nd).

Table 4.6: (a) Upper table: Field observations of the coastal conditions from WaveNet, the Liverpool tide gauge and the Met Office station wind speed for the 7 deployment days when WireWall data were collected in 2018/2019 (Table 3.6). Numerical estimates of the wave conditions at the structure toe are provided by SWAN. (b) Lower table: The measurements of total overtopping (m^3/m) from the WireWall system and the mean estimate of total overtopping from BayonetGPE (O19). Note that the results from WireWall on the 22nd January are from one unit only and are particularly uncertain.

a)

Deployment	Overtopping duration, s	HW level, m OD	H_{m0}, m at HW	T_p, s at HW	Wav dir, deg at HW	Wav spread, deg at HW	$H_{m0,t}$, m at HW	$T_{p,t}$, s at HW	Depth at the toe, m	Wind speed, m/s at HW	Wind dir, deg at HW
24/10/2018	0	4.1	1.3	5.5	289.5	25.5	0.6	4.0	1.4	9.0	300.0
25/10/2018	5000	4.3	0.9	5.0	286.5	34.5	0.6	3.9	1.7	6.6	270.0
26/10/2018	5000	4.4	2.3	6.5	304.0	28.0	0.7	4.8	1.7	8.4	345.0
08/10/2018	0	4.7	0.9	3.8	162.0	28.5	0.3	3.0	2.2	6.0	150.0
22/01/2019	7000	4.8	1.5	6.3	289.5	25.5	0.8	4.9	2.5	6.0	227.5
23/01/2019	65000	5.0	0.8	5.1	287.0	26.0	0.6	4.5	2.7	2.3	50.0
25/01/2019	6000	4.8	1.7	5.7	290.0	18.0	0.9	4.5	2.6	10.5	270.0
22/03/2019	7500	5.3	0.8	4.9	283.0	26.0	0.7	4.1	2.8	7.7	220.0

b)

Deployment	Overtopping at wire3 (~30 cm inland), m^3/m	Variability at wire3 +/- m^3/m (0 if only one unit)	Overtopping at wire2 (0 cm inland), m^3/m	Variability at wire2 +/- m^3/m (0 if only one unit)	Overtopping sensible upper limit m^3/m	Sensible limit +/- m^3/m (0 if only 1 unit)	Overtopping BayonetGPE (O19) m^3/m	BayonetGPE (O19) -1 s.d. m^3/m	BayonetGPE (O19) +1 s.d. m^3/m
24/10/2018	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
25/10/2018	0.00	0.00	0.15	0.00	0.00	0.00	0.01	0.00	0.10
26/10/2018	1.80	0.10	4.20	0.50	4.00	0.00	0.10	0.01	0.75
08/10/2018	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
22/01/2019	34.00	0.00	62.00	0.00	55.20	0.00	8.12	2.42	27.60
23/01/2019	0.00	0.00	0.00	0.00	0.00	0.00	2.80	0.66	11.96
25/01/2019	26.00	0.00	70.00	0.80	54.50	13.00	12.94	4.47	37.77
22/03/2019	7.50	0.50	21.00	2.00	14.00	1.70	18.11	5.91	55.64

Summary

BayonetGPE (O19) is expected to underestimate the wave overtopping at Crosby due to the influence of an onshore wind counteracting the effect of the sea wall return curve.

Uncertainty in WireWall results occurs due to overtopping water coming from an alongshore direction through the rig.

For the 4 deployments where overtopping occurred and was measured by WireWall, the BayonetGPE (O19) estimates agreed with the measurements (i.e. were within the BayonetGPE +/- 1 s.d. bounds) on two occasions, but underestimated by more than 1 s.d. on two occasions.

The wave and water level conditions on the 22nd and 25th of January 2019 were very similar, but more overtopping occurred on the 22nd, which had a lower wind speed. This could suggest subtle differences in wave period and wave spreading may also be very important overtopping controls, but the WireWall results from the Master unit on the 22nd need to be confirmed by data from the two Slave units.

4.12 BayonetGPE estimates for winter 2018/2019 compared with estimates for past photographic evidence and return period curves data

The BayonetGPE (O19) estimates (all performed in October 2019) for the days when field observations were made are compared with the estimates for past events (Figure 4.35) identified by photographic evidence since 2013 (Section 4.1). Although our field data are limited in time to six tides when overtopping was predicted by BayonetGPE (O19) the water levels cover most of the range of previously observed overtopping conditions when the public are visiting the Crosby beach. The wave heights considered also cover the two main data classifications, with significant wave heights at the toe of the structure falling between 0.5 to 0.75 m or between 0.75 and 1 m. The numerical estimates give us confidence that the WireWall field data are representative of typical winter conditions. The WireWall data are limited by the fact no storm event occurred.

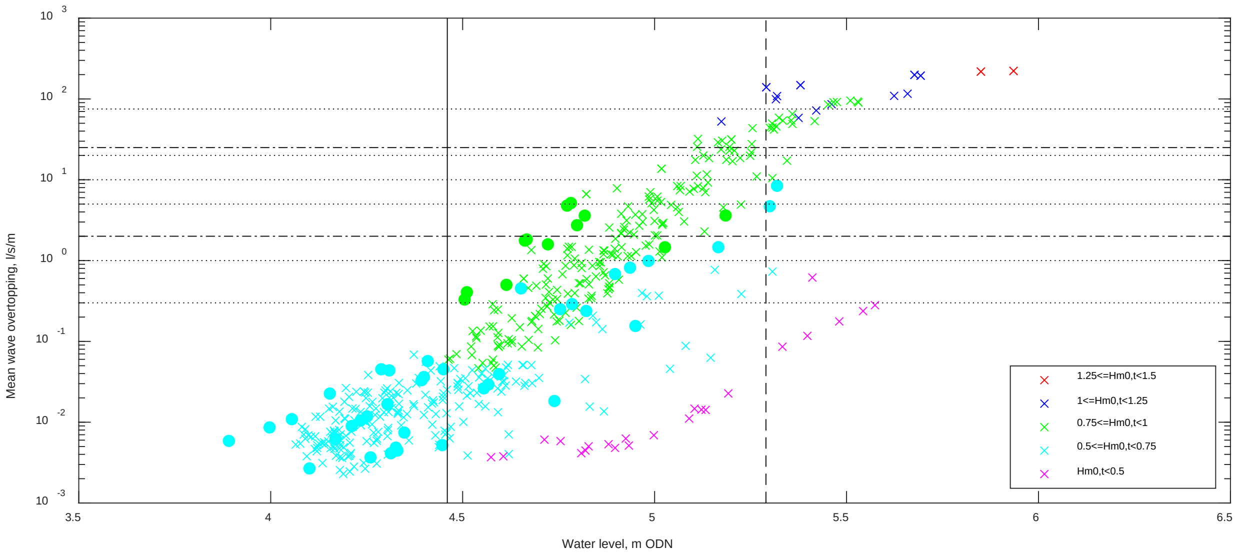


Figure 4.35: Comparison of the BayonetGPE (O19) discharge estimates for winter 2018/2019 (dots) compared with the BayonetGPE (O19) estimates for the photographic evidence (crosses) shown in Figure 4.6a. Each data point represents a discrete estimate at 15 minute intervals when coastal monitoring data are available.

When compared with the return period curves for Liverpool Bay, the field events are considered to be more frequent than a 1 in 2 year annual probability event, nearly all of them are more frequent than a 1 in 1 year annual probability event (Figure 4.36). In some cases the BayonetGPE (O19) estimates for the field observations give higher overtopping discharges than the BayonetGPE (O19) estimates for events of the same severity identified from the photographic evidence. We expect this is because we are expanding the combinations of less energetic wave and water level combinations. The majority of the winter 2018/2019 events have low offshore wave heights suggesting the waves were not depth limited. Visual observations confirmed that the waves broke directly onto the stepped revetment during the overtopping window on calmer days, which may explain the higher overtopping discharge. During our deployments and site visits we noticed that the public were only taking photos of the more impressive overtopping when the promenade was clearly becoming wet. Many of the events for which WireWall was deployed were considered “splashy” (see Table 3.6), i.e. consisted of just small plumes of spray which did not overtop onto the promenade: since these are not very impressive they may not be represented (captured on camera) in our public social media evidence base.

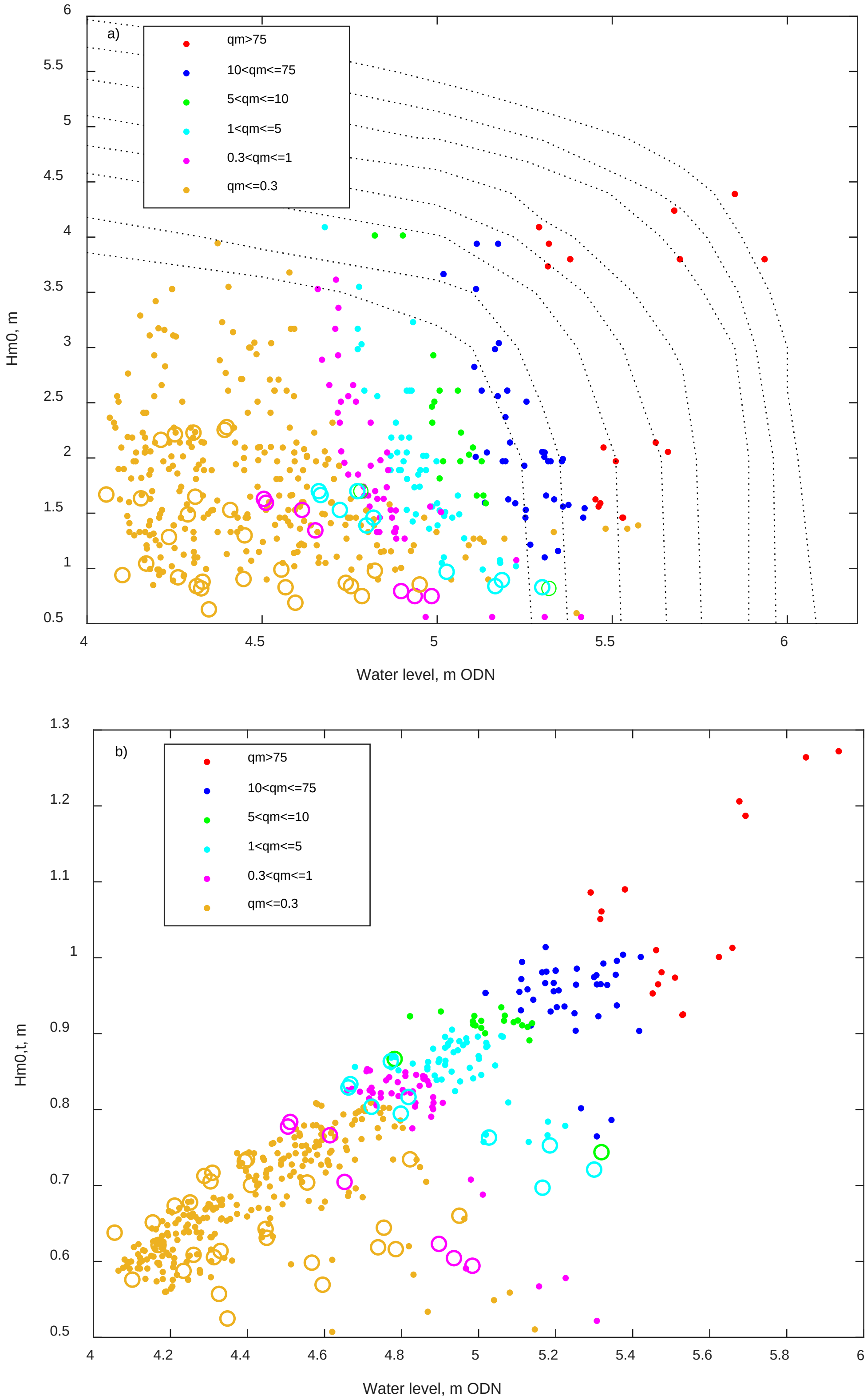


Figure 4.36: Comparison of the BayonetGPE (O19) estimates for winter 2018/2019 (dots) compared with the BayonetGPE (O19) estimates for the photographic evidence (crosses): a) relative to the return period curves shown in Figure 4.11a. Here Hm0 is offshore data from WaveNet. b) considering the wave height and water level at the structure toe.

Summary

The numerical estimates give us confidence that the WireWall field data are representative of typical winter conditions, i.e. more frequent than a 1 in 2 year event. A longer study period is required to capture more extreme events.

The data for the field measurements expand the conditions observed by the Facebook record and show higher overtopping discharges can occur for low-energy conditions than first expected.

4.13 BayonetGPE field estimate comparison against physical model (tank) data

The overtopping discharges estimated by BayonetGPE (O19) for the winter 2018/2019 field observations are compared with the longitudinal tank data from the physical modelling experiments (Figure 4.37). The physical model data are representative of the wave conditions at Crosby but extend the water levels to future scenarios where the sea level is higher than at present. The data overlap for offshore wave conditions < 1 m and water levels between 5 and 5.5 m ODN giving confidence in the numerical approach. The tank data are closer to the lower numerical estimates in the field, which could be expected as there is no wind influence in the flume estimates while it is considered in the SWAN wave transformation for the field estimates.

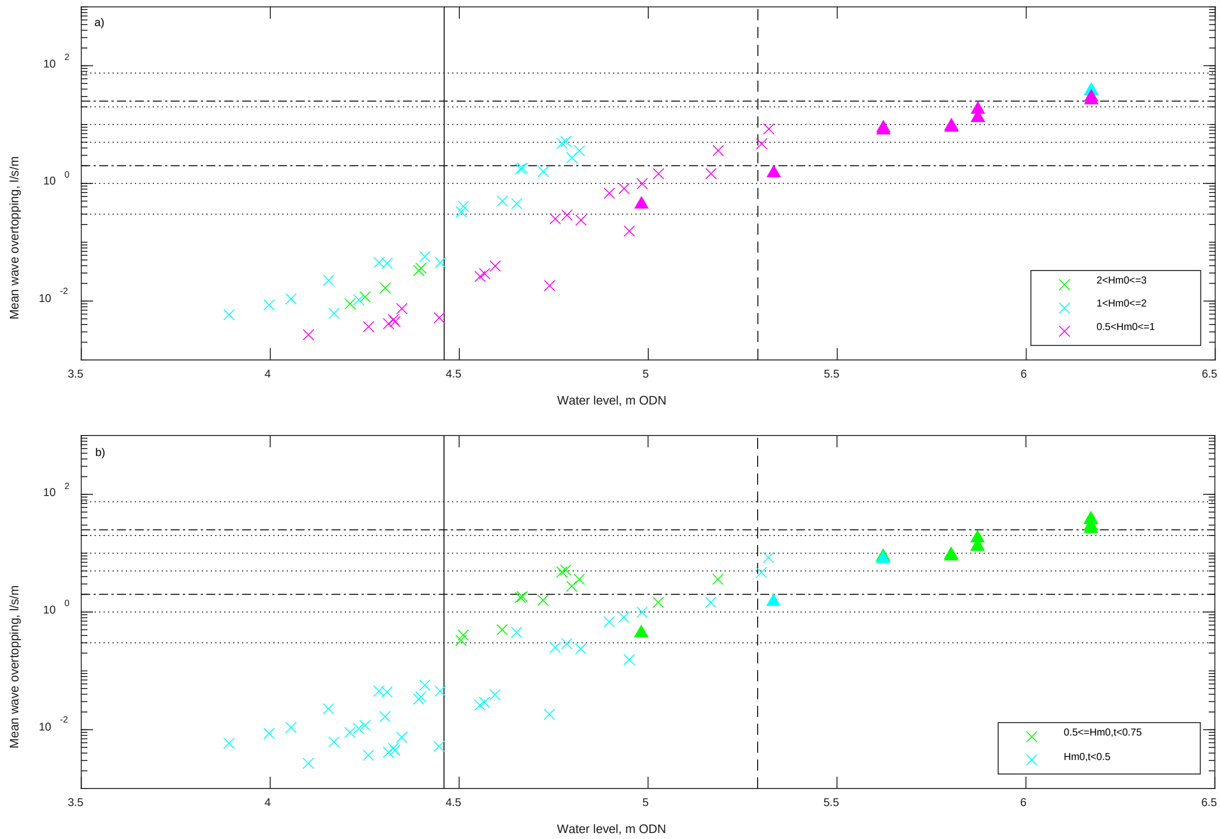


Figure 4.37: Comparison of the BayonetGPE (O19) estimates for winter 2018/2019 (crosses) compared with the physical model tank data (triangles). The threshold lines are the same as those in Figure 4.6. The data are colour coded to represent a) the significant wave height at WaveNet and b) the significant wave height at the structure toe (from SWAN or the flume gauge).

4.14 EA flood forecasting service comparison

During the winter 2018/2019 there were no flood alerts or warnings issued by the EA's flood forecasting service. However, three of the deployment events were evidently hazardous to pedestrians on the promenade due to the frequency, size and inland distance covered by the overtopping waves. In a couple of cases the spray, carried by the onshore winds, reached the car park and the overtopping flow was also able to overtop the splash wall approximately 5 m inland of the promenade due to its momentum. These events occurred on the 26th October 2018, 22nd January 2019, 25th January 2019 and 7th March 2019, the latter was not measured by WireWall. For these cases video footage has been shared with the EA to support decisions around a review of the alert thresholds. In none of the observed cases was a flood warning required as no inundation within the car park occurred. However, the visual and WireWall observations showed that wave spray potentially posed a hazard to those using the promenade due to the potential for them being: cut off from access points; soaked on cold windy days without access to shelter; and hit by debris being brought over the sea wall at speed. For footage see our YouTube clips (Appendix V) https://www.youtube.com/playlist?list=PL2nHwISkP2SkSY3sEEWOqzK3tcSmVdxR7.

To try and ascertain why there were no alerts issues, when the threshold seems appropriate, we compare our numerical estimates for winter 2018/2019 to the conditions included within the EA's hazard forecast matrix (Figure 4.38). The key difference between our numerical approach and the one used to set up the EA's forecast system will be the development and update of the BayonetGPE database since the EA system was set up in 2009. While the BayonetGPE (O19) estimates exceed the EA alert and warning thresholds for overtopping discharge they do not reach the EurOtop thresholds for pedestrian safety for waves of 1 m (2nd and 3rd threshold from the top). This suggests the EA overtopping estimates are under predicted.

Comparing the BayonetGPE (O19) estimates to the range of conditions in the EA's forecast matrix we see the water level range is adequate, but BayonetGPE (O19) estimates overtopping discharges that are towards the upper limit of those available in the matrix and occasionally higher for water levels between 4.5 and 5.5 m ODN. Our low wind conditions generate higher wave conditions at the toe of the structure than considered within the matrix. This could cause underestimation of the overtopping conditions as the wave conditions are interpolated from much smaller values. A recommendation from this work would be to increase the wave heights considered to include typical windy conditions, i.e. 0.5 m $\leq H_{m0,t} \leq$ 1 m should be considered at the structure toe for wind speeds < 30 mph.

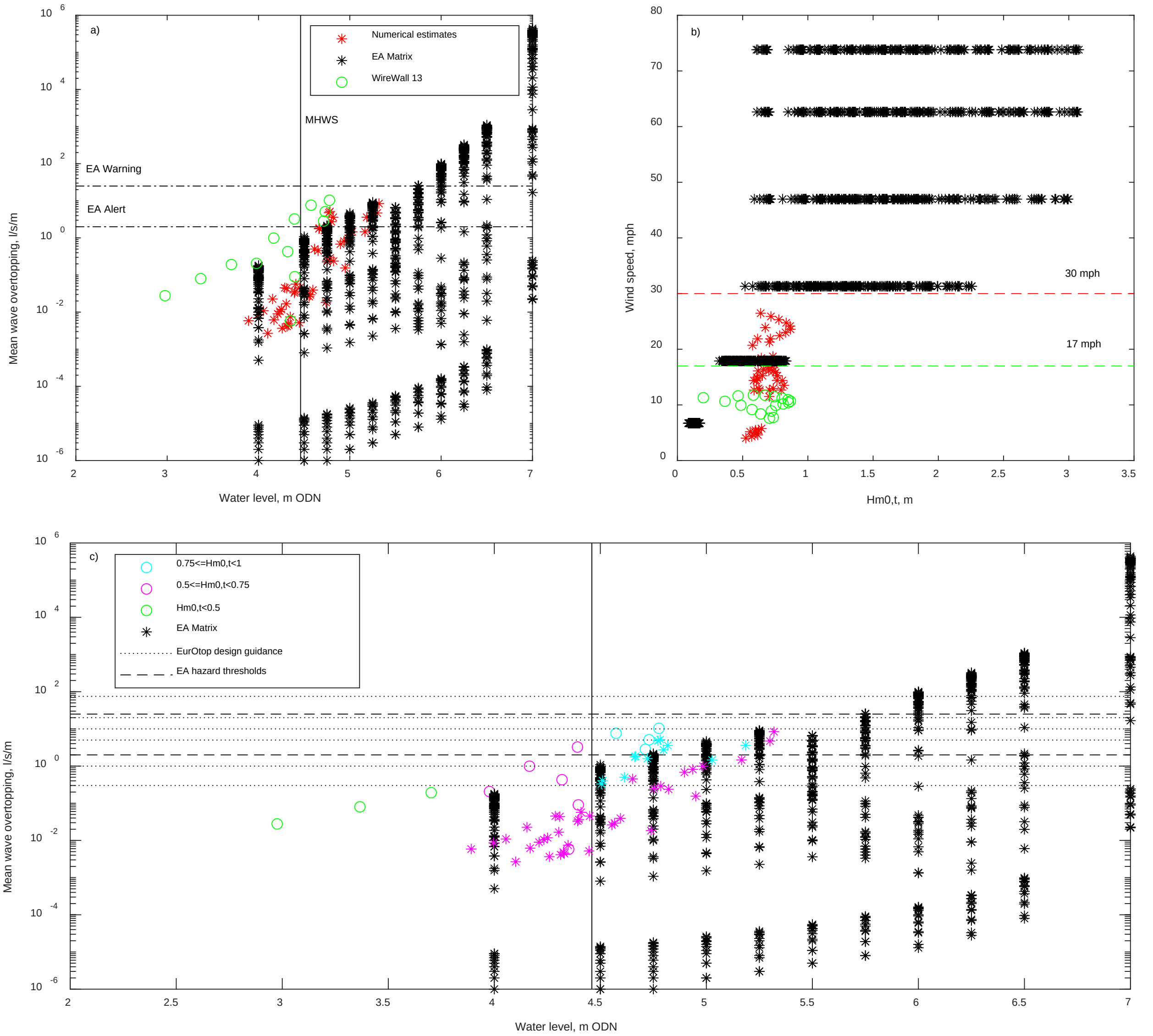


Figure 4.38: Comparison of the BayonetGPE (O19) estimates for the winter 2018/2019 deployment days (coloured *) compared with the conditions within the EA's matrix (black *), WireWall measurements for 26th October 2018 and 25th January 2019 (coloured O) and the EA's local and EurOtop guidance safety thresholds (horizontal dashed lines). The threshold lines are the same as those in Figure 4.6. The WireWall data are the mean discharge in 15 minute averaging windows for wire pair13 (i.e., the discharge that passes inland of the hand railing) on the Master unit (most north).

Figure 4.39 shows the EA predictions of overtopping are biased much lower than those from BayonetGPE (O19) for the 25th January 2019, when WireWall measured overtopping at the handrail (i.e. at wire3) that exceeded the EurOtop 1 m $H_{m0,t}$ hazard threshold for pedestrians and the EA alert threshold (Figure 4.32). This is particularly noticeable from 14:00, when the water level (and thus wave height at the toe) and wind speed are dropping, although the wave height offshore is maintained. We assume the main reason for this is the limited wave height range for low winds within the matrix. The similarity in the first 3 overtopping data points suggests when wind conditions are > 25 mph EurOtop 2007 (on which the EA matrix is based) estimates overtopping conditions similar to those in BayonetGPE (O19), but when the wind drops the interpolation options in the matrix underestimate overtopping significantly for lower wind speeds.

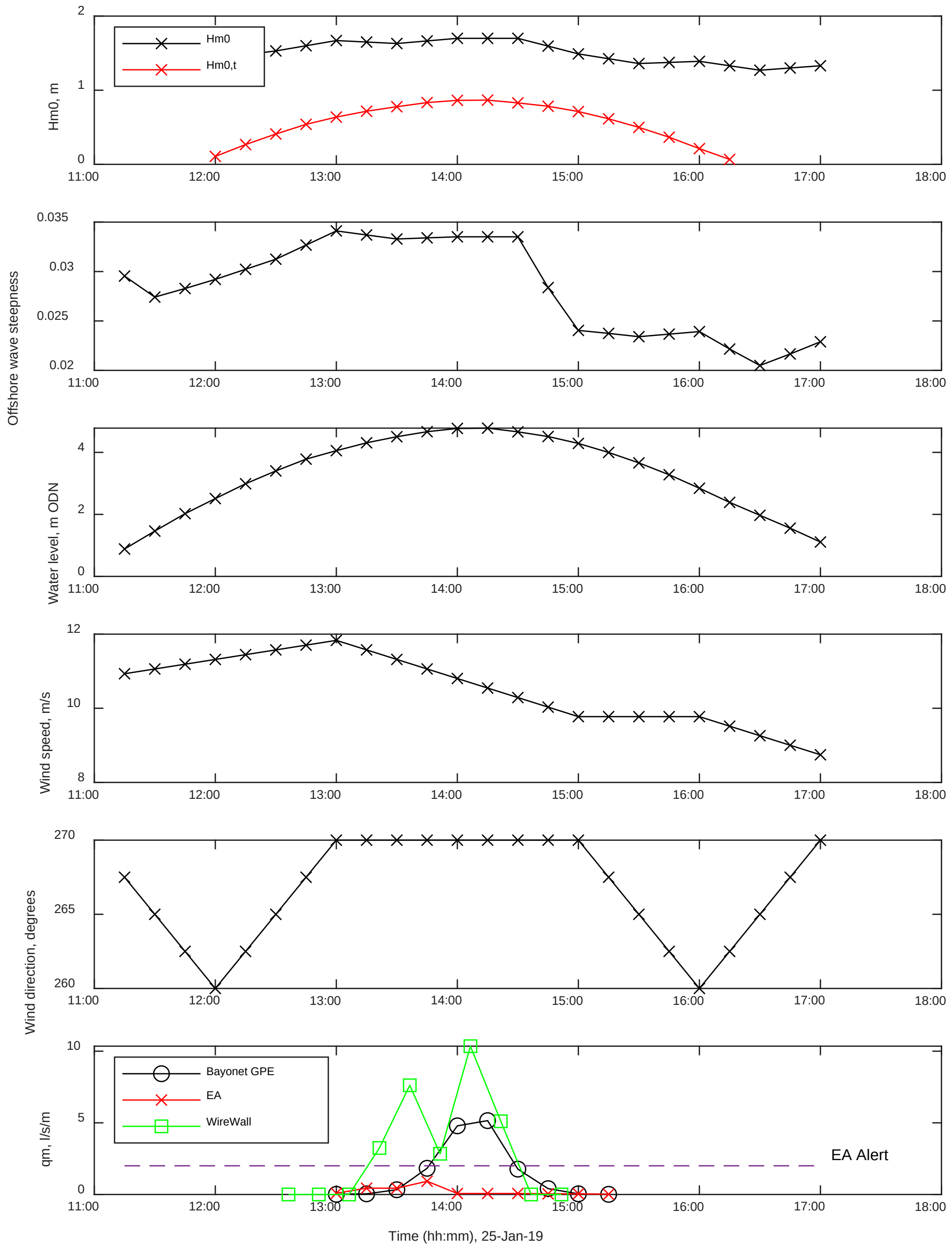


Figure 4.39: Comparison of the BayonetGPE (O19) and EA forecast matrix estimates for the 25th January 2019, along with oceanographic input data from SWAN, wind observations and WireWall measurements. The WireWall data are the mean discharge in 15 minute averaging windows for wire pair13 (i.e., the discharge that passes inland of the hand railing) on the Master unit (most north).

A key difference between the WireWall approach and that of the EA is the location (structure-beach profile). WireWall and the associated numerical estimates focused on the northern end of the car park, while the EA forecast location is towards the southern end of the car park. It is known that beach levels increase towards the south (e.g. Figure 4.40a). The difference in the beach level at the toe of the structure was approximately 2 m lower, when surveyed at Hall Road during WireWall deployments (October 2018 – March 2019) than in the static profile surveyed for the EA's system documented 9th October 2009 (it is likely the survey was taken earlier in the year prior to delivery of the accompanying documentation for the EA matrix). Figure 4.40 (b-d) shows high beach levels close to the Hall road survey line when training with SC during their April 2018 survey. By the WireWall deployments the beach had lowered and often exposed the sheet piling (e.g. Figure 4.40e). This shows that seasonal viability in beach level at the structure toe can change by the order of 1 m. Section 4.3 shows how a 0.5 m change in beach level can noticeably change the overtopping estimates.

Figure 4.40: a) Looking south from the bottom of the slipway along the Crosby sea wall 17th March 2015. The beach level during a SC survey 13th April 2018 a) just south of the slipway b) seaward of the slipway and c) at the slipway looking north. c) The beach level prior to high water on the 25th January 2019 with the sheet piling just exposed in front of the 3 most northern stepped revetment sections.

For the WireWall field deployments the significant wave height at the toe of the defence (modelled by SWAN) ranged from 0.11 to 0.76 m. These small waves ($H_{m0,t} \leq 1$ m) are representative of those associated with overtopping on a river, small lake or wide canal, all often associated with grass covered embankments. However, they caused overtopping at Crosby with its stepped revetment and vertical wall. For sheltered seashores a 1 m< $H_{m0,t} \leq 3$ m is assumed to be more likely to pose an overtopping hazard. When there is a clear line of sight of the sea the hazard to those on the crest of the defence is given in Table 1.1 (end of Section 1). During our study BayonetGPE (O19) estimated a maximum mean overtopping discharge of 8.42 l/s/m (+2 s.d. = 79.78 l/s/m or +1 s.d. = 25.92 l/s/m). From the GoPro footage the more energetic field deployments (26th October 2018, 22nd January 2019 and 25th January 2019) posed a hazard to pedestrians on the promenade. The measured WireWall overtopping reaching wire3 (on the inland side of the hand railing) ranged between 1 l/s/m and 10 l/s/m at high water on these days suggesting a limit is needed for smaller wave conditions ($H_{m0,t} < 1$ m) at this site for the existing structure and that this needs to be lower than the lowest EurOtop threshold 10 l/s/m for $H_{m0,t}$ =1 m.

From the field deployments, conditions that pose a potential hazard to pedestrians around high water (the main window 1 hr before high water and ½ hr after high water) can be identified as a water level > 4 m ODN with west to north winds > 12 mph. The wind conditions can be associated to local wind seas with wave heights > 1.3 m. If the winds were stronger prior to high water then larger remnant waves still pose an overtopping hazard under the lighter wind conditions coinciding with the higher water elevations. The conditions at the toe of the structure modelled by SWAN and BayonetGPE (O19) overtopping estimates are available for each simulation from BODC (see Appendix IV).

It should be noted that 7th March 2019 posed a hazard to pedestrians and was probably the most extreme overtopping event during winter 2018/2019 that occurred at Crosby. Although WireWall was not deployed (due to a concern with the Master electronics box during calibration) camera footage illustrates the severity compared with other observed events (Section 4.9). At high water (11:45am) the monitored coastal conditions were: a water level of 4.28 m ODN, a H_{m0} of 2.62 m, a T_p of 8.3 s, a wind speed of 26.18 mph (11.70 m/s) and a wind direction of 260º.

Summary

It is recommended that the EA forecast matrix needs to include wave heights of 0.5 to 1 m at the structure toe for wind speeds < 30 mph to capture more typical winter overtopping conditions. It is thought the current system under predicts overtopping due to interpolation of smaller wave heights and due to updates of BayonetGPE since the release of EurOtop 2007 not being incorporated. Ideally a prediction tool that includes wind influence and beach level variability is needed for the current structure design.

During our deployments the wave heights impacting the structure toe were lower than the thresholds given in the EurOtop (2018) guidance and the measured overtopping was often lower than the lower limits for pedestrians when $H_{m0,t}$ = 1 m. This suggests the development of hazard thresholds for smaller wave conditions would be beneficial for public safety at this site.

5. Evaluation of the modelling and measurement approach

The Crosby seafront offered an ideal location to use as a case study for comparing current industry-standard tools with unique field measurements of overtopping. The available coastal monitoring provided a complete dataset to capture the coastal conditions that drove the overtopping. The frequent overtopping on windy spring tides also provided ideal conditions to test the prototype WireWall system. The only limitation on planning deployments was the need for low water to occur during daylight hours so that the system could be deployed and recovered safely. The beach surveys took place up to a few days before or after the deployment, for similar safety reasons.

The numerical approach used a beach transect that was directed offshore from the slipway. WireWall was however set back on the sea wall and should be representative of the conditions experienced in the vicinity of the Hall Road car park. It should also be noted that we measured at one location and spatial variability along the sea wall will occur due to alongshore variability in beach level, structure profile/design and shoreline orientation to the Mersey channel and exposure to prevailing conditions.

5.1 Limitations of the 1DH (cross-shore) modelling approach

For the numerical overtopping estimates a full dataset of input parameters were available within a month of the deployment taking place. The main limitations of the input data for BayonetGPE (O19) were: (a) The application of a 1DH profile approach in SWAN, since the wave direction was usually at an angle to the sea wall and bathymetric refraction will have had an influence due to the Mersey Channel. (b) The bathymetry was not updated during the tidal cycle and was often collected a few tides previously. (c) Wave-current interactions were not included: capturing wave refraction is potentially important to accurately transform the waves to the toe of the structure. (d) The 5 m resolution of the beach profile may not be adequate to resolve how short-term localised changes in beach level at the toe of the structure mediated the wave conditions at the point of impact. From the flume experiments we know a small change in water level can cause the water to just exceed the level of an additional step, noticeably changing the wave overtopping volumes.

Without a full scale monitoring campaign to collect boundary conditions for a 2DH regional SWAN model application the modelling could be improved using a SWAN model applied to the intertidal beach profile and forcing this model directly by the AWAC wave and water level data. It would be recommended to have data at 15 minute intervals rather than hourly to capture the tidal asymmetry over the high water overtopping window.

5.2 Evaluation of the physical modelling approach

The Crosby sea wall design was not ideal for the flume experiments. The recurve works well, so in laboratory conditions without an onshore wind blowing spray over the wall, or oblique wave impact creating an alongshore component to the overtopping plume, the dense spray conditions that overtopped were not replicated.

The WireWall technology worked well when converted into "electronic rulers" within flume collection tanks. The system was able to record high accuracy wave-by-wave depth changes within the tanks to provide a time series of data rather than solely the final total volume. While the flume allowed a way to validate the WireWall technology there were unforeseen difficulties in experiment set up. Water splashing in and out of tanks, and in between tanks, affected the accuracy of the tank data. The tanks also filled up faster than expected so pumps were used which added additional uncertainties into the tank results. To test WireWall multiple short runs were performed to avoid the use of pumps in the tanks, but these were not long enough to generate the 1000 waves required in order to contribute to the BayonetGPE database. Additional long (> 1000 waves) runs were thus made (mostly in the absence of WireWall) to incorporate data that represented the stepped structure with recurved sea wall in future releases of the EurOtop guidance. In general WireWall provided a less restrictive measurement approach able to collect wave-by-wave overtopping data and its inland distribution continuously over long periods with no interference from splash behind the structure and without the need for pumps. The accuracy and repeatability of the WireWall data within the flume gives confidence in its capability. The similarity in uncertainty collected by WireWall and the longitudinal tanks also gives confidence in the use of this system to collect data of the same quality as used to develop EurOtop, but with the ability of being more portable to collect a wider range of data and site specific data.

5.3 Limitations of the field measurements

WireWall was deployed in the field at Crosby to measure overtopping when offshore significant wave heights ranged from 0.5 m to 2.5 m, observed by the WaveNet buoy. All conditions were lower than the threshold for typical winter storm conditions 3.44 m (Table 4.2). The performance of the field system can therefore only be evaluated for typical winter (windy spring tide) conditions, which we found could still cause a hazard to pedestrians using the promenade around high water. It is felt the ~ 2 m WireWall field rig is ideal for short-term deployments (of a few days) to assess the appropriateness of generic hazard alert thresholds for a specific site for operational public safety management and to validate hazard forecasting services. If data were to be collected frequently over multiple winters the dataset created would have the potential to assess changes in the site specific overtopping hazard and would have a greater chance of observing storm conditions to validate tools used for new scheme design under more extreme conditions.

In both the flume and the field there was a lot of fine spray passing through the rig. While 1 cm droplets would have registered on the wires there is the potential that those drops would not have connected with multiple wires in the staggered rows. For the majority of events the overtopping plume had a diagonal component to its pathway through the rig. Water could potentially register on some wires within a row and not others. Very fine droplets carried by the wind could also influence the speed calculation. By averaging the data over 5 and 15 minute intervals and using median speeds in calculations allows some of the errors to be averaged out as water droplets will enter and leave the rig at different positions. The comparison of measurements between different wire pairs and rows of wires allow uncertainty margins to be put on the measurements to allow them to be used appropriately (see Section 4.10). The provision of data over a shorter averaging interval (< 5 mins) becomes very noisy. Provision of the mean and maximum discharges within the averaging window indicates the behaviour of the individual waves during these intervals.

Having 18 wires running on 3 electronics units also allowed data substitutions to be made where it is suspected a wire has become erroneous due to temporary water ingress. A complete time series of data are available for each deployment although the data may not always be for the same wire combinations or electronics units. The most valuable data has been identified to be the overtopping calculated between wire pairs 12, 13 and 23 as these provide information on the water passing inland of the handrail on the promenade (pairs 13 or 23) and a measure of the total volume of water in the vertical plume (pair 12) that falls to sea rather than becoming transported inland.

Camera footage was critical to this study to see the behaviour of the individual waves to understand what the data were showing us to develop the processing algorithms. The camera data can also be used to find the times of individual wave events of interest to look at in more detail. While a full view and side view camera were useful the most valuable view for data analysis was a close up on the base of the wires from land to sea through the rig to see which wires were being impacted.

Even with exposure to overtopping debris (Figure AIII.10) the redundancy in the system works well and our estimate of uncertainty in the WireWall measurements themselves is small, with total volumes from multiple units differing by less than 25% at most (Table 4.6b), and some of this difference will be due to real variability in the overtopping impacting different units. However, interpreting which total volume to use (from wire pairs 12 or 13) adds additional uncertainty, i.e. the volume of water measured at the handrail (13) is generally only half that measured at the crest of the structure (12). We consider that the volumes passing wire3 (at the rail) best represents hazard to the public, and also is the most direct comparison to the flume data where the tanks were located slightly inland of the sea wall. However, a cautious approach would suggest using the mean of the two, i.e. the mean of the volumes at the rail (wire3) and at the crest (wire2), which would lead to an associated uncertainty of 50%. Note that is applicable only to the location of the measurement system and does not account for uncertainty due to the real variability in overtopping along the 1 km length of the structure.

The WireWall system worked well to collect a time-series of wave-by-wave overtopping data at the crest of a sea wall and at points distributed inland. The high frequency and

high variability in the data mean that the most useful data are provided by running mean values. Those identified as most useful to assess time varying overtopping conditions would be data at 5 and 15 minute intervals, with the latter aligning with the frequency at which other coastal observations are provided. These average data seem suitable for hazard threshold setting and calibration for warning services and response plans.
The main limitations of the prototype WireWall system that we would like to address in future projects are as follows. Without a telemetry system or smart monitoring staff are required onsite to manually carry out “health checks” and download data. The data processing is very time consuming without automated routines. Due to every tide and wind-wave conditions creating slightly different overtopping the development of such routines requires much more data collection. Identifying the standard approach (thresholds to capture all individual wave contributions) to analyse the different conditions was challenging and limited immediate provision of data.

5.4 Desired developments for potential deployments

Going forward we would like to marinise the prototype WireWall system so it can be deployed for months at a time to capture data over a whole winter season. The aim would be to develop the system so that it can be deployed for at least 3 months (ideally 6 months) with minimal maintenance. This would increase the potential of measuring storm conditions to allow both an assessment of the system's performance in higher energy (more violent) conditions and also collect data that include green water overtopping conditions which are more suitable for comparison with BayonetGPE to assess the tool’s performance at this site.

A fully marinised WireWall would require:

- Robust connectors at the top of the rig and secure electronics housing.
- Potentially replacing the wires with coated rods to make a more robust system that does not require tensioning.
- Addition of on-board processing and telemetry, initially for system health checks and eventually for data transfer.
- Training for local engineers to be able to maintain the system and download data.

In addition, it would be useful to incorporate an addition unit of 6 horizontal wires, mounted one above the other and aligned with the face of the sea wall, in order to measure the vertical component of the overtopping plume. This would allow the capture of the 3D plume structure and provide information on the total overtopping velocity rather than just the dominant horizontal component alone. Ideally, to thoroughly validate the system and the data analysis, the use of a collection tank system would be incorporated in field deployments.

Deployment at multiple field locations to demonstrate alongshore variability in overtopping conditions would be of value for coastal management. A field location where validation tanks could also be deployed would be very valuable for any follow-on study. This would allow validation in the field without the scale issues that can occur in flume studies. In the absence of field validation, additional flume experiments in controlled conditions for other structures to create a range of overtopping conditions (green water and spray) would allow further validation of WireWall under different conditions.
Validation under conditions that provide more violet overtopping plumes and green water wave run up conditions with suitable tanks are of interest going forward. Ideally a way to carry out field validation of both WireWall and BayonetGPE (O19) will be sought. This is

most likely to occur if we can identify sites that would be suitable for us to put collection tanks within the promenade/sea wall of the existing structure or as part of the design for a new structure.

The development of automated processing software would be necessary to more rapidly process data, for both flume and field applications. However, to automate the processing more training data (across a larger range of overtopping conditions) would be needed against which the current processing software could be tested and refined.

To collect a complete set of observations at the point of impact an automated high resolution measurement of beach level would also be of interest. This could be achieved with laser scanners or possibly xBand radar and would allow intertidal surveys pre- and post- high water when overtopping occurs. Higher frequency AWAC data at the LW mark would also be of value to validate the numerical wave transformation and local water depths within SWAN. Alternatively, the AWAC could directly force the offshore boundary of a much shorter (intertidal) SWAN model.

5.4.1 Other applications using the capacitance wire technology

Our capacitance wire technology could also be developed to obtain measurements of the waves and water levels directly in front of the sea wall face. These data could be used as input to tools such as BayonetGPE and/or be used to validate the use of models such SWAN to propagate offshore wave and water level conditions onshore to the toe of the structure.

To make the technology more accessible for local coastal authorities our “dipstick” systems (that we developed to obtain wave-by-wave depth measurements in the flume collection tanks) could be further developed into a portable depth-measurement tool. This would be ideal for rapid temporary deployment to measure the depth of water on the promenade to obtain data on spatial variability of overtopping flood water, or, if combined with a telemetry and on-board processing system, it could provide a more permanent, observation based, real-time warning system. This type of system could provide simpler time-varying depth-only data to validate a hazard alert threshold simply by triggering a yes/no communication to calibrate/validate thresholds settings in operational forecasting systems or to flag up the need for a post-event defence inspection. Developing a low-power, low-maintenance depth measurement system with versatile installation options would allow a range of different measurements, such as wave height and water level at the toe of the structure, and potentially even water levels within the structure.

6. Conclusions

Site-specific observations are vital for setting tolerable hazard safety thresholds. Sea wall construction costs are at least £10K per linear meter in the UK. With reductions in public funding and 3200 km (i.e. about £3Bn) of coastal defences, cost savings are required that do not reduce the flood resistance. Issues when designing coastal defences are:

1) The numerical tools to estimate wave overtopping are based on a very limited number of field measurements.

2) Previous experiments do not provide data on the overtopping speed - a crucial factor in estimating hazards to people, vehicles and infrastructure.

Due to the scarcity of data, overtopping estimates can have an uncertainty of a factor of three in magnitude, and public safety thresholds may be uncertain to three orders of magnitude. Unnecessarily large safety margins (with associated higher monetary and carbon costs) are thus factored into scheme design. To address these issues a low-cost capacitance wire technology previously used to measure waves in the open ocean was radically adapted to deliver a relocatable system capable of making the first field measurements of wave overtopping volumes and speeds on a wave-by-wave basis. System validation was undertaken at HR Wallingford's flume facility prior to undertaking successful field deployments at Crosby during winter 2018/2019. The new field data have quantified wave overtopping for a small number of wind, wave and tidal conditions. The results presented demonstrate that for Crosby where wind influence is important the uncertainty in the overtopping estimates can be up to two orders of magnitude.

Using HRW's flume to validate WireWall we show that the overtopping volumes as measured by WireWall agreed with those from the traditional method of collection tanks to within the uncertainty of the tank data (at least +/- 20%). In addition, the WireWall measurement system provides the following benefits for physical modelling studies:

1) Continuous overtopping measurements unlimited by collection tank capacity.
2) Easy collection of wave-by-wave and cumulative wave overtopping volume distributions behind the sea wall crest.

Through this study it became clear that the flume set up and the design of suitable collection tanks needs considerable care and thought to ensure that real-world wave conditions can be simulated and used for validation of numerical tools. The Crosby sea wall fronting Hall Road car park performs well in the absence of onshore winds and localised 2D interactions (alongshore propagation of the overtopping plume). This makes it a difficult structure to study in the flume since alongshore processes and the effects of wind cannot be replicated.

The prototype WireWall field system measured the horizontal speed of coastal wave overtopping at the high frequencies (400 Hz) required to capture key data on individual wave events and calculate overtopping volumes. At present, the prototype system is suitable for short-term deployments lasting a few days. The system's design targeted shoreline management needs associated with sea defence performance monitoring, new scheme design and flood modelling (whether hazard mapping or forecasting). It was deployed at Crosby during the winter of 2018/2019 to collect data to inform the planning of a new coastal scheme. Data were collected during 5 tides representing windy spring tides, some of which posed a hazard to pedestrians on the promenade for an hour around high water. The overtopping discharge had an asymmetric behaviour creating a greater hazard on the incoming tide, and peaking just before high water. The overtopping discharge (hazard) then rapidly diminished on the ebb tide. The data collected demonstrates the WireWall capability and validates the public safety alert thresholds used locally for early warning. We found the thresholds were suitable, while the EA's flood forecasting service needs updating to include less extreme wind and wave conditions that are more commonly causing nuisance overtopping hazards during spring tides. An update to account for variability in beach level would also be of value over at least decadal timescales and a way to consider the seasonal variability in beach levels should be included. We found that noticeable overtopping of the promenade (potentially hazardous to people) occurred if:

- water levels were > 4 m ODN
- winds were from west to north west and >12 mph (or 5.5 m/s)
- offshore wave heights > 1.2 m (in the absence of wind data)

During fieldwork visual inspection of the overtopping along the car park frontage was carried out. The most vulnerable locations to overtopping were the southern corner, the slipway access area, just north of the slipway where wave reflections occurred and the northern corner of the promenade. The WireWall data may therefore represent a slightly conservative measurement of the different conditions experienced along the car park frontage.

Field data from WireWall have also been used to assess the overtopping estimates obtained from the SWAN (v41.20) – BayonetGPE (O19) numerical method. The numerical results presented (Sections 4.11.2 and 4.11.3) are an order of magnitude lower than those measured to pass the hand railing (wire3) by WireWall. WireWall is thus shown to be able to collect site specific information to calibrate/validate flood forecasting systems (e.g. Pullen et al., 2008) and hazard mapping approaches (e.g., Prime et al., 2015). Once calibrated/validated such numerical tools can be used to provide new overtopping estimates for past events and future projections, expanding the numerical results to supplement observational information. Longer-term monitoring (beyond a single winter period) would have the potential to calibrate site-specific tolerances in safety thresholds for a wider range of storm conditions to better inform the design of the new scheme at Crosby. The methodology provides 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. It also provides 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 also improves understanding of the local conditions that cause overtopping and allow our partners to test their flood forecasting and early warning services. At Crosby the EA alert thresholds of 2 l/s/m is lower than the EurOtop (2018) guidance for $H_{m0,t}$ =1 m, but seems appropriate at this location for the existing structure. Our results suggest that an additional hazard threshold in EurOtop (2018) for pedestrians on seashores with sea walls for 0.5 m < Hm0,t < 1 m would be beneficial for alert services.

The Crosby case study suggests that for macro-tidal locations (i.e. those with a large inter-tidal range) with fetch limited waves and shallow beach gradient, wave overtopping warnings could be simplified to consider water levels and local wind conditions alone, i.e. no need to account for waves. This is due to (a) the water levels restricting the height of the waves that impact the sea defence and (b) the local wind history being a proxy for wave conditions and (c) the wind being critical to the resultant direction of travel of an overtopping plume. Using our field results we will continue to work with the EA to refine the existing local hazard alert system and contribute data to any future service refresh. The data will also be available to the Sefton Council to contribute towards the planning of a new coastal scheme. The key messages from this work are to use the most recent version of BayonetGPE in design work and cost-benefit analysis, while keeping in mind that there could be uncertainty in the BayonetGPE (O19) estimates of up to three orders of magnitude for typical winter spring tide conditions.

For the two events presented in Section 4.11.2 (26th October 2018) and 4.11.3 (25th January 2019) the BayonetGPE (O19) estimates were biased low compared with WireWall. Initial results indicate that for the highest tides observed (22nd March 2019) with lower wave conditions BayonetGPE (O19) might be biased high compared with WireWall. With the data collected we are unable to compare results for more extreme conditions. The comparisons will be shared with Sefton Council and EA.

More widely, the project continues to develop and disseminate a generic observational-numerical approach to reduce uncertainty in overtopping estimates used in sea wall design and early warning systems, to deliver regional Shoreline Management Plan (SMP) objectives. The WireWall system can be made available[1] to our partners if they wish to continue monitoring of future events at Crosby, and to other groups who wish to initiate similar monitoring at other sites. During 2021 we will continue to develop the WireWall system by: 1) ruggedising it to monitor overtopping during targeted time periods centred over high water for months at a time; and 2) adding 2-way telemetry to facilitate smart monitoring and the return of system health check and hazard alert data. Trials are planned to be carried out under the higher energy wave environments of Penzance and Dawlish in south west England. For more information see the NERC-funded Coastal REsistance: Alerts and Monitoring Technologies (CreamT) project (NE/V002538/1, http://gotw.nerc.ac.uk/list_full.asp?pcode=NE%2FV002538%2F1).

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[1] CASSIS (Coastal and Shelf Seas Instrumentation Services): https://projects.noc.ac.uk/cassis/

Figure A.1: Some of the NOC WireWall team. Left to right: Margaret Yelland, Geoff Hargreaves, Jenny Brown, Robin Pascal, Chris Balfour and Barry Martin

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Appendix I: Project outputs and information

Alongside this project report additional information can be found online as follows:

1. Data are archived with the Channel Coastal Observatory where the project webpage is hosted. https://www.channelcoast.org/ccoresources/wirewall/

2. The project twitter feed @WireWall_NOC was active from August 2018 to December 2019. It will remain and be used as and when related measurement activities continue. We encourage the use of #WireWall when tweeting about project related activities. https://twitter.com/wirewall_noc

3. A research clip, WireWall - The Movie, lasting up to 4 minutes, which describes the project aims and shows footage through the various experiments is available on YouTube. This is available for others to use for outreach activities to raise hazard awareness. https://youtu.be/a5Y33SWdNU4

4. Footage from the fieldwork at Crosby is available on YouTube to show the different types of wave overtopping for the existing coastal structure during winter 2018/2019: https://youtube.com/playlist?list=PL2nHwISkP2SkSY3sEEWOqzK3tcSmVdxR7

5. A 'hands on Science' Lego demo (Appendix VI) is available to showcase the technology behind WireWall and to engage the public in shoreline management activities and promote awareness of coastal flood hazard. The outreach tool is available from NOC Liverpool or Southampton, contact marinedataproducts@noc.ac.uk

6. A narrated coastal walk funded by AGU celebrate 100 grants is also available for our study site. The tower high waves in the Blitz Beach poem are inspired by WireWall, https://noc.ac.uk/education/educational-resources/changing-shores-crosby. A playlist of the poetical narration is also available on YouTube https://www.youtube.com/playlist?list=PLoYJVOchmO7HtiWLMwU8q6WLQcZ91prSf.

Appendix II: Available coastal monitoring data used by the WireWall project

The WireWall project carried out both numerical and physical modelling to estimate wave overtopping volumes and horizontal speed at the sea wall located in Crosby, north of Liverpool. The monitoring data described below was used in the numerical assessment of overtopping volumes to design the new sensor, plan deployments and compare the numerical and observed events measured during winter 2018/2019.

The project has used freely available data from the North West Regional Coastal Monitoring Programme and other national networks as follows:

- To provide input to numerical approaches and physical experiments.
- To provide validation of the wave modelling.

The required data (Tables AII.1 – AII.5) were to obtain from the following sources:
https://www.channelcoast.org
https://www.cefas.co.uk/cefas-data-hub/wavenet/
https://www.bodc.ac.uk/data/hosted_data_systems/sea_level/uk_tide_gauge_network/
http://www.ntslf.org/
http://www.ceda.ac.uk/
https://www.facebook.com/groups/526198870745222/

Table AII.1: Cell Eleven Regional Monitoring Strategy (CERMS) contributions:

Data	Quantity
Laser Scan of the Hall Road sea wall structure.	xyz data for a transect 34 m south of the Hall Road profile, collected 11th December 2013.
Beach Survey data for Hall road and Serpentine Road profiles.	All 32 surveys collected between 1996 – 2017 to assess variability in beach levels.
Kenneth Pye Associates Ltd Data Cell 11 Regional Monitoring Strategy Results of sediment particle size analysis report. Sediment size distributions for the upper, middle and lower Crosby beach.	2010 report providing D_{50} and D_{90} sediment sizes.
AWAC data at Crosby.	10 minute water level data and hourly wave data for 2017 used (three 3-month deployments). Data from October 2018 – March 2019 also used for 7 tides to complement the WireWall dataset.
Halcrow North West & North Wales Coastal Group Joint Probability study for the NW Coastal Group in support of the SMP2. Model data validated against coastal monitoring data since 2002.	2011 report, providing return period levels for waves and water levels at the Liverpool Bay wave rider.
Wave condition alerts from the Gwynt Y Môr real time wave observations provided by Channel Coastal Observatory (CCO).	Real-time alerts set up from 2017 used to inform WireWall deployment conditions.

Environment Agency (EA) TRITON flood forecasting system overtopping volumes and alert trigger levels.	Forecasting matrix for Crosby car park.
Rapidar data collected by Marlan Maritime Technologies.	2017 data was used to identify wave patterns in the Crosby coastal zone.

Table AII.2: WaveNet contribution.

Data	Quantity
Wave spectra and bulk parameters (Hs, Tp, direction) obtained from the CEFAS wave buoy archive for Liverpool Bay.	30 minute data 2002-2017
Wave forecast data for Liverpool Bay.	Real time total water level forecasts run by the Met Office. Obtained for the 2018/2019 deployments.

Table AII.3: National Tidal and Sea Level Facility (NTSLF) contribution.

Data	Quantity
Total water levels from the UK National Tide Gauge Network at Gladstone Dock, part of the Permanent Service for Mean Sea Level (PSMSL). Data archived with the British Oceanographic Data Centre (BODC).	15 minute data 2002-2017
Surge forecast data and tidal predictions for Gladstone dock from the National Tidal and Sea Level Facility (NTSLF).	Real time total water level forecasts. Surge forecasts are run by the Met Office and tidal predictions produced by the National Oceanographic Centre (NOC). Obtained for the 2018/2019 deployments.

Table AII.4: Met Office (MIDAS Land and Marine Surface Station Data) contributions.

Data	Quantity
Wind data from Crosby weather station obtained from the Centre for Environmental Data Analysis (CEDA).	Hourly data 2002-2017

Table AII.5: Other contributions.

Data	Quantity
Photo graphic evidence of past overtopping events at Crosby.	Photos of events from 2013 to present.
Photo graphic evidence of past overtopping events in the North West.	Photos of events during 2013/2014
Guidance on industry standard modelling approaches to sea wall design.	Information on best practices provided.
Photo graphic evidence of past overtopping events in the North West.	From 2013 to present
Knowledge of the physical processes at Crosby from xBand radar.	January-March 2017, Rapidar deployment
Project data archiving alongside the Regional Coastal Monitoring Programmes in England and Wales.	Website hosting the WireWall outputs.

Appendix III: Visual images from each field deployment

During the field deployments in winter 2018/2019 (Table 3.6) a range of different low energy overtopping conditions were observed. An image from each event is shown (Figure AII.1 – AII.9) to illustrate the different types of overtopping. The conditions vary from a gentle splash causing spray to only impact the more seaward wires (e.g., Figure AII.5) or thin single jets to pass through the rig missing wires, to spray that passes through the rig connecting with multiple wires (e.g., Figure AII.2), to a dense plume of spray passing through the rig (e.g., Figure AII.4). The height of the overtopping spray varied under all conditions. Sometimes it was below the horizontal railings (e.g., Figure AII.5), while the biggest events were just above the (2.4 m) height of the rig (e.g., Figure AII.4). Many waves also caused plumes either at the height of the top horizontal railing (e.g., Figure AII.2) or came through closer to the bottom railing.

Figure AIII.1: Photos from the Field visit 25th October 2018.

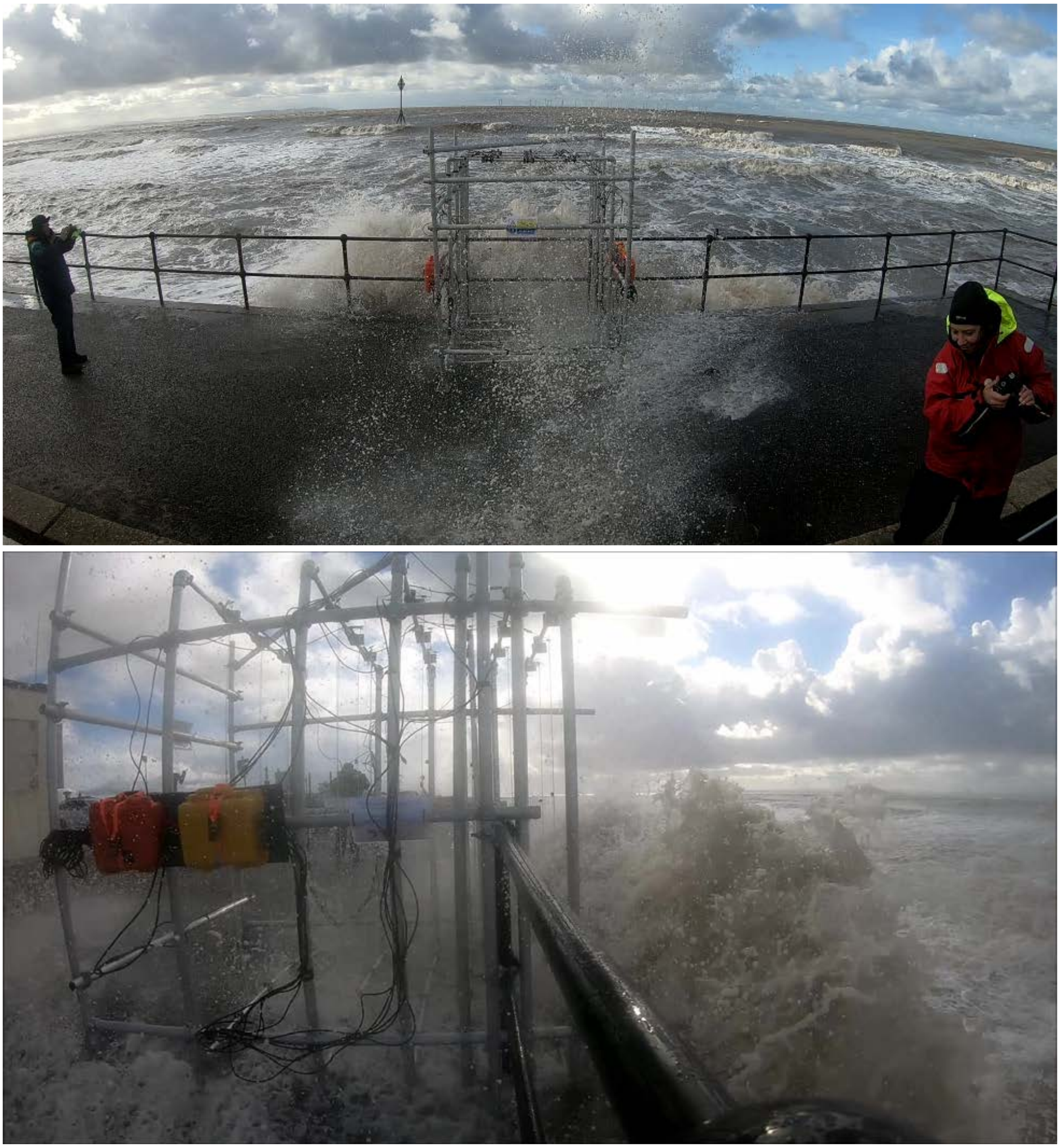

Figure AIII.2: Photos from the Field visit 26th October 2018. Also see Figure 3.10.

Figure AIII.3: Photos from the Field visit 8th November 2018.

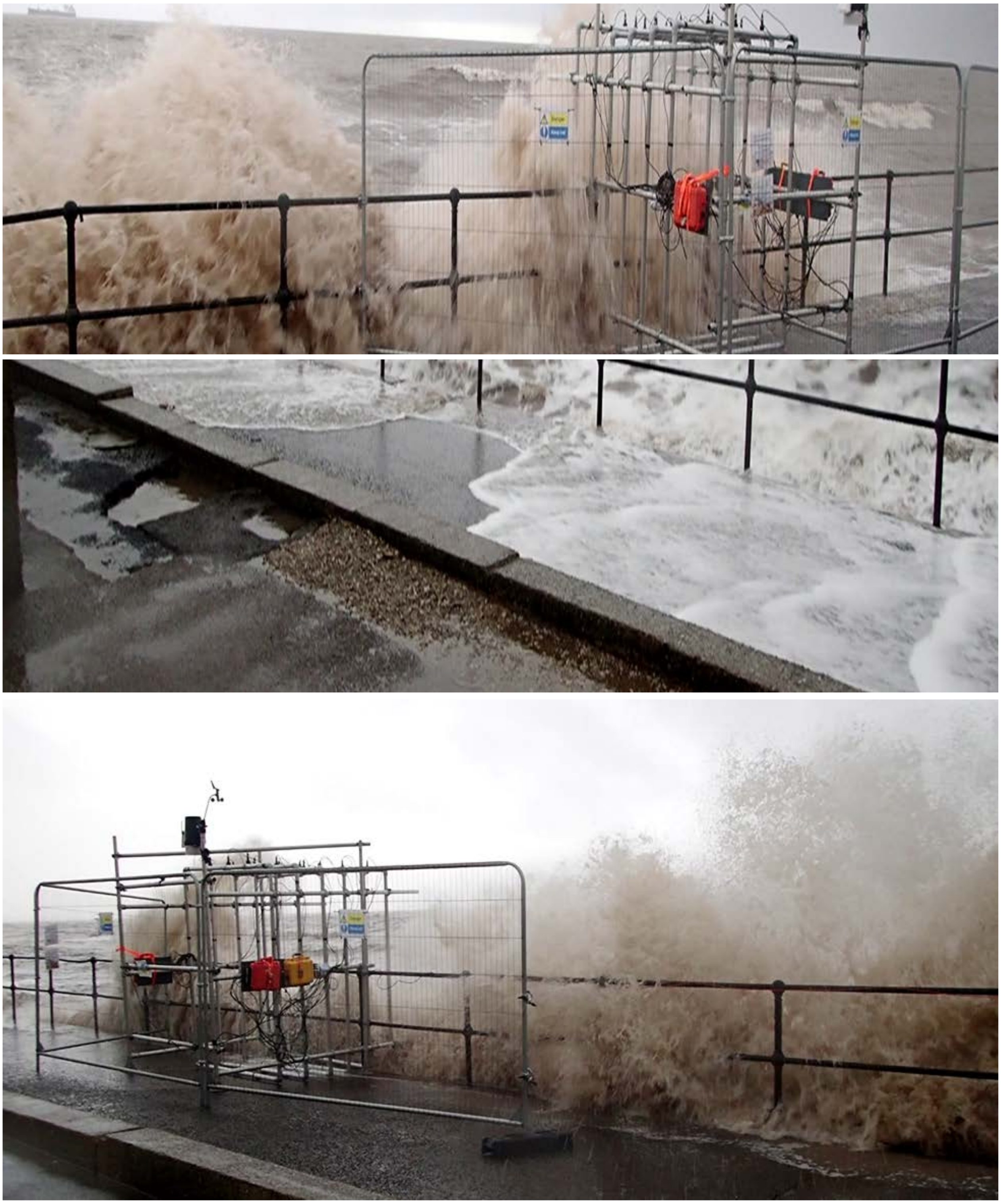

Figure AIII.4: Photos from the Field visit 22nd January 2019.

Figure AIII.5: Photos from the Field visit 23rd January 2019.

Figure AIII.6: Photos from the Field visit 25th January 2019.

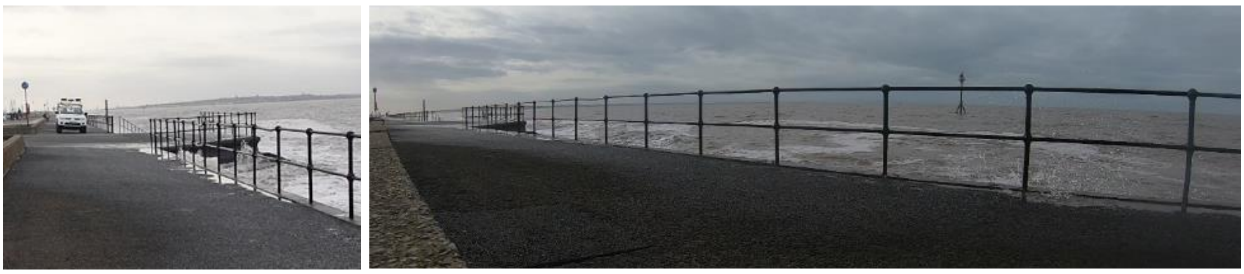

Figure AIII.7: Photos from the Field visit 19th February 2019.

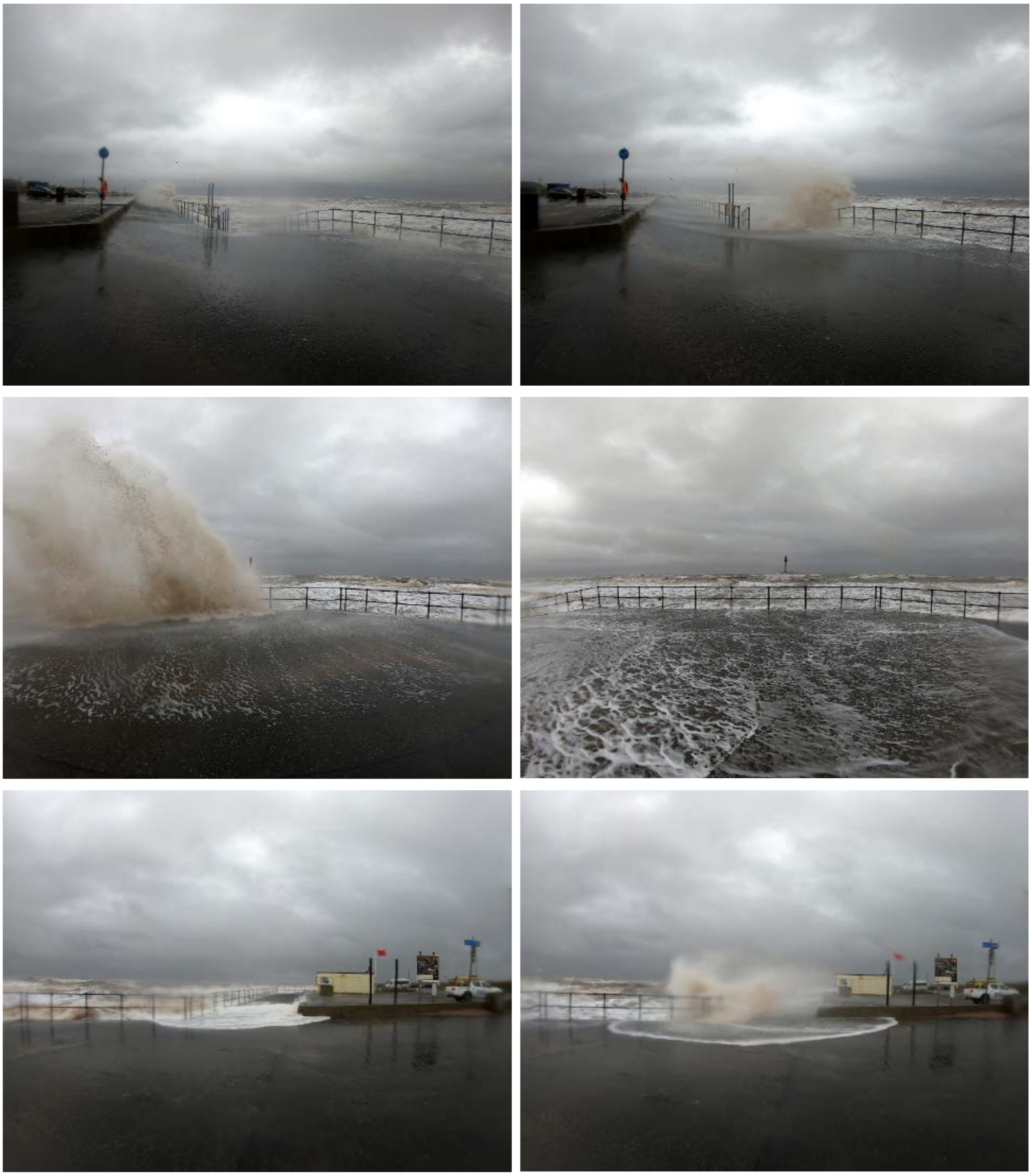

Figure AIII.8: Photos from the Field visit 7th March 2019.

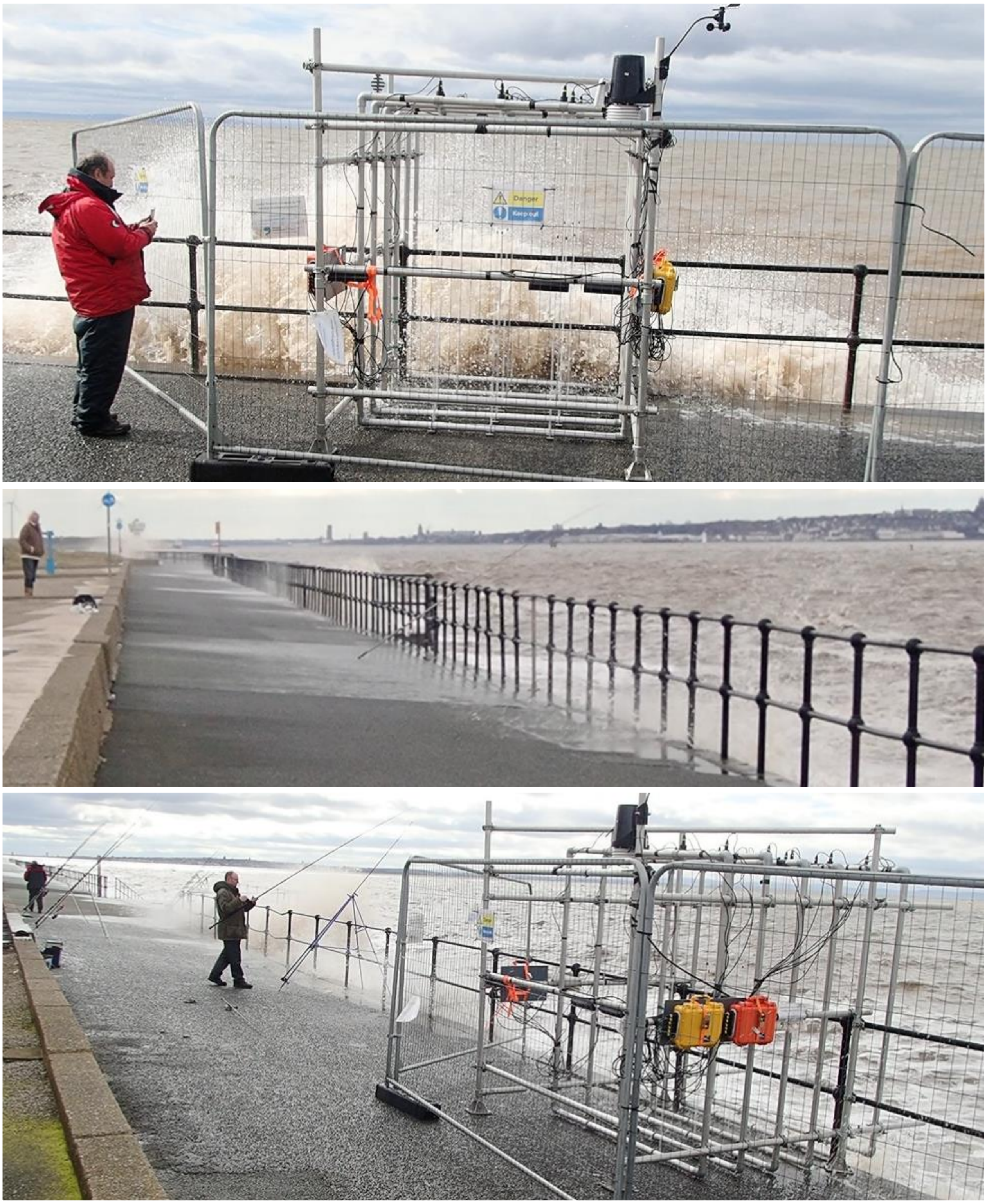

Figure AIII.9: Photos from the Field visit 22nd March 2019.

Figure AIII.10: Example of debris overtopping the wall during WireWall deployments. Debris found on arrival at site morning of the 8th November 2018 (left). Brick debris overtopping south of the rig during on the 22nd January 2019 (right).

Appendix IV: Data archive / CSV files

The data presented in this report are available from the British Oceanographic Data Centre (BODC). Five datasets are available from the project as csv files. These contain processed data from: 1) The numerical wave overtopping estimates for past events used to design the system and plan deployments; 2) The numerical wave overtopping estimates for the joint wave and water level conditions with a 1 in 1 year return period probability to a 1 in 200 year return period probability in Liverpool Bay; 3) The dock side tests; 4) The physical laboratory experiments; and, 5) The field trials during windy spring tides. For Crosby these data can be used to validate/calibrate numerical tools used for coastal scheme design and flood hazard forecasting. Beach profile data collected alongside the overtopping measurements have been archived with the Northwest Regional Coastal Monitoring Programme, https://www.channelcoast.org/northwest/.

The data (Table AIV.1) can be found using the following keywords through the European Directory of Marine Environmental Data (EDMED, https://www.bodc.ac.uk/resources/inventories/edmed/): Wave overtopping volume, Horizontal wave overtopping velocity, Coastal Flooding, Crosby beach, WireWall.

Each dataset has its own DOI for reference (Table AIV.1) and the direct links to the data are provided alongside this report on the Channel Coastal Observatory Website.

Table AIV.1: The post processed datasets archived with BODC that accompany the information within this report. (see EDMED entry: report 7068/https://www.bodc.ac.uk/resources/inventories/edmed/report/7068/)

Data source: Past photographic evidence (Sections 4.1 and 4.3)
Abstract: Numerical wave overtopping volume estimates from the BayonetGPE wave overtopping tool associated with the EurOtop (2018) manual and modelled wave and water level conditions at the toe of the structure transformed from national coastal monitoring networks using the SWAN model. Mean, upper and lower 1st and 2nd standard deviation wave overtopping volumes are estimated by BayonetGPE (generated by HR Wallingford, October 2019) for the Hall Road Car Park, Crosby Beach survey profile (reference: 11A02250). The data are associated with photographs of events when there is a record showing some level of overtopping occurring at Crosby beach. The photographic data were collected for the period January 2013 to December 2017 from Facebook (page: I'm at Crosby Beach and the weather is ...) and project partners. The numerical estimates of overtopping were generated using: beach surveys (available from Channel Coastal Observatory) from 24th February 2017, 4th April 2017, 4th October 2017 and 1st September 1996; a laser scan of the sea wall collected 11th December 2013 (available from Sefton Council); Seazone bathymetry from 05/12/2014, originally collected by the UK Hydrographic Office at 1 arc second; wave conditions (available from WaveNet, Centre for Environment, Fisheries and Aquaculture Science (CEFAS)); water levels tide gauge data (available from the National Tidal Sea Level Facility (NTSLF) who deliver data through the British Oceanographic Data Centre (BODC)). The coastal conditions were transformed to the toe of the existing structure using the 3rd generation spectral wave model SWAN. The bottom friction was set to use bed ripples and a sediment size of 0.23 mm (the Median grain size, d50, for the upper beach at Crosby, KPAL 2010). BayonetGPE was then used to estimate the resulting overtopping discharges. *Citation: Brown J.; Pullen T.; Silva E.; Prime T.; Yelland M.J. (2020). WireWall project numerical wave overtopping volume estimates at Crosby Hall Road Carpark (north of Liverpool UK) using a beach profile in 1996 and three in 2017, estimates are for coastal conditions when there is photographic evidence of overtopping occurring between 2013 - 2017. British Oceanographic Data Centre, National Oceanography Centre, NERC, UK. doi:10/d898.* *doi:10.5285/acd939f0-38e5-57b0-e053-6c86abc0aa19* *https://www.bodc.ac.uk/data/published_data_library/catalogue/10.5285/acd939f0-38e5-57b0-e053-6c86abc0aa19/*
Data source: Joint Probability analysis overtopping estimates (Section 4.5)
Abstract: Numerical wave overtopping volume estimates from the BayonetGPE wave overtopping tool associated with the EurOtop (2018) manual and modelled wave and water level conditions at the toe of the structure transformed from nearshore national monitoring networks using the SWAN model. Mean, upper and lower 1st and 2nd standard deviation wave overtopping volumes are estimated by

BayonetGPE (generated by HR Wallingford, October 2019) for the Hall Road Car Park, Crosby Beach survey profile (reference: 11A02250). The data are associated with joint wave and water level conditions at the Liverpool Bay Wave Buoy Location that form the 1 in 1 year to 1 in 200 year return period curves in a joint probability analysis for the North West Coastal Group delivered by Halcrow in 2011. These return period curves represent the conditions to design new coastal schemes and analyse event severity. The numerical estimates of overtopping were generated using: beach surveys (available from Channel Coastal Observatory) from 24th February 2017, 4th April 2017, 4th October 2017 and 1st September 1996; a laser scan of the sea wall collected 11th December 2013 (available from Sefton Council); Seazone bathymetry from 05/12/2014, originally collected by the UK Hydrographic Office at 1 arc second. The coastal conditions were transformed to the toe of the existing structure using the 3rd generation spectral wave model SWAN. The bottom friction was set to use bed ripples and a sediment size of 0.23 mm (the Median grain size, d50, for the upper beach at Crosby, KPAL 2010). BayonetGPE was then used to estimate the resulting overtopping discharges.

Citation: Brown J.; Pullen T.; Silva E.; Prime T.; Yelland M.J.(2020). WireWall project numerical wave overtopping volume estimates, for profiles in 1996 and 2017. Estimates are calculated at Crosby Hall Road Carpark (north of Liverpool UK) for joint wave and water level conditions that represent the return period curves in Liverpool Bay developed in 2011. British Oceanographic Data Centre, National Oceanography Centre, NERC, UK. doi:10/d9s9.

doi: 10.5285/ae80bb3c-8aad-4bc7-e053-6c86abc0c7c9
https://www.bodc.ac.uk/data/published_data_library/catalogue/10.5285/ae80bb3c-8aad-4bc7-e053-6c86abc0c7c9/

Data source: Dock side tests (Section 3.2.2)

Abstract: The prototype WireWall measurement system was designed using bucket and balloon tests at the National Oceanography Centre's dockside, Southampton, during April to August 2018. Initially the electronics were configured using a frame of 6 vertical wires through which buckets of water were thrown. Once satisfied the system was recording at an appropriate rate for the wire spacing a single electronics unit was set up with 6 wires positioned horizontally to measure the fall velocity of water under gravity when a balloon full of water was burst at a known height above the top wire. The wires were spaced 10 cm apart. For each balloon test the velocity was calculated between different wire pairs for comparison against Newton's theory.

Citation: Yelland M.J.; Pascal R.W.; Pinnell R.; Cardwell C.L.; Jones D.S.; Brown J.(2020). WireWall project data, August 2018, generated during the dockside experiments performed at the National Oceanography Centre Southampton British Oceanographic Data Centre, National Oceanography Centre, NERC, UK. doi:10/d9qh

doi: 10.5285/acd939f0-38e8-57b0-e053-6c86abc0aa19
https://www.bodc.ac.uk/data/published_data_library/catalogue/10.5285/acd939f0-38e8-57b0-e053-6c86abc0aa19/

Data source: Flume experiments (Section 4.8)

Abstract: The prototype WireWall measurement system was initially trialled in the controlled environment of HR Wallingford's flume facility during three 5-day periods: 9th July 2018, 20th August 2018, 17th September 2018. An additional 5-day experiment was also run to collect data to compare with BayonetGPE: 3rd September 2018. In all experiments a 1:7.5 scale model of the beach and sea wall structure at Crosby (north of Liverpool, UK) was built within the flume using a laser scan collected 11th December 2013 by the Sefton Council. The flume was 45 m long, 2 m deep and 1.2 m wide. It was equipped with a piston-type wave paddle controlled by HR Wallingford's Merlin software. Wave and water level data to simulate conditions were obtained from the Liverpool Bay WaveNet buoy and Liverpool Gladstone Dock NTSLF tide gauge. During these experiments total cumulative wave-by-wave overtopping data were measured using collection tanks and WireWall. The collection tank data were recorded using small capacitance wire probes within the tanks. For long runs (over 1000 waves), numerical estimates using the BayonetGPE tool (EurOtop 2018) were also used to assess its capability at this site. The data archived represented the total volume of water that overtopped the structure during each experiment, which comprised of different wave conditions and still water levels.

Citation: Yelland M.J.; Pullen T.; Silva E.; Pascal R.W.; Jones D.S.; Pinnell R.; Cardwell C.L.; Brown J.(2020). WireWall project data generated during the flume experiments performed at HR Wallingford during July to September 2018. British Oceanographic Data Centre, National Oceanography Centre, NERC, UK. doi:10/d9n9

doi:10.5285/acd939f0-38e6-57b0-e053-6c86abc0aa19
https://www.bodc.ac.uk/data/published_data_library/catalogue/10.5285/acd939f0-38e6-57b0-e053-6c86abc0aa19/

Data source: Field deployments (Sections 4.10 and 4.11)

Abstract: The prototype WireWall measurement system was deployed at Hall Road Crosby (north of Liverpool, UK) and measured overtopping eight times between October 2018 and March 2019. Deployments took place during tides with a range greater than the mean spring tide when there was an onshore wind. The system measured the inland distribution of wave-by-wave overtopping discharge and horizontal velocity for a couple of hours either side of high water. Wave and water level data to numerically estimate conditions when monitoring data became available were obtained from the Liverpool Bay WaveNet buoy and Liverpool Gladstone Dock NTSLF tide gauge. A beach profile collected during low water prior to deployment was used in the numerical estimates. During these experiments a time series of data were collected during the overtopping window. Numerical estimates using the SWAN model and the BayonetGPE tool (EurOtop 2018) were compared to the measurements. The observed data archived for the 26th October 2018 and 25th January 2019 represent the horizontal overtopping discharge and horizontal overtopping velocity averaged over different periods selected by the project's wider interest group (5 min and 15 min). The numerical (SWAN-BayonetGPE) data are archived at 15 minute intervals for eight events.

Citation: Brown J.; Yelland M.J.; Pascal R.W.; Jones D.S.; Balfour C.A.; Hargreaves G.; Martin B.; Cardwell C.L.; Pinnell R.; Bell P.S.; Pullen T.; Silva E.; Prime T.(2020). Key WireWall project data generated during the field deployment at Hall Road Crosby (North of Liverpool UK), between October 2018 and March 2019 British Oceanographic Data Centre, National Oceanography Centre, NERC, UK. doi:10/d9pz

doi: 10.5285/acd939f0-38e7-57b0-e053-6c86abc0aa19
https://www.bodc.ac.uk/data/published_data_library/catalogue/10.5285/acd939f0-38e7-57b0-e053-6c86abc0aa19/

Appendix V: WireWall clips available on the CCO YouTube Channel

Wave Overtopping Clips collected in Cell Eleven of the regional monitoring programme
https://youtube.com/playlist?list=PL2nHwISkP2SkSY3sEEWOqzK3tcSmVdxR7

A selection of short clips form GoPro and Smart Phone camera footage, taken during the WireWall deployments (Winter 2018/2019), have been released on the Channel Coastal Observatory's YouTube channel (https://www.youtube.com/channel/UCn38zaaqXQQ2Q7ybwCI2dVw).

These clips demonstrate the different types of overtopping conditions experienced during a selection of windy high tides, which exceed mean high water spring tide 9.39 m CD, observed during the WireWall project. In addition, they show examples of what the wave overtopping conditions are like for the existing structure at Crosby during typical windy winter days. The videos provide a visual understanding of the local hazards from wave overtopping. These can be used as an evidence base to recalibrate local hazard forecast thresholds or to select offshore conditions known to cause overtopping for the existing structure to allow assessment of the performance of proposed scheme designs.

The footage shows wave overtopping around high water on the 7th March 2019, 25th January 2019 and 26th October 2018 at Crosby Beach, Hall Road car park (Hall Rd W, Waterloo, Liverpool L23 8SY). The conditions on these days were as follows:

- 7th March 2019: high water Liverpool Gladstone Dock was predicted to be 9.14 m CD at 11.45 GMT. High tide the wind speeds were around 11.7 m/s (22.75 knots) from the west. Offshore waves were around 5.55 m.
- 25th January 2019: high water Liverpool Gladstone Dock was predicted to be 9.65 m CD at 14:09 GMT. High tide the wind speeds were around 10.5 m/s (20.4 knots) from the west. Offshore waves were around 1.7 m.
- 26th October 2018: high water Liverpool Gladstone Dock was predicted to be 9.44 m CD at 12:49 GMT. High tide the wind speeds were around 8.0 m/s (15.6 knots) from the north west. Offshore waves were around 2.3 m.

Car Wash (7th March 2019)
https://youtu.be/wPFzGnpbcVU

Why you shouldn't park too close to the sea on a windy day! Even when the weather's not considered to be stormy, the few hours either side of high water can be hazardous to those at the beach when there's a brisk onshore wind and high tides. The clip illustrates the possible hazard to parked cars as the wind blows wave spray over the sea defence at Crosby (north of Liverpool). It was only water coming over this time, but there is always the chance debris and material from the beach can be thrown into public areas by rough seas. During windy days take care when accessing the beach or leaving your car for the day, the conditions can change as the tide comes in.

Example of wave spray being blow across the promenade and into the carpark at Crosby Beach.

Wind Blown Spray (7th March 2019)

https://youtu.be/XNbBeRrpDes

Strong onshore winds at high tide causing hazardous wave spray and flows of water over public access areas at Crosby (north of Liverpool). The large tidal range at this site means waves are only hazardous for a few hours either side of high water when the water levels are high enough to allow the waves to impact the sea defence. If visiting the beach on a blustery day don't forget your route out could get cut off by the incoming tide and you may need to use an alternative beach access point to return.

Example of wave spray being blow across the promenade and flows of water jumping over the rear splash wall at Crosby Beach.

Wind Blown Waves (7th March 2019)
https://youtu.be/S6SudSr3mYs

Don't stand too close to the water's edge to get your perfect photo! Wave overtopping is irregular and a much larger wave might come over carrying debris from the beach with it. The clip shows typical winter conditions at Crosby (north of Liverpool) that lasted a few hours either side of high water.

Example of wave overtopping at the slipway on Crosby Beach, hazardous dense spray and surface water.

Blown Over (25th January 2019)
https://youtu.be/O1MK8WV4S-k

Watch out for wave spray! High tides can allow waves to break directly onto sea defences. As the waves break and run up the stepped revetment at Crosby (north of Liverpool) a strong onshore wind can blow fast moving spray over the promenade. The spray can easily be over head high and can come from different directions, especially when there's a 'confused' sea – this occurs when waves travel inland from different directions.

Examples of high fast wave spray being blown straight and diagonally over the promenade at Crosby.

Dumped On The Wall (25th January 2019)
https://youtu.be/uOFN_6C1OCc

Dense spray plumes shoot into the air as waves impact sea defences. The recurve (curvature of the top of the sea wall) at Crosby (north of Liverpool) directs the majority of the water back to sea, but an onshore wind and the existing momentum can cause some of the water to come over the defence. Dense spray can come over from the plume and as this collapses under gravity a flow can spread across public access routes. Even if you're stood back from the spray watch out for the sudden rush of water across the promenade.

Example of a wave plume overtopping and flowing over the promenade at Crosby.

High Water Surprise (25th January 2019)
https://youtu.be/HQHzRkh27VE

It doesn't take a storm to generate wave plumes higher than 2 m at Crosby beach (north of Liverpool). If there's a strong onshore wind during the rising tide at this site, dense wave plumes can be seen for a few hours at high water. They often increase in size until an hour before high water. Smaller plumes can be seen from about 2 hours before high water and last for up to an hour after high water. Make sure you don't get caught out by the high water wave spray on windy days when the wind is from the west or north west.

Example of an over 2 m high wave plume overtopping at Crosby.

Little Splash Big Spray (25th January 2019)
https://youtu.be/24TwWUFuOes

During high spring tides at Crosby (north of Liverpool) an onshore wind can cause waves to spray over the sea defence as the tide rises, allowing the waves to break onto the revetment. As waves overtop a sea wall the conditions can be different along its length, with some waves causing a little splash in one location and others having a larger impact only a few paces further along. The wind influence can cause the spray to move diagonally across a promenade so you could still get wet even if you're not stood at the point of wave impact.

Example of a different wave spray conditions as the wind blows wave spray through over the promenade at Crosby.

Returned To Sea (25th January 2019)
https://youtu.be/IOZcvEWAJLk

The return curve on the sea wall at Crosby (north of Liverpool) directs the majority of uprush back to sea as waves impact the sea defence. Just a few bits of spray come over due to the onshore wind.

Example of the return curve at Crosby doing exactly what it's supposed to do.

Side Impact (25th January 2019)
https://youtu.be/dd6QHjHuHYc

A sequence of waves impacting the sea wall at Crosby (north Liverpool). The waves break on the stepped revetment, run up and shoot vertically into the air as a dense plume that also travels south along the sea wall. The return curve directs the majority of water back to sea while an onshore wind sends some of the plume over the crest. The second wave in the sequence creates a flow on the promenade that reaches the splash wall, which redirects the flow back to sea away from the carpark.

Example side view of waves impacting the sea wall at Crosby.

Super Soaker (25th January 2019)
https://youtu.be/2OsCiVFwDVU

It doesn't take a storm to create hazardous waves! Strong westerly winds on a high spring tide can cause large overtopping wave plumes at Crosby (north of Liverpool). This wave plume is over 2 m high and brought a large volume of water over the sea defence. You wouldn't have wanted to be walking past at the same moment this super soaker arrived.

Example of a high and fast wave plume overtopping at Crosby.

They Keep Coming (25th January 2019)
https://youtu.be/9CaCmG0vkrM

A sequence of waves overtopping at Crosby (north of Liverpool). The example shows how breaking waves interact with the return flow on the revetment before causing run-up and wave overtopping. The 3 waves cause a flow of water along the promenade from north to south during the event.

Example of an overtopping wave sequence at Crosby focusing on the waves as they run up and overtop the sea defence.

Thrown Over The Wall (25th January 2019)
https://youtu.be/UzIDNgg9NCI

An example high wave plume overtopping the sea wall at Crosby (north of Liverpool). The momentum of the plume and onshore wind bring the dense spray over the defence crest as the plume falls under gravity.

Example of a large wind wave overtopping at Crosby.

Up And Over (25th January 2019)
https://youtu.be/VLe_ZJBw1ig

An example low wave plume overtopping the sea wall at Crosby (north of Liverpool). The momentum of the plume and onshore wind bring a low dense spray over the defence crest as the plume falls under gravity.

Example of a large wind wave overtopping at Crosby.

Warning Shot (25th January 2019)
https://youtu.be/a5hJ9XrqYoE

On a rising tide with a moderate onshore wind the water levels will reach an elevation up against the sea defence at Crosby (north of Liverpool) that allows waves to start overtopping (splashing, shooting, sloshing over the sea wall). If you notice waves starting to overtop and it's not yet high tide you should consider the possibility that the amount of water coming over and pooling on access areas is likely to get worse until the tide falls back to its current level. Time to check your watch! If there's still time until high water occurs the conditions could get worse. Consider your safe access route. Take a look at "High Water Surprise" to see the change.

Example of a just over railing high wave plume overtopping through railings at Crosby.

Water From All Directions (25th January 2019)
https://youtu.be/zOJJE221QFU

As waves repeatedly overtop the sea wall at Crosby (north of Liverpool) there are times when the return flow on the promenade collides with an incoming wave. The return flow is reflected by the splash wall and interacts with the overtopping plume at the sea wall crest.

Example of the reflected wave return flow interacting with the incoming wave plume.

Wave Overtopping Sequence (25th January 2019)
https://youtu.be/kr18rok0zsY

They came in sets of 3! As waves were observed to overtop at Crosby (north Liverpool) it was noticed the plumes often came over in groups of waves and then stopped for a while before starting again. If visiting the coast and large waves are overtopping don't be tempted to get closer if the overtopping drops off. A set of larger waves might be about to return at any moment.

Example of an overtopping sequence at Crosby.

Wave Spray (26th October 2018)
https://youtu.be/YgSNwO5ESbE

If it's a bright and breezy winter day you might find the waves causing a noticeable spray over the sea wall at Crosby (north of Liverpool). Watch out you might get wet and don't forget the waves might still be building or the sea rising so the conditions could get worse.

Example of wind-blown spray from the wave run up on the revetment at Crosby.

Appendix VI: Wider Engagement

To deliver a system capable of collecting lab and field observations that was suitable for addressing the needs of the wider coastal community, a Wider Interest Group (WIG) of stakeholders was formed. This group were 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) coastal infrastructure. By the end of the project the group had an international membership exceeding 100 people. To engage this community of academics, practitioners and consultants two workshops were held at the NOC in Liverpool (Figure AVI.1) with the option to join by VC. WIG Workshops in June 2018 and 2019 focused on ensuring the system was transferable to other sea defence infrastructure and flood management assets. The WIG members represent those groups monitoring and modelling overtopping in the UK for coastal management purposes, and help to maximize the future impact of WireWall.

The first workshop was held 6 months into the project (26th June 2018) alongside the annual Regional Coastal Monitoring Programme meeting. The workshop was held prior to flume experiments to ensure the approach was fully transferable to other sea defence infrastructure and met a range of coastal management and planning requirements. The workshop concentrated on collecting information to specify the data requirements for coastal management and research purposes and also collect information about different infrastructure types and deployment needs to specify the requirements for the rig design. In addition to 4 project partners and 8 members of the research team 43 people attended either in person or by VC.

The second workshop was held towards the end of the project (4th June 2019), soon after fieldwork when the preliminary flume and field data (for the 9th July 2018 flume experiment and for the 26th October 2018 field deployment) were processed. The aim of this workshop was to evaluate the system's capability and data delivery to inform future developments and data archive needs. In addition to the workshops, occasional emails were sent to update the group on progress and the delivery of outputs. In addition, 5 project partners and 7 members of the research team 38 people attended either in person or by VC.

Figure AVI.1: Wider interest group meetings held at the NOC in Liverpool 26th June 2018 and 4th June 2019.

Alongside meetings with the interest groups a "Hands on science" demonstration display was also made to showcase the new technology at public engagement and business events (Burgess et al., 2020). The demo was used at numerous events (Table AVI.1) to raise awareness of coastal flood hazards, coastal hazard research, emerging measurement technology and shoreline management. While the demo used the actual WireWall electronics, the Crosby sea wall was built from Lego with Lego figures that could be knocked over by hand-held wave generators (AKA water pistols). The use of two water pistols to introduce competition between friends, families and colleagues created an eye catching approach that attracted good audiences at events (Figure AVI.1).

Table AVI.1: Events where the WireWall Lego demo was used after being made during April/May 2018.

Date	**Internal NOC events**	**External events**	**Location**
9th June 2018	NOC Open Day		Southampton
18th June 2018		UKRI visit to NOC	Southampton
26th June 2018	WireWall project meeting		Liverpool
2 – 4th July 2018		Sea-Level Futures Conference	Liverpool
6th July 2018		Birkenhead High School	Birkenhead
20 – 22nd July 2018		BlueDot Festival	Jodrell Bank
31st July 2018		London International Youth Science Event	Southampton
15th Aug 2018		Ainsdale discovery Centre as part of LISCO	Ainsdale
29th August 2018		Crosby Beach as part of LISCO	Crosby
12 – 13th September 2018		Marine & Civil Coastal Engineering Expo	Birmingham
7th November 2018		UK Marine Climate Change Impact Partnership	London
13 – 15th November 2018		Marine Autonomous Technology Workshop	Southampton
25 – 27th February 2019		Oceanology International Americas	San Diego
14th March 2019		Mersey Maritime International Awards	Liverpool
9-11th April 2019		Ocean Business	Southampton
2nd May 2019		Environmental Science Careers Fair	University of Liverpool
11th May 2019	NOC Open Day		Liverpool
18th May 2019		Marine Awareness Day	Crosby
4th June 2019	WireWall project meeting		Liverpool
8th June 2019	NOC Open Day		Southampton
11 – 13th June 2019		Seawork and Marine & Coastal Civil Engineering Expo	Southampton
18 – 20th June 2019		Flood and Coast Conference	Telford
12th July 2019	STEM Visit	Liverpool Life Sciences School	Liverpool
16th August	Chief Executive Board Chair Visit		Liverpool
21st August 2019		ICE Civil Engineering Family Fun Sessions	Liverpool
17 – 19th September 2019		Environment Evidence 2019 – Marine Evidence	Swansea
11 – 12th September 2019		Flood Expo	Birmingham
10th September 2019	NOC apprentice networking event		Liverpool

10th September 2019	NERC fellows lab tour		Liverpool
30th Septmeber – 2nd October 2019		Coastal Structures 2019	Hannover

A project Twitter feed @WireWall_NOC (and #WireWall) was also launched on 7th August 2018 (Figure AVI.2) to communicate to audiences beyond the WIG. After 1 year it had 300 followers, who included the north west coastal community and national coastal practitioners, and the number of followers is still growing. The feed was used to communicate about project advances and also generally raise awareness of coastal hazards, local activities and coastal management. The theme followed that of the Lego demo, following the Lego figures as they accompanied the scientists and engineers on numerous trips: visits to HRW flume, fieldwork in Crosby, and various meetings and conferences related to coastal processes. The Lego figures had great public appeal and are also used by other coastal groups, allowing us to form connections with a wide range of people.

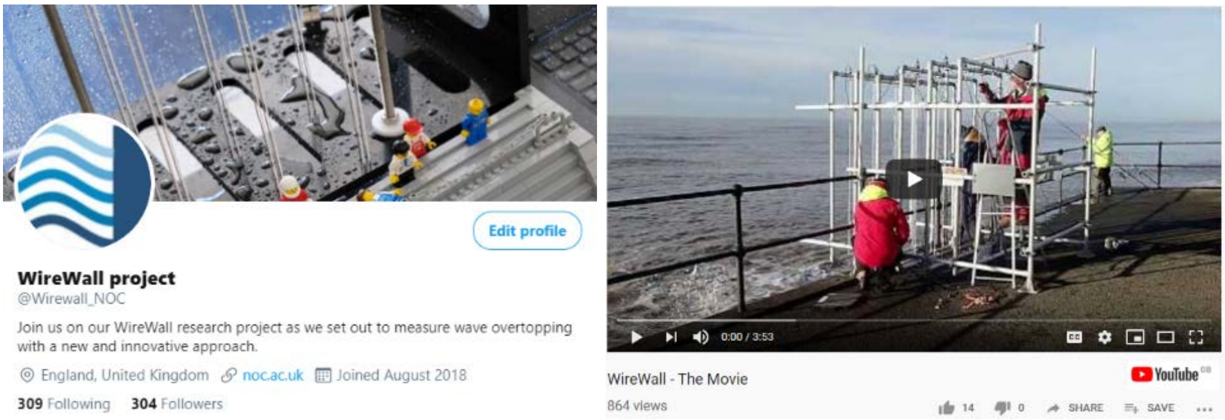

Figure AVI.2: The WireWall social media channels Twitter profile (left) and YouTube movie (right). Snapshots from 4th September 2019.

Throughout the project a video diary was maintained and edited into an approximately 4 min movie, released on YouTube on the 21st February 2019 towards the end of the fieldwork. This has proven to be a great resource to communicate about the projects aims, flume tests and fieldwork during outreach and business events. The YouTube description provides signage to our website, twitter feed, video play list archive with CCO and our later funded narrated coastal walk, each of which link back to "WireWall - The Movie!" and between each other. It was found that each public communication through twitter or news articles for any of our outreach activities led to noticeable increases in views. At the end of summer 2019 we had over 800 views, and were one of the most watch videos on the NOCnews channel in the last 10 years. By summer 2020 we had ~ 400 followers on twitter, over 1100 views of our movie and had built new research collaborations to continue research proposals.

Alongside our own public communications regular news articles were released in NOCnews and put on the NW Coastal Forum's online news feed. We also provided material for Facebook to be publicised by Green Sefton and Friends of Crosby Beach, who also frequently tweeted or retweeted about our activities at the beach.