Conference Paper, Published Version

Pullen, Tim; Silva, Eunice; Brown, Jennifer; Yelland, Margaret; Pascal, Robin; Pinnell, Richard; Cardwell, Cristopher; Jones, David

WireWall – Laboratory and Field Measurements of Wave Overtopping

Coastal Structures 2019 - Nils Goseberg, Torsten Schlurmann (eds) - © 2019 Bundesanstalt für Wasserbau
ISBN 978-3-939230-64-9 (Online) - DOI: 10.18451/978-3-939230-64-9_117

WireWall – Laboratory and Field Measurements of Wave Overtopping

T. Pullen & E. Silva
HR Wallingford, Wallingford, UK

J. Brown, M. Yelland, R. Pascal, R. Pinnell, C. Cardwell & D. Jones
National Oceanography Centre, UK

Abstract: 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 £10,000 per linear meter. With reductions in public funding and 3200 km of coastal defences, cost savings are required that do not cause a reduction in flood resistance. Increasingly there is a requirement to design new coastal flood defences with site specific tolerable hazard thresholds, with regard to wave overtopping during storms of varying severity. The traditional and preferred method for establishing these thresholds has always been physical modelling, but it is recognized that these can cost many 10s thousands of Euros. This is not always feasible, and coastal asset managers have long been looking for affordable methods that can be used to assess overtopping in the field. Recent advances in technology mean existing wave height sensors can now measure at the high frequencies (a few 100 Hz) required to obtain overtopping data, making this the ideal time to initiate a step-change in coastal hazard monitoring capabilities. By converting the existing wave measurement technology into an overtopping monitoring system "WireWall", we can measure the excursions of overtopping volumes and velocities in the lee of a structure. These then can be readily integrated to obtain wave-by-wave volumes and overtopping discharges (l/s/m). 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. Deployments of WireWall at this site will provide site-specific data and calibrated overtopping that will feed into the design of a new sea wall. Before deployment in the field, an extensive set of tests were carried out in a 2D wave flume. Starting with known wave conditions from a buoy near the Crosby sea wall, and values from a joint probability wave and water level study, a representation of the sea wall has been tested. Extensive testing was performed to calibrate the WireWall rig. Using traditional methods of assessing wave overtopping in the flume, the WireWall measurements could be directly calibrated against the known volumes collected in the overtopping tanks. At the time of writing, analysis of the laboratory and the flume wave overtopping data is ongoing. The paper describes how WireWall works, describes the laboratory measurements, the field deployments and presents and compares the analysis from the two systems. A successful deployment of the calibrated WireWall rig at Crosby was during the winter of 2018/2019, where waves can be seen overtopping the sea wall is shown in Fig. 1.

Keywords: Laboratory measurements, Field measurements, Wave overtopping

1 Introduction

The WireWall project (Brown et al., 2018) involves oceanographic measuring equipment adapted for use on land to measure wave overtopping discharges. Measurements in the laboratory using the same equipment scaled down and traditional laboratory methods to measure wave overtopping discharges. Each of the three sets of measurements focused on Crosby sea wall in Liverpool Bay.

Crosby sea wall

Our case study site Crosby is impacted by fetch limited waves from westerly and north westerly directions that can include significant wave heights of up to 5.5 m. During large storm surge events the surge can reach up to 2 m with skew surge values over 0.8 m (Brown et al., 2010 a and b). The large tidal range (8.27 m mean spring tidal range, http://www.ntslf.org) means hazard from overtopping is limited to a few hours either side of high water when waves are able to impact the sea defence (Fig. 1).

Fig. 1. The Crosby sea wall frontage, 5 December 2013. Photo provided by the Sefton Council.

This site also provided a challenging location as rubble debris on the beach was likely to come over the sea wall in extreme conditions. This allowed the testing of the WireWall system's built in redundancy to ensure appropriate data was still collected if or when the system sustained damage.

In Liverpool Bay long-term monitoring data of tides and water levels are available from the Liverpool Bay Wave Buoy and (Liverpool) Gladstone Dock tide gauge. This provides offshore boundary conditions for numerical estimates. In addition to this monitoring the local authority (Sefton Council) collect bi-annual beach profiles, survey the defence and have recently (February 2017) deployed an Acoustic Wave And Current (AWAC) and "Rapidar" radar system (Bird et al., 2017) to collect more detailed information on the waves, water level and currents close to the shore. This allowed us to use the SWAN (Simulating WAves Nearshore, Booij et al., 1999) model to transform offshore wave conditions to the toe of the structure and setup BayonetGPE (Pullen et al., 2018) to estimate the overtopping hazard for recorded conditions.

Using the UK's flood forecasting system (wave predictions at the wave buoy site and surge predictions at the tide gauge location combined with a tidal prediction) an early warning formulation has been developed for emergency response planning based on previous XBeach (Roelvink et al., 2009) simulations for the Sefton coast (Souza et al., 2013). When the winds are in the westerly quadrant the following criteria are assessed:

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

$\eta + \frac{1}{2} Hs > 7.2$, *potential hazard to prom users* $\eta + \frac{1}{2} Hs > 7.6$, *carpark closure due to flooding*

where η = total water level (m OD) and Hs = the off shore significant wave height (m).

The thresholds are based on the prom level (7.2 m OD) and the splash wall (7.6 m OD) at the back of the prom fronting the carpark (Fig. 2). When the waves break on the prom, wave run-up into the carpark was expected, while wave impact on the sea wall still poses a hazard to pedestrians. This hazard is dependent on water levels either causing the wave overtopping to be thrown vertically upward and taken over the defence crest by wind, or the waves to overtop as a green water jet over the crest. Westerly winds exceeding 15 ms-1 (~ 30 mph) are considered strong enough to pose an overtopping hazard when offshore significant wave heights exceed 4 m and coincide with total water levels greater than 4.57 m OD (often a spring tide with surge). Under these conditions wind-blown spray following wave breaking on the sea wall often occurs.

Fig. 2. The Crosby sea wall frontage.

2 Overall approach

The WireWall approach measured coastal wave overtopping at the high frequencies (few 100 Hz) required to capture key data on individual wave events. 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 2018/19 to collect data to inform the planning of a new coastal scheme. 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. If successful, this will allow our partners to continue monitoring future events at Crosby, and other groups to initiate similar monitoring at other sites.

Three key activities are set to achieve our aim:

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

A2. The mobile, battery-powered WireWall system was configured to record wave-by-wave overtopping volumes and velocities at Crosby using a 3-D mesh of (cheap and easily replaceable) capacitance wires and accompanying electronics. It was designed to withstand high velocity (40 m/s) jets and incorporated redundancy to minimize the impact of data loss due to damage. It was tested in the labs and at the dockside of the National Oceanography Centre (NOC) in Southampton. The system was calibrated using tank data in the flume at HR Wallingford (HRW).

Following flume tests the system was transferred to the NOC in Liverpool for deployment at Crosby. The system used a modular approach to allow flexibility in the configuration. Each standalone module consisted of a frame carrying multiple capacitance wires all powered from, driven by and logged to, a single waterproof electronics unit to ensure high frequency data synchronization.

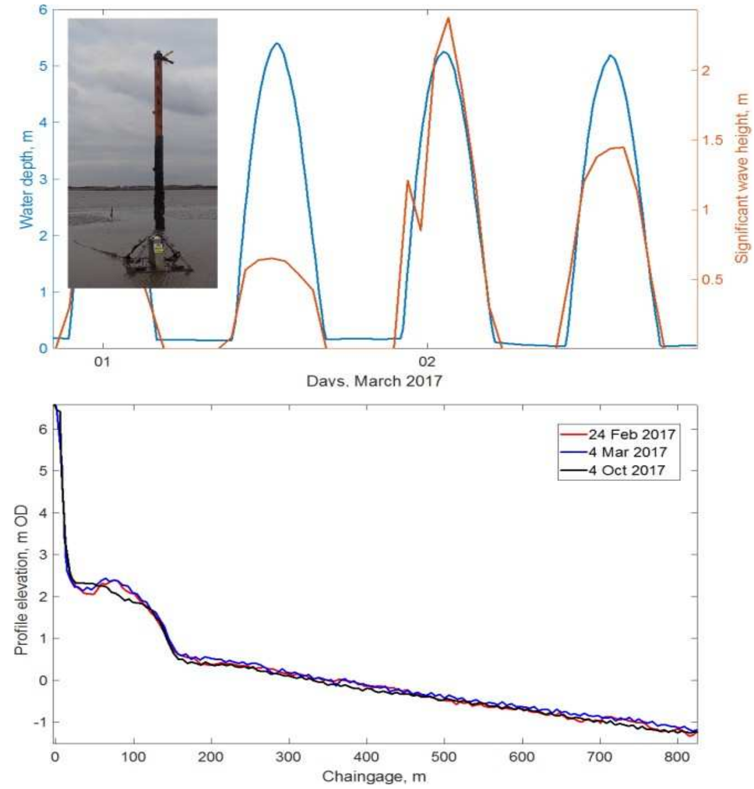

Fig. 3. An example of the AWAC (top) and beach profile (bottom) data collected as part of the Northwest Coastal Monitoring Strategy.

The frames were open faced and aligned with the oncoming wave direction to capture the velocity of the overtopping jet. Up to 6 frames were mounted within robust rigs to form a 3-D mesh to capture spatial variability in overtopping and to provide redundancy. The field rigs were sized to fit within the railing spacing at Crosby and designed to be rigidly secured to the existing infrastructure.

The system was deployed in the field for 24 hour periods at a vulnerable location (determined by Sefton Council) on the sea wall during conditions that were forecast to cause overtopping. The chosen position was in front of the carpark at the northern end of the slipway, which aligns with the Hall Road beach profile line. Here the sea wall is positioned at the mean high water spring mark and beach levels are lower, leading to overtopping hazards on high tides. The deployments targeted both typical (winter spring tide) and extreme (storm) wave and water level conditions that caused overtopping during the winter 2018/2019. All spring tides exceeding mean high water spring (4.46 m OD) were watched as potential deployment windows, as typical winter wave and wind conditions are likely to cause some overtopping, even if low impact, for a short period at high water. Extra deployments on the slipway (Fig. 2) near the vulnerable northern end of the sea wall were considered to allow testing in lower impact conditions, but were not necessary. Pre- and post- event beach profiles were collected using a Leica GNSS Rover (antenna), coupled with a Leica CS15 Viva Controller (handset) and data from the WaveNet and UK tide gauge network during the deployment was obtained. This provided concurrent input to the numerical tools set up in A1 to validate the numerical overtopping estimates against the observed Crosby overtopping events in A3.

A3. Field data from the system were used to quantify the local overtopping hazard at Crosby and compare with EurOtop and validate SWAN (A1) for the observed events, thus delivering a method to use measurements from WireWall to calibrate flood forecasting systems (e.g. Pullen et al., 2008) and hazard mapping systems (e.g., Prime et al., 2015). Once calibrated/validated these tools will be used to provide new overtopping estimates for historic events, expanding the numerical results to supplement the observational data from the project. This dataset was used to calibrate site-specific tolerances in safety thresholds for a wide range of storm conditions to better inform the design of the new scheme at Crosby. The methodology 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 improve understanding of the local conditions that cause overtopping and allow our partners to test their flood forecasting and early warning services.

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

Fig. 4. WireWall field measurements (Spring tide 26 October 2018).

3 Laboratory tests

The overtopping tests measured mean and individual overtopping discharges, for the existing sea wall located at Crosby in the north west of England. A combination of known wave conditions from a buoy near the Crosby sea wall and values from a joint probability wave and water level study were tested on a representation of the sea wall in a 2D flume.

The physical model tests were carried out at a scale of 1:7.5, and a bathymetry representative of the Crosby beach and nearshore profile were built in the flume. A multi-chamber overtopping tank collected the discharges, recording the spatial distribution in the lee of the structure. Wave heights, H_{m0toe}, varied from 0.80m to 0.94m and peak wave periods, T_p, from 5.72s to 7.65s with different sea water levels.

3.1 Test facilities

The tests were carried out in one of HR Wallingford's wave flumes, which is 45m long, 2m deep and 1.2m wide. It is equipped with a piston-type wave paddle which is 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.

3.2 Wave calibrations

All sea-states were defined by their spectral wave height, H_{m0}, peak period, T_p, still water level, SWL, peak enhancement factor, γ_0, and storm duration. Test conditions were calibrated in the flume before construction of the test section, to minimize corruption of incident waves by reflections. Calibration was an iterative process. Incident and reflected wave spectra were determined using a four point reflection wave gauge array and the calibrated wave was based on the incident spectra.

The data recorded by the array was analyzed to separate the incident and reflected wave spectra, and determine the incident significant wave height, $H_{m0,i}$.

3.3 Test methodology

A series of six "NOC dipsticks" were used to measure the depth of water during tests in the first six chambers in the multi chamber overtopping tank. The measurements at the two rear chambers of the tank were manually recorded at the end of each test. Mean overtopping discharges were calculated by measuring the depth of water in the chambers before and after each test. Fig. 5 to Fig. 8 show the front, side and back view of the Crosby structure used during model tests, the flume WireWall frame and multi chamber overtopping tank.

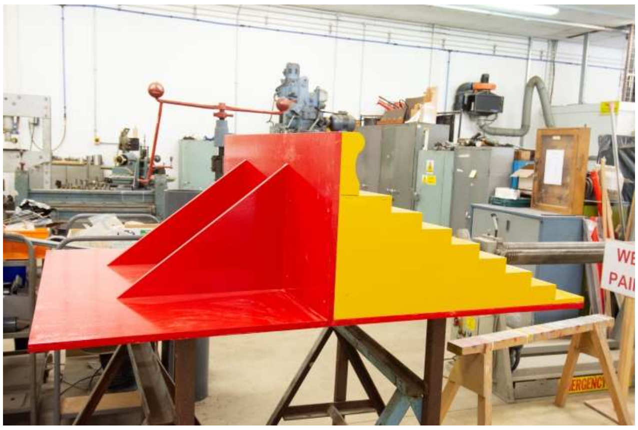

Fig. 5. Crosby sea wall after construction.

Fig. 6. Crosby sea wall during testing using overtopping tank with eight chambers.

Fig. 7. WireWall set up using overtopping tank with eight chambers.

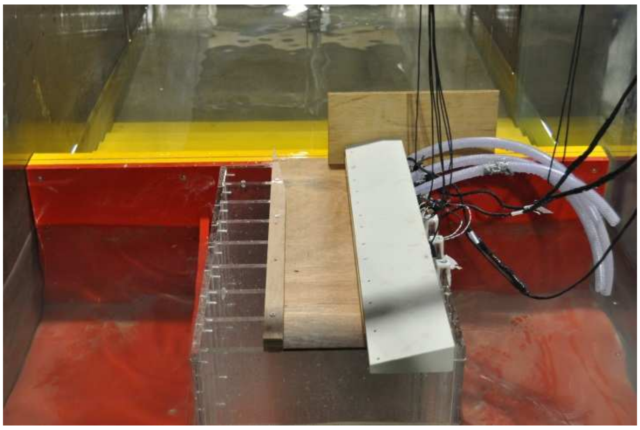

Fig. 8. Set up of structure created for overtopping tank to reduce the volume of overtopping.

4 Laboratory overtopping results

Here are presented the results of mean overtopping discharges recorded for two Test Series. Test Series HRW, where the multi chamber overtopping tank as shown in Fig. 8 collected the discharge volumes behind the model Crosby seawall (see Fig. 6). Test Series NOC (see Fig. 7) where the WireWall system was installed in the flume, collecting the overtopping volumes at the lee of the Crosby model seawall. The recorded mean overtopping discharges for Test Series HRW are presented in Tab. 1 and for Test Series NOC in Tab. 2. Note that WireWall was installed during full runs of only three of the wave conditions.

The data recorded for both Test Series is plotted for HRW and NOC respectively in Fig. 9 and Fig. 10. A comparison plot, with both Test Series data and BayonetGPE (Pullen et. al. 2018) predictions is shown in Fig. 11. The data is represented in terms of relative freeboard (R_c/H_{m0}) against relative overtopping discharge ($q/(gH_{m0}^3)^{0.5}$).

Tab. 1 Mean overtopping results from the HRW series

Wave condition	H_{m0} (m)	T_p(s)	q (l/s/m)
WC01	0.87	6.27	14.67
WC06	0.91	5.72	27.19
WC07	0.94	6.60	37.48
WC14	0.83	6.42	9.12
WC15	0.80	7.65	8.37
WC13	0.87	6.27	1.45
WC12	0.87	6.27	0.44

Tab. 2 Mean overtopping results from the NOC series

Wave condition	H_{m0} (m)	T_p(s)	q (l/s/m)
WC01	0.87	6.27	11.07
WC07	0.94	6.60	29.20
WC15	0.80	7.65	11.08

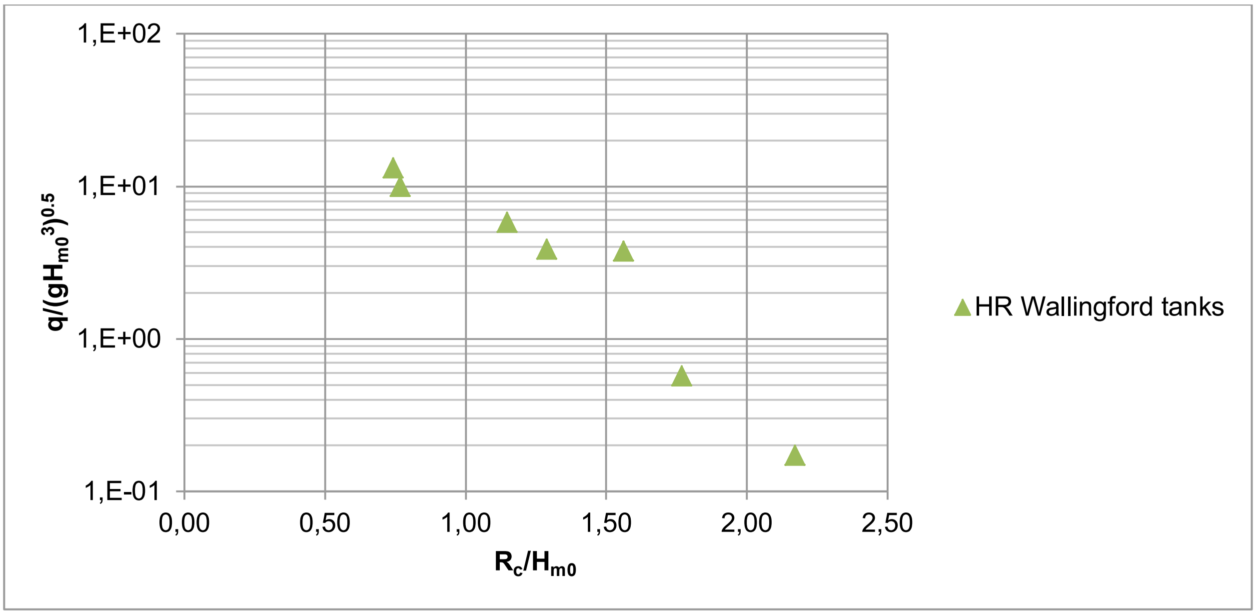

Fig. 9. HRW Series overtopping discharges.

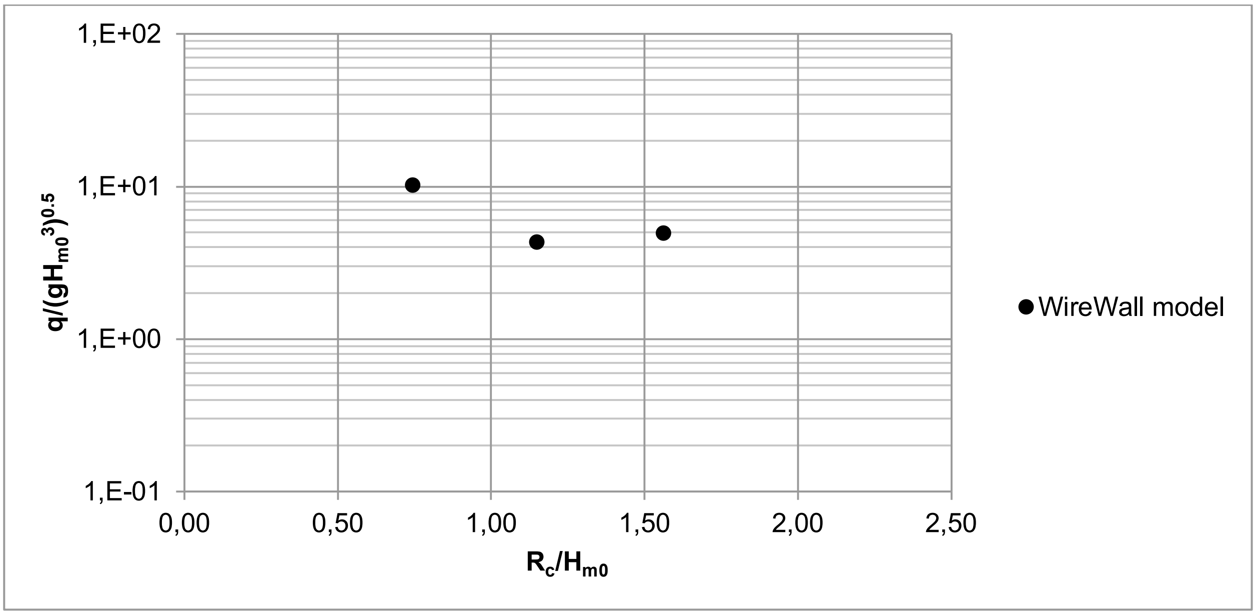

Fig. 10. NOC Series overtopping discharges.

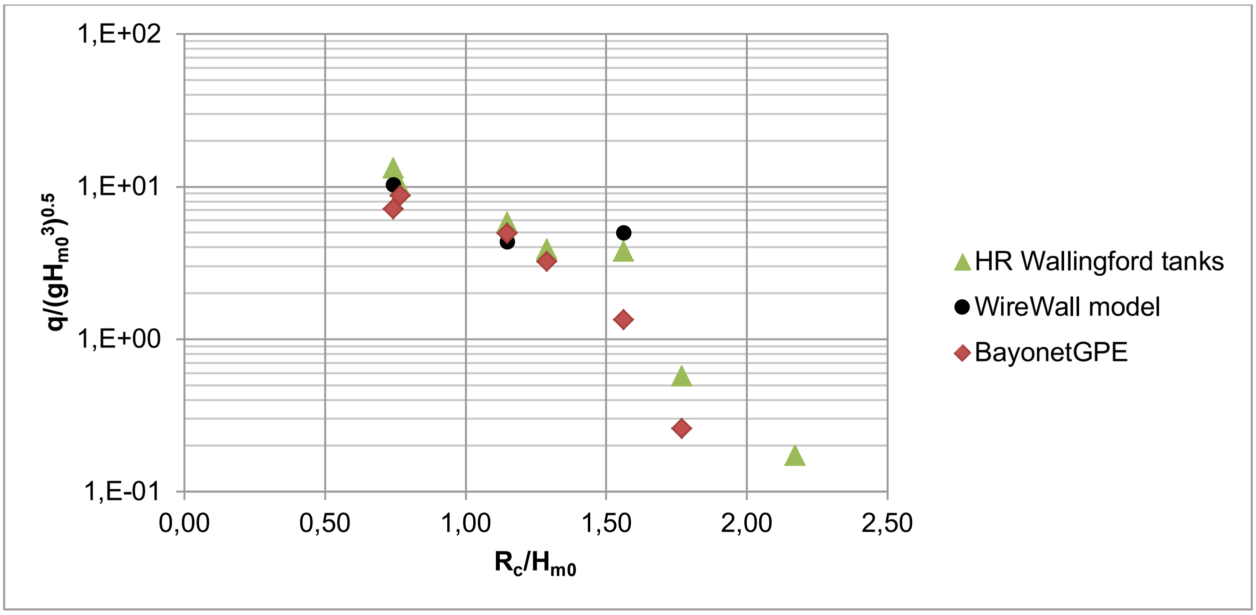

Fig. 11. HRW and NOC series comparison of overtopping discharges with BayonetGPE predictions.

5 Field overtopping results

WireWall was deployed at the seawall at Crosby on the 26 of October of 2018, during the spring tide and overtopping was measured during this event. Initial comparison between the WireWall measurements and the BayonetGPE predictions showed significant discrepancy. Further investigation showed that this was due to the way that the structure was schematised for input into BayonetGPE. Once the schematisation had been generalised, the comparison showed very good agreement (Fig. 12), with the upper 1st standard deviation of the BayonetGPE predictions agreeing with the WireWall measurements. The data is represented in terms of elapsed time since 09:30GTM (s) against mean overtopping discharge, q ($m^3/s/m$).

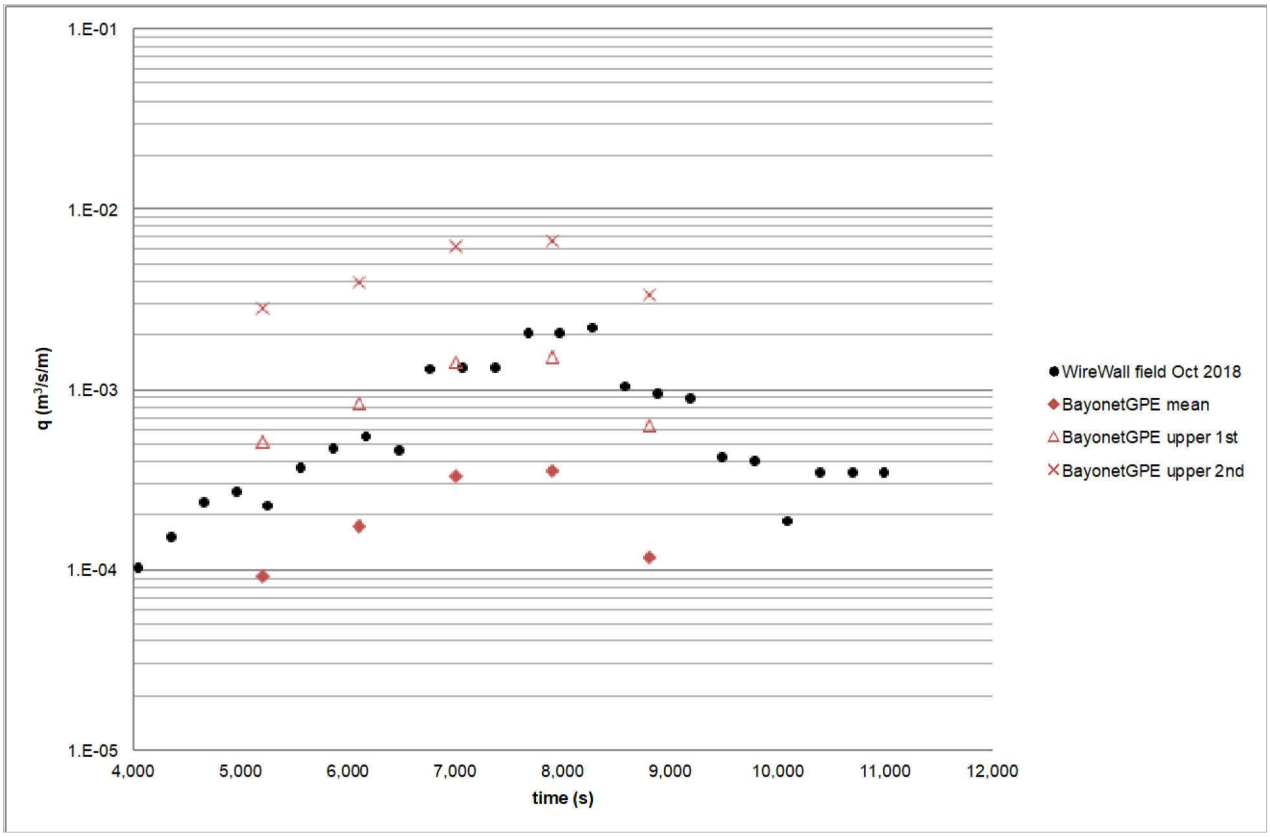

Fig. 12. Comparison of overtopping discharges from WireWall field data with BayonetGPE predictions.

6 Discussion

A series of tests were run on a model seawall of Crosby using known nearshore waves and a subset transferred to the toe following a standard Joint Probability Analysis. For each of these overtopping was measured by conventional means in calibrated overtopping tanks, and the mean overtopping discharges have been shown in Fig. 9. The overtopping was also measured for three of the physical model tests using WireWall, shown Fig. 10. The comparison of the data in Fig. 11 shows extremely good agreement between the assessment of the overtopping for the WireWall system when compared to standard methods.

To enable comparison with the field and laboratory results, BayonetGPE has been used to predict the discharges for both sets. The BayonetGPE predictions shown in Fig. 11 clearly indicate that they are in agreement with the measured values. In Fig. 12 the results of the field assessment of overtopping by WireWall are shown along with the BayonetGPE predictions. The two are in good agreement. Given that there are no equivalent laboratory measurements (i.e. from tanks) for the field deployments, the use of BayonetGPE and the WireWall system together is ideal for giving confidence in both the numerical and the observed field results.

Acknowledgements

The 2D physical model tests have been developed at HR Wallingford funded by NERC via the WireWall project. WireWall is a NERC-funded project (grant NE/R014019/1) that has demonstrated research excellence by delivering a new system (WireWall) through innovative engineering. The success of the project has been achieved through a real collaborative team effort across the National Oceanography Centre sites (in Southampton and Liverpool, NOC) and HR Wallingford (HRW). We acknowledge the national monitoring programs and organizations responsible for collecting and disseminating the publically available data used in this project: WaveNet (via the Centre for Environment, Fisheries and Aquaculture Science), UK tide gauge network (via the National Tidal Sea Level Facility and British Oceanographic Data Centre) and the Northwest Coastal Monitoring Programme (via the Channel Coastal Observatory and the Sefton Council).

References

Bird, C., Bell, P., Plater, A. (2017). Application of marine radar to monitoring seasonal and event-based changes in intertidal morphology. *Geomorphology*, 285, pp. 1-15.

Booij, N., Ris, R.C., Holthuijsen, L.H. (1999). A third-generation wave model for coastal regions, Part I, Model description and Validation. *Journal of Geophysical Re- search*, 104(C4), pp. 7649-7666.

Broeders, J., Pascal, R.W., Cresens, C., Waugh, E.M., Cardwell, C.L., Yelland, M.J. (2016). Smart electronics for high accuracy wave height measurements in the open ocean. *Oceans 2016 MTS/IEEE Monterey*, p.5.

Brown, J.M., Souza, A.J., Wolf, J. (2010a). An 11-year validation of wave-surge modelling in the Irish Sea, using a nested POLCOMS-WAM modelling system. *Ocean Modelling*, 33(1-2), pp. 118-128.

Brown, J.M., Souza, A.J., Wolf, J. (2010b). An investigation of recent decadal-scale storm events in the Eastern Irish Sea. *Journal of Geophysical Research*, 115(C05018), p.12.

Brown, J., Yelland, M., Pascal, R., Pullen, T., Bell, P., Cardwell, C., Jones, D., Milliken, N., Prime, T., Shannon, G., Ludgate, J., Martin, A.; Farrington, G., Gold, I., Bird, C., Mason, T. (2018) WireWall: a new approach to coastal wave hazard monitoring. In: Protections 2018, 3rd International Conference on Protection against Overtopping, Grange-Over-Sands, UK, 6-8 June 2018. 1-7.

Horsburgh, K., Ball, T., Donovan, B., Westbrook, G. (2010). Coastal Flooding in MCCIP Annual Report Card 2010- 11, *MCCIP Science Review*, p.10, Available at: www.mccip.org.uk/arc [Accessed 24 Nov. 2017].

Killen, J. (1952). A capacitive wave profile recorder. University of Minnesota, *St. Anthony Falls Hydraulic Laboratory*, Tech. Paper 11, Series B, p.7.

Pascal, R.W., Yelland, M.J., Srokosz, M.A., Moat, B.I., Waugh, E.M., Comben, D.H., Clansdale, A.G., Hartman, M.C., Coles, D.G.H., Hsueh, P.-C., Leighton, T.G. (2011). A spar buoy for high frequency wave measurements and detection of wave breaking in the open ocean. *Journal of Atmospheric and Oceanic Technology*, 28(4), pp. 590-605.

Phillips, B., Brown, J., Bidlot, J.-R., Plater, A. (2017). Role of beach morphology in wave overtopping hazard assessment. *Journal of Marine Science and Engineering*, 5(1), 5010001.

Priestley, S. (2017). Flood risk management and funding. *House of Commons Library*, Briefing Paper, Number CBP07514, 22 November 2017, p.47. Available at http://researchbriefings.parliament.uk/ResearchBriefing/Summary/CBP-7514#fullreport [Accessed 25 Nov. 2017].

Prime, T., Brown, J.M., Plater, A.J. (2015). Physical and economic impacts of sea-level rise and low probability flooding events on coastal communities. *PLOS ONE*, 10(2), e0117030.

Pullen, T., Allsop, W., Bruce, T., Kortenhaus, A., Schuttrumpf, H., van der Meer, J. (2007). Wave overtopping of sea defences and related structure: Assessment manual, p.193. Available at: www.overtopping-man- ual.com [Accessed 25 Nov. 2017].

Pullen, T., Allsop, W., Bruce, T., Pearson, J. (2009). Field and laboratory measurements of mean overtopping discharges and spatial distributions at vertical seawalls. *Coastal Engineering*, 56(2), pp. 121-140.

Pullen, T. and Liu, Y. and Otinar Morillas, P. and Wyncoll, D. and Malde, S., Gouldby, B.P. (2018). A generic and practical wave overtopping model that includes uncertainty. Proceedings of the Institution of Civil Engineers - Maritime Engineering.

Pullen, T., McCabe, M., Carter, D. (2012). Field and laboratory measurements of wave overtopping at Anchorsholme, UK. Proc. 33rd Int. Conf. *Coastal Engineering*, Santander, ASCE.

Pullen, T., Tozer, N., Sayers, P., Hawkes, P., Saulter, A., Flowerdew, J., Horsburgh, K. (2008). Use of field measurements to improve probabilistic wave overtopping forecasts Proc. 31st Int. Conf. *Coastal Engineering*, Hamburg, ASCE, p.13.

Richardson, S., Pullen, T., Clarke, S. (2002). Jet velocities of overtopping waves on sloping structures: measurements and computation. Proc. 28th Int. Conf. *Coastal Engineering*. Cardiff, ASCE, p.13.

Roelvink, D., Reniers, A., Van Dongeren, A. P., de Vries, J. V. T., McCall, R., & Lescinski, J. 2009 Modelling storm impacts on beaches, dunes and barrier islands).

Sandoval, C., Bruce, T. (2017). Wave Overtopping Hazard to Pedestrians: Video Evidence from Real Accidents. Proc. Of the ICE Conf. *Coasts, Marine Structures and Breakwaters*, Liverpool, Paper 146, p.12.

Souza, A.J., Brown, J.M., Williams, J.J., Lymbery G.L. (2013). Application of an operational storm coastal impact forecasting system, *Journal of Operational Ocean- ography*, 6(1), pp. 23-26.

Wadey, M., Brown, J., Haigh, I.D., Dolphin, T., Wisse, P. (2015). Assessment and comparison of extreme sea levels and waves during the 2013/14 storm season in two UK coastal regions. *Natural Hazards and Earth System Science*, 15(10), pp. 2209-2225.