WIREWALL A FOLLOW UP: LABORATORY AND FIELD MEASUREMENTS OF WAVE OVERTOPPING

TIM PULLEN[1], JENNY BROWN[2], MARGARET YELLAND[2], ROBIN PASCAL, RICHARD PINNELL, CHRIS CARDWELL AND DAVID JONES

[1]HR Wallingford, Howbery Park, Wallingford, UK, OX10 8BA

[1]t.pullen@hrwallingford.com

[2] National Oceanography Centre

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Summary. At the Protections 2018 conference, the WireWall wave overtopping research project was introduced. WireWall uses recent advances in high frequency capacitance wire technology that can measure overtopping data. Wave overtopping has now been measured in the laboratory and in the field using the WireWall system. Here we provide an update on the validation of the system in flume tests and results from the first field measurement campaign.

Before deployment in the field, an extensive set of tests were carried out in one of the 2D wave flumes at HR Wallingford. These tests simulated known wave conditions from a buoy near the field measurement site, and a representation of the sea wall at the site. The structure (shown in Figure 1) underwent extensive testing and was used to validate the WireWall rig. Using traditional methods of assessing wave overtopping in the flume, the WireWall measurements were directly validated against the known volumes collected in the overtopping tanks.

The WireWall field system was deployed at Crosby, Liverpool during the winter of 2018/19, where waves regularly overtop the sea wall. Comparison between the WireWall measurements and the BayonetGPE predictions for one of the Crosby deployments shows good agreement, with the predictions and the WireWall measurements being within the uncertainties estimated for the BayonetGPE predictions.

1 INTRODUCTION

The WireWall project involves oceanographic measuring equipment adapted for use on land to measure wave overtopping discharges (Pascal et al 2011, Broeders et al., 2016, Brown et al. 2020a). Measurements in the laboratory validated the WireWall measurement system against traditional laboratory methods to measure wave overtopping discharges (Yelland et al. 2022). The measurements focused on the Crosby sea wall in Liverpool Bay.

2 CROSBY SEA WALL

Our case study site Crosby (Brown et al, 2020a) 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 (Figure 1).

Figure 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 was 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, and using predicted wave heights and water levels, thresholds of potential wave overtopping events were identified. These informed the go/no-go decisions for the field deployments.

3 THE WIREWALL CONCEPT

The WireWall approach measured coastal wave overtopping at the high frequencies (400 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 (Brown et al. 2020a, Yelland et al. 2022). 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 and improve operational coastal hazard management. If successful, this will allow our partners to continue monitoring future events at Crosby, and other groups to initiate similar monitoring at other sites.

3.1 Desktop review and overtopping prediction

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, Figure 2) and existing coastal monitoring networks (WaveNet and the National Tidal Sea Level Facility). Historical overtopping events were identified using images gathered from social media (see Brown et al 2021a for details). 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 (Brown et al. 2020a, Brown et al, 2021a).

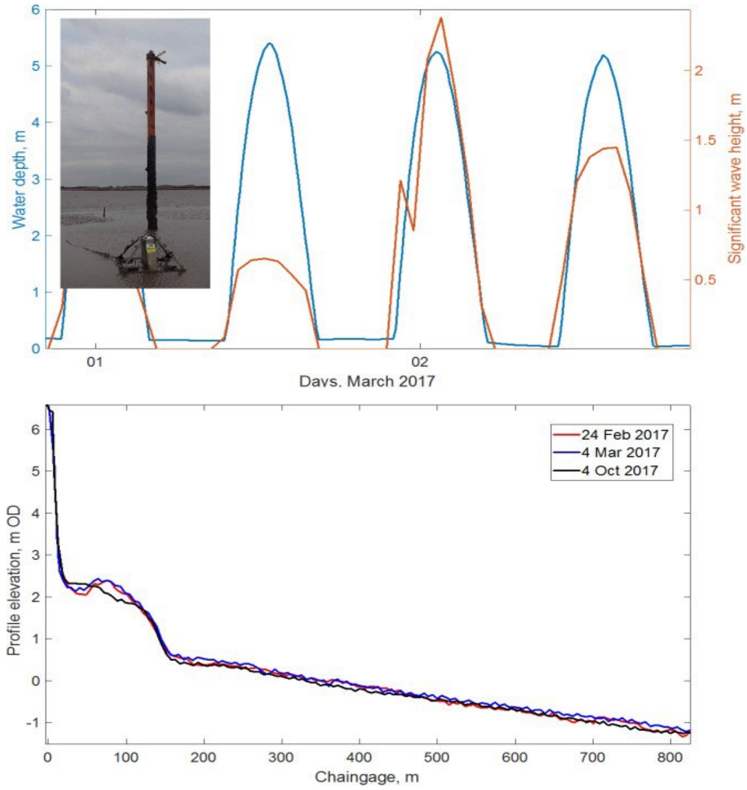

Figure 2. An example of the AWAC (top) and beach profile (bottom) data collected as part of the Northwest Coastal Monitoring Strategy.

3.2 Validation and deployment of WireWall

The mobile, battery-powered WireWall system was configured to record wave-by-wave overtopping volumes and velocities 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 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 validated using tank data in the flume at HR Wallingford (HRW) (see Brown et al. 2020a, Yelland et al. 2022 for details).

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.

The frames were open faced and aligned with the oncoming wave direction to capture the horizontal speed and discharge of the overtopping jet. Up to 6 frames were mounted within robust rigs to form a 3D 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 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 sea wall, which is close to the Hall Road beach profile line (extending from the slipway). 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 when there is an onshore wind. 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 springs (4.46 m OD) were considered 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 (Figure 3) 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 during desktop study to further validate the numerical overtopping estimates against the observed Crosby overtopping events in discussed below.

Figure 3. The Crosby sea wall frontage.

3.3 Measured storms at Crosby

Field data from the system were used to quantify the local overtopping hazard at Crosby and compare with EurOtop and validate SWAN 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). 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 (Brown et al. 2020a). 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. WireWall results from the Crosby field deployments have also recently been used to validate a set of deep-water-parameter-based formulae for mean overtopping discharge at smooth slopes (Lashley et al, 2022).

Figure 4. WireWall field measurements (Spring tide 23 January 2019).

4 LABORATORY TESTS - METHODOLOGY AND RESULTS

The overtopping tests measured mean and individual (i.e. wave-by-wave) overtopping discharges, for the physical model of the existing sea wall located at Crosby in the north west of England (Brown et al. 2020a, Yelland et al. 2022). 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: See Table 1 for the various wave and water level combinations used.

4.1 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.

4.2 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. Wave 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 analysed to separate the incident and reflected wave spectra, and determine the incident significant wave height, $H_{m0,i}$.

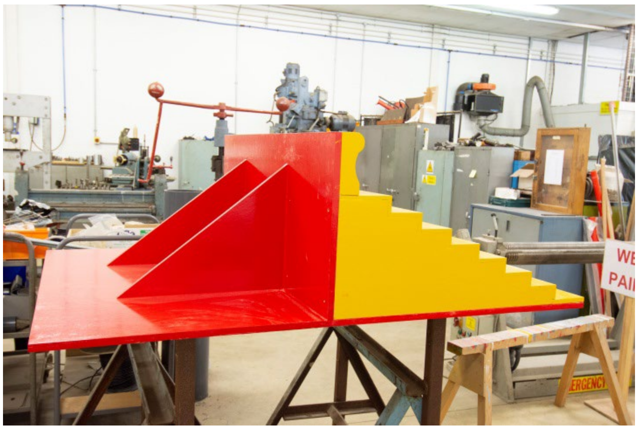

Figure 5. Crosby sea wall after construction.

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

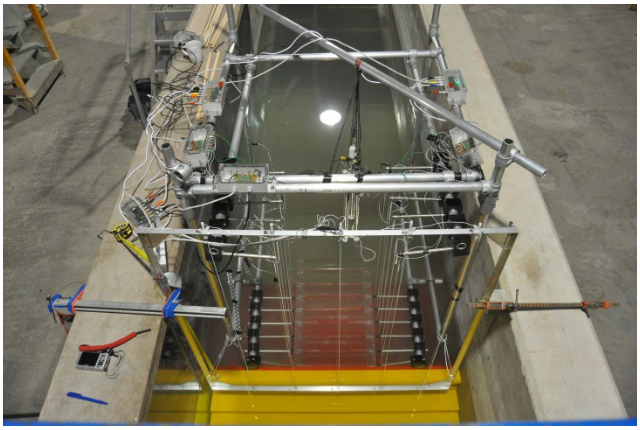

Figure 7. WireWall set up using overtopping tank with eight chambers.

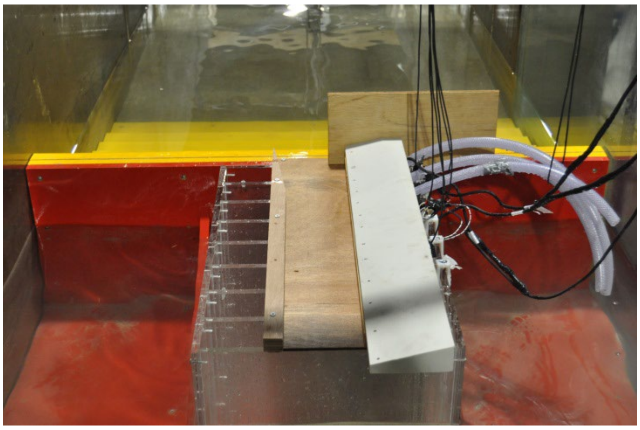

Figure 8. Set up of structure created for overtopping tank to reduce the volume of overtopping.

4.3 Test methodology

A series of six WireWall "dipsticks" (capacitance sensors measuring at 1 Hz) 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. Figure 5 to Figure 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.

4.4 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 Figure 8 collected the discharge volumes behind the model Crosby sea wall (see Figure 6). Test Series NOC (see Figure 7) where the WireWall system was installed in the flume, collecting the overtopping volumes at the lee of the Crosby model sea wall. The recorded mean overtopping discharges for both series are presented in Table 1.

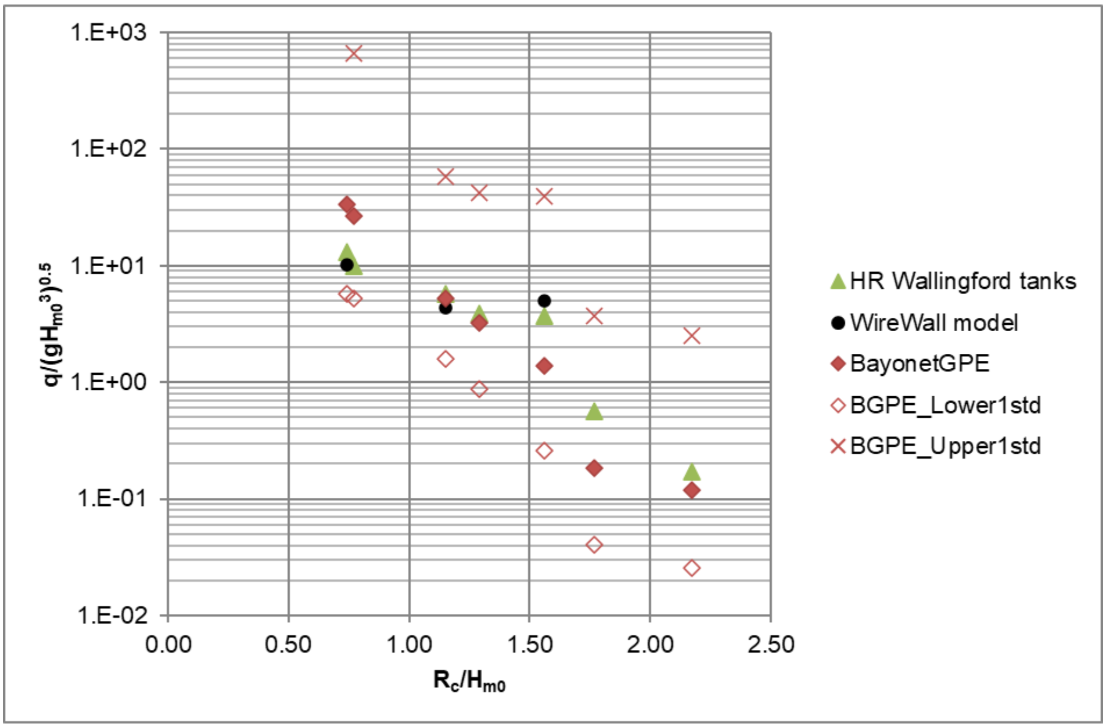

Figure 9. HRW and NOC series comparison of overtopping discharges with BayonetGPE predictions.

The results from the HRW tanks and WireWall are in very good agreement (Figure 9). The data is represented in terms of relative freeboard (R_c/H_{m0}) against relative overtopping discharge ($q/(gH_{m0}^3)^{0.5}$). Also shown are predictions from the BayonetGPE numerical predictions (Table 1). BayonetGPE is a generic metamodeling overtopping model, based on the application of Gaussian Process Emulation techniques. It is the latest in a series of overtopping models that utilise empirical (metamodelling) techniques that have been fitted to physical model data to generate predictions of overtopping rates. BayonetGPE provides a mean prediction plus a range of statistical predictions based on how closely the schematisation (hydraulic and geometrical data) match with the empirical data.

The mean BayonetGPE predictions and the laboratory and WireWall results are all extremely close. Typically overtopping predictions will show a range of ±x3 when compared to measured data, which is apparent in Figure 9. The wider range of the standard deviations is partially due to there being a sparsity of metadata in BayonetGPE, but also the higher complexity of the structures geometry. All the data are all available from the British Oceanographic Data Centre (Yelland et al., 2020) and are described in detail in (Brown et al. 2020a, Yelland et al. 2022).

Table 1. Wave conditions and mean results (q) from the flume tests and BayonetGPE. Note that WireWall was not installed for some of the wave conditions.

			TANKS	WIREWALL	BAYONETGPE		
WAVE CONDITION	Hm0 (m)	Tp (s)	q (l/s/m)	q (l/s/m)	mean q	-1 s.d.	+1 s.d.
WC01	0.87	6.27	14.2 ± 2.1	14.0 ± 1.4	13.4	4.0	148
WC06	0.91	5.72	27.2 ± 2.3	-	71.8	14.4	1794
WC07	0.94	6.6	34.1± 4.5	28.3 ± 3.8	96.1	16.2	3382
WC12	0.87	6.27	0.4	-	0.3	0.1	6
WC13	0.87	6.27	1.5	-	0.5	0.1	10
WC14	0.83	6.42	9.1 ± 0.3	-	7.6	2.1	101
WC15	0.8	7.65	8.4 ± 0.8	9.1 ± 1.6	3.1	0.6	89

5 FIELD OVERTOPPING RESULTS

WireWall was deployed at the sea wall at Crosby on the 25th January 2019, during the spring tide and overtopping was measured during this event. Comparison between the WireWall measurements and the BayonetGPE predictions (shown in Figure 10) show agreement in that the +/- 2 standard deviation of the BayonetGPE predictions encompass most of the results from the WireWall system (Brown et al 2020a, Yelland et al 2022), i.e. similar agreement to that seen in the flume studies. The data is represented in terms of elapsed time (s) since 12:30 GTM against mean overtopping discharge, q (m^3/s/m). The WireWall data and BayonetGPE predictions for all deployments are available from the British Oceanographic Data Centre (Brown et al, 2020b).

6 DISCUSSION

A series of flume tests were run on a model sea wall 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 using overtopping collection tanks, and the mean overtopping discharges are shown in Figure 9. The overtopping was also measured for three of the tests using WireWall, also shown in Figure 9. The comparison of the data in Figure 9 shows extremely good agreement between the measurements from the WireWall system when compared to the standard laboratory methods for assessing wave overtopping (a chute and a collection tank).

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 Figure 9 clearly indicate that they are in agreement with the measured values, i.e. within the +/- 1 standard deviation of the BayonetGPE mean predictions. Given that there are no equivalent laboratory measurements for the field deployments, the then use of both BayonetGPE and the WireWall system is ideal for giving confidence in results from the field.

In Figure 10 the results of the field measurements of overtopping by WireWall are compared to the BayonetGPE predictions. These are in agreement to within the +/- 2 standard deviation uncertainty of the BayonetGPE predictions, and thus it is demonstrated that the WireWall field measurements of overtopping present a new, reliable and accurate method.

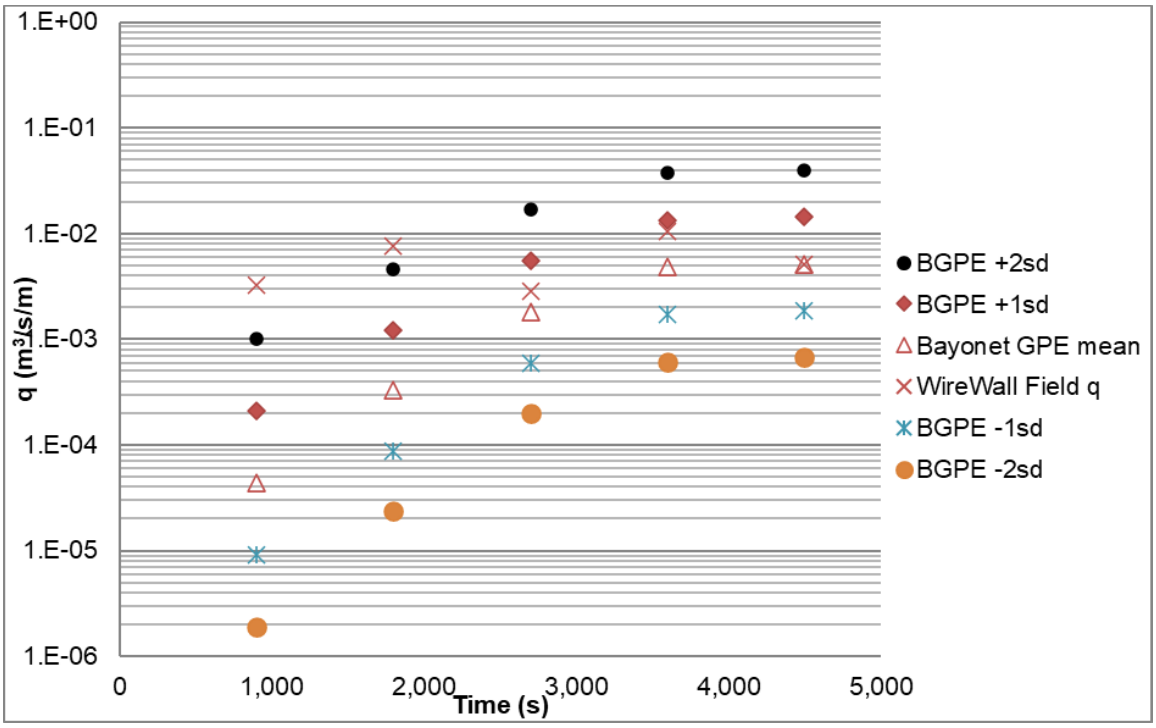

Figure 10. Comparison of overtopping discharges from WireWall field data (25 Jan 2019) with BayonetGPE predictions.

Figure 11. WireWall deployment at Dalwish (Devon, UK). A full WireWall (1) system is located at the crest of the sea wall, with two smaller WireWall systems located further inland on the seawards (2) and landwards (3) side of the railway tracks. Also visible is a B-SCAN system installed by the University of Plymouth to measure daily beach levels fronting the sea wall.

More recently, the WireWall system has been deployed at a coastal site in Devon for 12 months (Figure 11), and at another coastal site in Cornwall for four months (under a separate project "CreamT") to demonstrate the potential to deploy the system for longer-term measurement and monitoring of coastal overtopping (Brown 2021b). These systems included the addition of telemetry so the observations could be viewed in near real-time alongside existing coastal and weather monitoring networks. The Devon example (Figure 11) shows different size system configurations, positioned to detect wave overtopping at the crest of the sea wall, crossing the public walkway and crossing the railway line. These data, collected over a sea-land transect, can be used to identify the coastal conditions that pose a hazard to different coastal infrastructure users.

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