

Article

Occurrences of Predicted Wave Overtopping Assessed Using In Situ Winter Observations at an Emergent Beach-Fronted Sea Wall

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Abstract

A growing reliance on (ageing) sea walls to protect people, property and infrastructure is a global coastal management issue. Wave overtopping hazard is increasing in likelihood throughout the year due to sea-level rise and is not only associated with winter storms. Adaptive management requires accurate predictive tools to explore future options and forecast hazard. Predictive tools, based on empirical rules derived mainly from scaled experiments, can be highly uncertain in real-world application due to limited multi-process representation. We analyse a unique 4-month field dataset of coastal wave overtopping at two locations, ~345 m apart, along a sea wall fronted by an emergent beach, in SW England. Nearly one order of magnitude difference in the number of waves overtopping occurs between the two sites, most likely due to the variability in the beach influencing the coastal dynamics. Higher beach levels reduce but do not always eliminate overtopping, even when the beach is emergent above the high tide level. The number of waves overtopping increases with higher water elevations. The likelihood of overtopping will potentially increase with sea-level rise while the emergent beach is sustained. During winter 2021/2022, overtopping was incorrectly predicted for 49% of the tides using an empirical approach that disregards wind influence and the temporal variability in and emergence of the beach levels in front of the sea wall. Predictive tools and approaches for beach-fronted vertical structures must account for non-static and emergent beaches, wind influence and broken waves.

Keywords: coastal wave overtopping; coastal hazard monitoring; coastal hazard management; coastal hazard forecasting; beach levels; sea-level rise; alongshore variability



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1. Introduction

Urban beaches worldwide are backed by coastal structures to protect local communities and infrastructure. Vertical sea walls with and without a recurved top to reduce reflection are common in urban areas and are designed to reduce, but not eliminate, wave overtopping [1]. At coastal locations that are vulnerable to wave overtopping, early warning

systems typically use a few select beach profiles, chosen to represent alongshore beach-structure variability, to predict overtopping hazard [2]. In the absence of empirical wave overtopping rules for emergent beach-fronted vertical structures, wave run-up models are used to predict wave conditions at the toe of the structure to input into empirical rules for vertical structures [3]. However, this approach does not account for wave overtopping by waves breaking on a dry foreshore or broken wave bores directly impacting the structure, although research is emerging [4].

Approximately 90% of all coastal areas will experience adverse climate impacts, exposing growing populations and associated critical infrastructure to climate-related hazards [5]. By the 2050s, “hold the line” management policies in England will be difficult to implement for approximately 30% of the shoreline [6]. At locations transitioning to “managed realignment”, nature-based solutions can buy time to prepare for the change [7]. With a move away from reactive protection to proactive coastal management that builds resilience, challenges in adaptive approaches that are dynamic in time must be overcome [8]. Adaptive schemes and sea walls that are maintained, but not to an increasing level of protection, require accurate wave overtopping forecasts to prepare for and manage (permissive) low-intensity flood events. Observations are key for vulnerability assessments, improving global and local flood model accuracy [9].

Overtopping is a complex process, and predictions are mostly based on empirical methods derived primarily from laboratory measurements applying dimensional analysis and scaling arguments [10]. Low energy events have received little attention to date because most predictive tools have been developed for structure design to protect against extreme events. More attention is now paid to the wave-by-wave overtopping distribution rather than applying mean discharges [11]. The probability distribution of individual wave overtopping volumes has been found to follow a 2-parameter Weibull distribution in laboratory experiments. The distribution function expresses the probability of an individual wave not exceeding a given overtopping volume per wave. By knowing the number of waves within a sequence, the maximum wave overtopping volume can be calculated following a logarithmic function [12]. The most widely used overtopping database to develop predictions is CLASH [13]. While comprehensive, it still has limitations in terms of: (1) the number of structure types considered; (2) a focus on extreme conditions; (3) the number of processes interacting within laboratory settings; and (4) the fact that many experiments are carried out in flumes, which represent long-crested waves, and do not represent the short-crested wind seas and 3-D processes (e.g., stem waves) that many structures are exposed to in reality. While new experiments emerge, some of which are at scale to assess nature-based solutions [14], there are still limited field observations for wave overtopping and limited investigations that consider spray-dominated impact [15], overtopping by wave bores impacting vertical sea walls [4] and the influence of wind on the overtopping discharge [16]. Most importantly in the context of this paper, there is a lack of observations from beach-fronted structures [17], especially field observations.

A large range of interactive coastal conditions influence the magnitude and frequency of wave overtopping. Vulnerability to wave overtopping will depend chiefly on the type/design of any protection scheme, a location’s exposure to the waves and wind, the health of the beach and the condition of any engineered scheme. Overtopping volume is strongly influenced by the beach profile fronting a vertical sea wall. Through its impact on beach levels, the sequencing of different severity wave events is therefore an important influence on wave overtopping hazard [17].

Large uncertainties in overtopping predictions continue to exist in real-world applications, although a semi-quantitative understanding of how the individual processes influence wave overtopping is well established [18]. To increase the reliability of site-

specific predictions, field observations are vital to identify the conditions that influence overtopping to calibrate/train predictions for local management and safety requirements. Emerging technologies to monitor coastal hazard in situ include the WireWall system to measure wave overtopping [19] and BScan to measure the foreshore profile [20]. Together, these technologies provide the opportunity to collect a spectrum of field data to evaluate wave overtopping hazard and predictive capability.

Using these technologies to supplement national coastal monitoring programmes and regional forecasting systems, a winter field dataset of wave overtopping at two locations along a sea wall is provided. Analysis of the field data highlights the contribution of alongshore and time-varying beach elevation in mediating processes that influence wave overtopping. By attaining and collating a field dataset (Section 2) of concurrent waves, water levels, winds, beach profiles and wave overtopping, this research aimed to demonstrate that predictive hazard assessment tools must account for non-static and emergent beach levels. To confirm this, the following objectives were achieved:

1. Assess the number of false/missed occurrences of wave overtopping and identify the type of conditions under which these occur (Section 3).
2. Evaluate the beach levels at which wave overtopping can occur (Section 3).
3. Quantify the difference in overtopping at two locations along a coastline frontage (Section 3).
4. Propose how the present-day winter overtopping frequency distributions could change in future due to sea-level rise, beach lowering and climate change (Section 4).
5. State the requirements to advance predictive wave overtopping capability (Sections 4 and 5).

2. Methods

In situ wave overtopping data have been observed at two locations along the crest of a beach-fronted vertical sea wall in Penzance, SW England (Figure 1a), in addition to daily upper beach profiles at the mid-point of the sea wall. The beach is mixed sand and gravel with a slope of ~ 0.15 . These field data represent 4 months during winter 2021/2022. Coastal monitoring (by South West Coastal Monitoring, as part of the National Network of Regional Coastal Monitoring Programmes, NNRCMP, of England) and wave overtopping forecasts (generated by the Operational Waves and Water Levels system, OWWL [21]) are available at this site to assess the coastal conditions that are associated with wave overtopping. We use existing national monitoring and regional forecasts available to coastal managers in near real-time so the results support their decision-making when responding to nearshore wave, surge and weather forecasts. This also helps identify the condition ranges to use as boundary forcing for more detailed modelling studies to investigate future scheme designs and adaptive management options. Overtopping thresholds based on conditions at the structure toe are not developed because coastal managers would require these parameters to be available from forecasts or be monitored to enable their application, which they are not. All elevations and heights are referenced to the standard for mapping used by UK coastal managers: Ordnance Datum Newlyn, ODN.

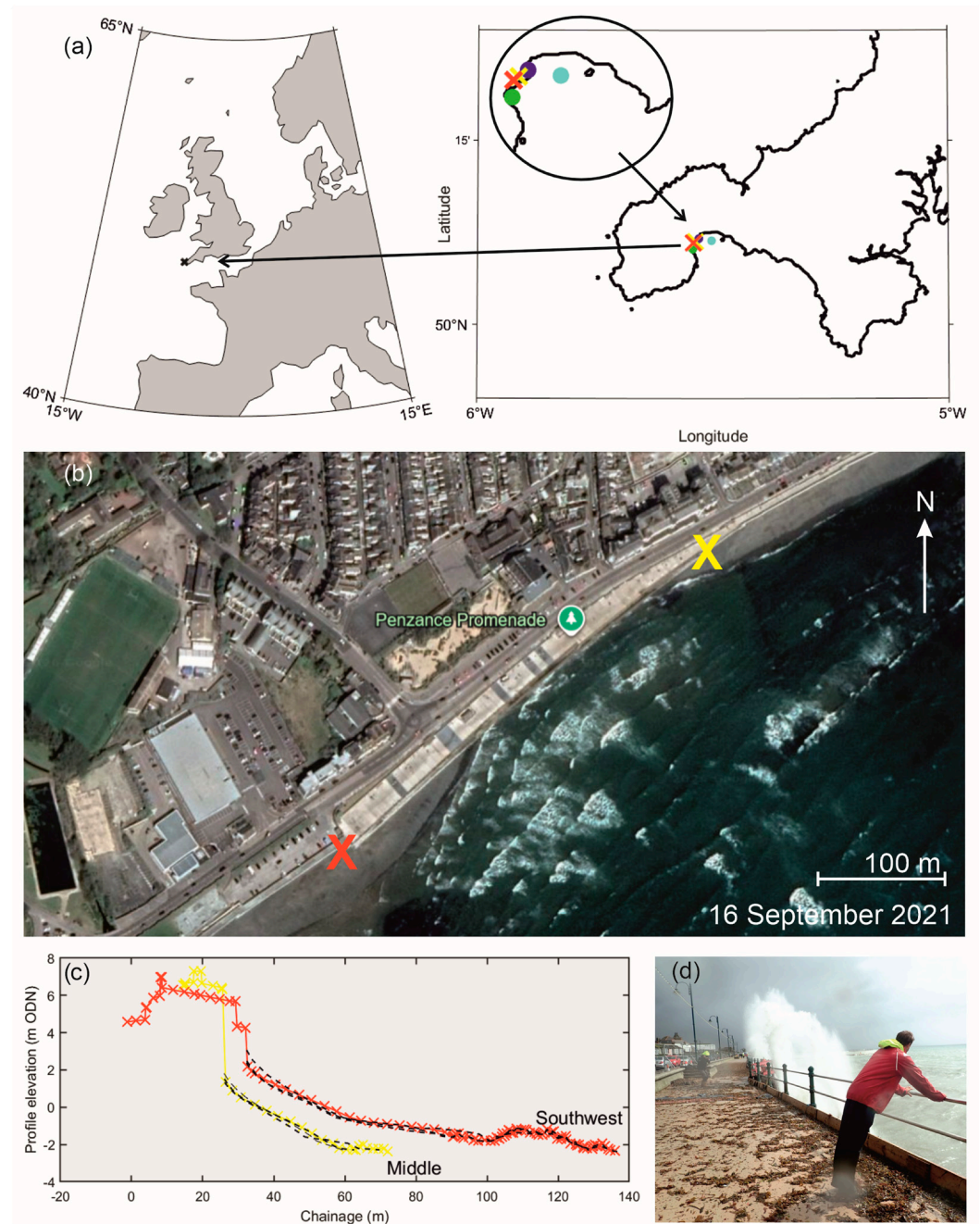


Figure 1. The Penzance study site in southwest England (mapping software by Pawlowicz [22]). (a) The location of the WireWall systems (X X), the BScan close to the northeast WireWall (X) and regional wave (•), wind (•) and water level monitoring (•). (b) Web-based Google Earth Images (version 10.104.67.2 at 50°06′47.22″ N 5°32′18.43″ W with data attribution to CNES/Airbus). (c) Baseline surveys (profiles 6e00852 and 6e00859) collected close to the WireWall locations (Middle and Southwest, respectively) by South West Coastal Monitoring prior to the study period (8 October 2021, -x -x, Middle used in OWWL) and during 2021/2022 (16 January 2021, 17 July 2022 and 11 October 2022, ---). (d) Example of wave overtopping and transported seaweed near the Middle location (25 August 2020).

2.1. Field Site

Penzance (Figure 1a) is a bay in the SW of England, exposed to Atlantic storms [23]. The site represents a beach-fronted vertical sea wall with a public walkway, which immediately protects a road, car parking, accommodation and shops (Figure 1b). A bullnose capping along the sea wall crest directs the wave overtopping by vertical spray seaward in the

absence of a strong onshore wind. The emergent beach varies in elevation in time and space (Figure 1c). Regular wave overtopping of the sea wall causes flooding, damage to property through impact by water and beach debris, and clean-up requirements to remove beach debris (seaweed and gravel/sand) from transport/access routes and public spaces (Figure 1d). As in many locations, management of the coastal defences has been reactive, with repairs reliant on emergency funding. Now there is a shift towards a proactive approach [24].

To support the Penzance Place Making initiative and Mount's Bay Coastal Resilience Strategy, future projections to explore management, development, climate and sea-level scenarios require a robust evidence base. In situ wave overtopping and concurrent beach levels observed for a winter can supplement expert judgment. These datasets demonstrate the site-specific influence of headland sheltering and nearshore rock outcrops on the alongshore beach elevations and the foreshore influence on wave overtopping. The beach width at the WireWall locations can clearly be seen in Google Earth (Figure 1b) to be wider at the Southwest location than at the Middle location. The varying protection offered by the beach is most likely to influence the occurrence of overtopping through mediation of the shallow water wave dynamics and water depth at the toe; thus, two locations are chosen to deploy a WireWall. Baseline survey data collected close to the WireWall locations (Figure 1c) show a higher and wider beach profile at the Southwest location than at the Middle location. The alongshore variability in beach profiles is caused by a combination of the influence of the rock outcrops and headland sheltering on the wave conditions.

The regional Operational Waves and Water Levels system (OWWL [21]) runs daily to predict mean overtopping discharge at the sea wall crest, near the Middle location. This single forecast point is used to give an indication of the overtopping hazard for the sea wall frontage; running multiple profiles would be inefficient within the regional application. The hazard forecast has been available to coastal managers across the SW region as a public NNRCMP resource since October 2018. The wave height at the structure toe is calculated prior to forecasting wave overtopping hazard using empirical equations from EurOtop [18]. The wave overtopping predictions do not account for wind influence on wave overtopping by spray. The system uses beach profiles collected at baseline survey lines biannually by South West Coastal Monitoring (Figure 1c). The forecast location used in this study (50.113928° N, 5.537456° W) is near the Queen's Hotel between the (Middle) WireWall and BScan deployment (equipment explained in Section 2.2). This location, in the middle of the sea wall section, is known to be vulnerable to wave overtopping due to relatively low beach levels. Based on the empirical overtopping rules in EurOtop [18], which do not account for situations with an emergent sea wall toe, OWWL is not able to predict wave overtopping discharge when the upper foreshore is predicted to be dry. During the field campaign, the predicted mean wave overtopping discharges were archived. The daily two-day forecast includes one day of hindcast conditions, informed by weather reanalysis, used here because these data represent the best possible predictions of the incident wave and water level conditions driving OWWL. The overtopping data were predicted at half-hourly intervals during the study, which is the Met Office forecast data interval that feeds the OWWL system.

Beach variability and local wind influence will create uncertainty in the OWWL predictions. An updated beach profile is incorporated when available from the biannual surveys, but in the interim the profile is static. For this study, the October 2021 (Middle) survey was implemented in OWWL (Figure 1c). During 2021 and 2022, the surveyed toe elevation (Middle location) varied from 1.33 m ODN to 1.82 m ODN (Figure 1c). The October 2021 OWWL set-up represents quite a low toe elevation of 1.36 m ODN. Previous

sensitivity analysis has demonstrated that overtopping discharge can vary by an order of magnitude at a single location due to profile variability [21].

2.2. Field Data Collection

A 4-month instrument deployment comprising two WireWall systems and one BScan took place during winter 2021/2022 (Figure 1a). The first WireWall system was deployed (16 November 2021–15 March 2022) at the crest of the sea wall positioned midway along the sea wall section (50.11382° N, 5.53767° W) that extends southwest from the Jubilee Pool. This location, in front of the Queen's Hotel, is known to be vulnerable to overtopping due to low beach levels. Hereafter, we call this WireWall location "Middle". The second WireWall system was deployed further southwest, approximately 345 m away (17 November 2021–15 March 2022) at the crest of the start of the next sea wall section (50.111848° N, 5.541466° W). This location, in front of the Wherry Town Lidl store, is known to be less vulnerable to overtopping. Hereafter, we call this WireWall location "Southwest". The alongshore locations were chosen after consultation with local authorities to capture variability in the wave overtopping response to coastal conditions and to minimise obstruction by the rigs to the coastal amenity. From the crest of the sea wall, a recurved lip protrudes seaward 21 cm at the Middle location (Figure 1b) and 25 cm at the Southwest location. Both sea wall sections are examples of vertical sea walls where the beach foreshore influences wave breaking prior to impact with the structure¹.

The individual overtopping waves (often wave spray travelling over the sea wall structure) were counted using the WireWall capacitance wire system. Previously validated in a flume and tested for short-term field deployment [19], the technology was ruggedised to trial long-term deployments [25]. WireWall was programmed to record continuously for 6 h centred on every predicted high tide. Tidal predictions for Newlyn, the nearest tide gauge location, were obtained from the commercial POLTIPS-3 software [26]. The delayed mode data (downloaded from the logger and quality controlled [27]) are used to investigate the variation in wave overtopping frequency distributions at the two locations. For both WireWall systems (Middle and Southwest), data from a wire 37 cm inland of the sea wall crest are analysed to assess wave overtopping with a landward component of travel. The data represent the number of overtopping waves reaching the wire position. Minimal data were lost due to the 6 h recording constraint, deemed appropriate to capture most overtopping while conserving batteries to support a 3-month maintenance cycle.

The WireWall information used here consists of timestamped individual wave overtopping events. The WireWall sensors consisted of vertical pairs of 3-metre insulated and uninsulated wires suspended in parallel under tension and 1 cm apart. The sensor pair shows a measurable change in capacitance when seawater or sea-spray bridges the gap between them, with the change in capacitance varying in proportion to the extent to which the wires are bridged. Each wave event detected is quality controlled (QC). The first QC check ensures the overtopping discharge signal of an individual wave exceeds the dry baseline capacitance value (calculated every 10 min) of that wire pair. This isolates the wave events. The second QC check ensures another wire pair adjacent to or seaward of the wire pair of interest registers the same event, i.e., detects an event within 2 s. This check removes isolated splashes or human/animal interference. The open scaffolding framework of the WireWall system was designed to ensure the wires were exposed to overtopping from all directions, with no directional sheltering from existing infrastructure. The 1 cm separation between the wires in the pair was chosen to stop rain from creating false overtopping events while allowing overtopping spray droplets of at least 1 cm diameter or jets of water to be detected. Recording at 400 Hz captures the time of each individual overtopping event. To compare the WireWall data with the OWWL data, the individual overtopping waves are

processed to determine if WireWall detected any wave overtopping up to 15 min either side of each OWWL prediction. If it did (not), that time is (not) flagged to be associated with observed overtopping. The mean overtopping discharge predicted by OWWL for the same time interval is also given a binary classification of ‘overtopping’, if the mean discharge is greater than $0 \text{ m}^2/\text{s}$, or ‘not overtopping’, if the mean discharge is $0 \text{ m}^2/\text{s}$. These binary (yes/no) overtopping datasets at the same 30-min intervals are then compared.

BScan [20] is a laser scanner positioned on a coastal defence, in this case the crest of the sea wall (from 9 September 2021–24 March 2022), to measure the beach profile (as a cross-shore transect). The location for the BScan (50.11413° N , 5.53686° W) was within $\sim 80 \text{ m}$ northeast of the Middle WireWall. The laser was positioned on a scaffold arm at a height of 3.2 m above the wall to measure across a reliable range of $12\text{--}15 \text{ m}$ with minimal shadowing of the signal from the sea wall. The BScan was programmed to scan every low tide to capture the beach levels at the structure toe. Daily profiles, the first low tide of the day, were archived (from 2 December 2021–4 March 2022) with quality-controlled data available for 63% of the days. The upper beach levels illustrated here are the mean value of the beach elevation from 0.5 m to 3.5 m offshore from the structure toe.

Due to planning permission requirements, controlling where equipment could be installed in the public areas, limitations in the approach are acknowledged. Observations are collected $\sim 30 \text{ m}$ from the OWWL predictions. The WireWall data are likely to represent a location with slightly lower beach levels, and the BScan data are likely to represent a location with slightly higher beach levels. The OWWL prediction at this location is provided to local managers to guide operational hazard management decisions for this frontage, knowing there will be uncertainty in the applicability of the predictions alongshore. Here, the comparisons of the observations with numerical predictions do not provide quantitative validation of OWWL, but provide a qualitative indication of the robustness of the prediction of when wave overtopping occurs for the frontage. Without the funding resources to measure the wave conditions across the surfzone, which will control the overtopping dynamics, this study is limited to an assessment of the beach emergence based on beach and water level data relative to the occurrence of overtopping. The data presented could be used by others in numerical/physical models to further investigate surfzone dynamics. Without having fully instrumented cross-shore profiles, differences in the overtopping at the two sites cannot be isolated to specific process contributions. The observed persistent alongshore variability in the beach profile is likely to influence the alongshore variability in both the shallow water wave conditions and the water depth at the structure toe, which all together influence the wave overtopping. Ideally, the wave overtopping observations and beach scans would have been collocated on the OWWL profile, and the BScan would have provided data every tide.

2.3. Metocean Data

The WireWall/BScan deployments complement local water level, wave and wind monitoring (Figure 2) available from the National Tidal and Sea Level Facility (NTSLF, water levels) and South West Coastal Monitoring (SWCM, waves and wind), located in Figure 1a. Quality-controlled monitoring data were obtained to reduce erroneous data, limit data loss due to telemetry issues, and provide access to advanced statistics (such as the wave energy period [28]). The 15 min water level data were from the Newlyn tide gauge (50.10300° N , 5.54283° W). The 30 min wave data were from the Penzance Directional Waverider (50.11443° N , 5.50279° W). The 10 min wind data were from the Penzance Harbour Meteorological Station (50.11735° N , 5.5298° W).

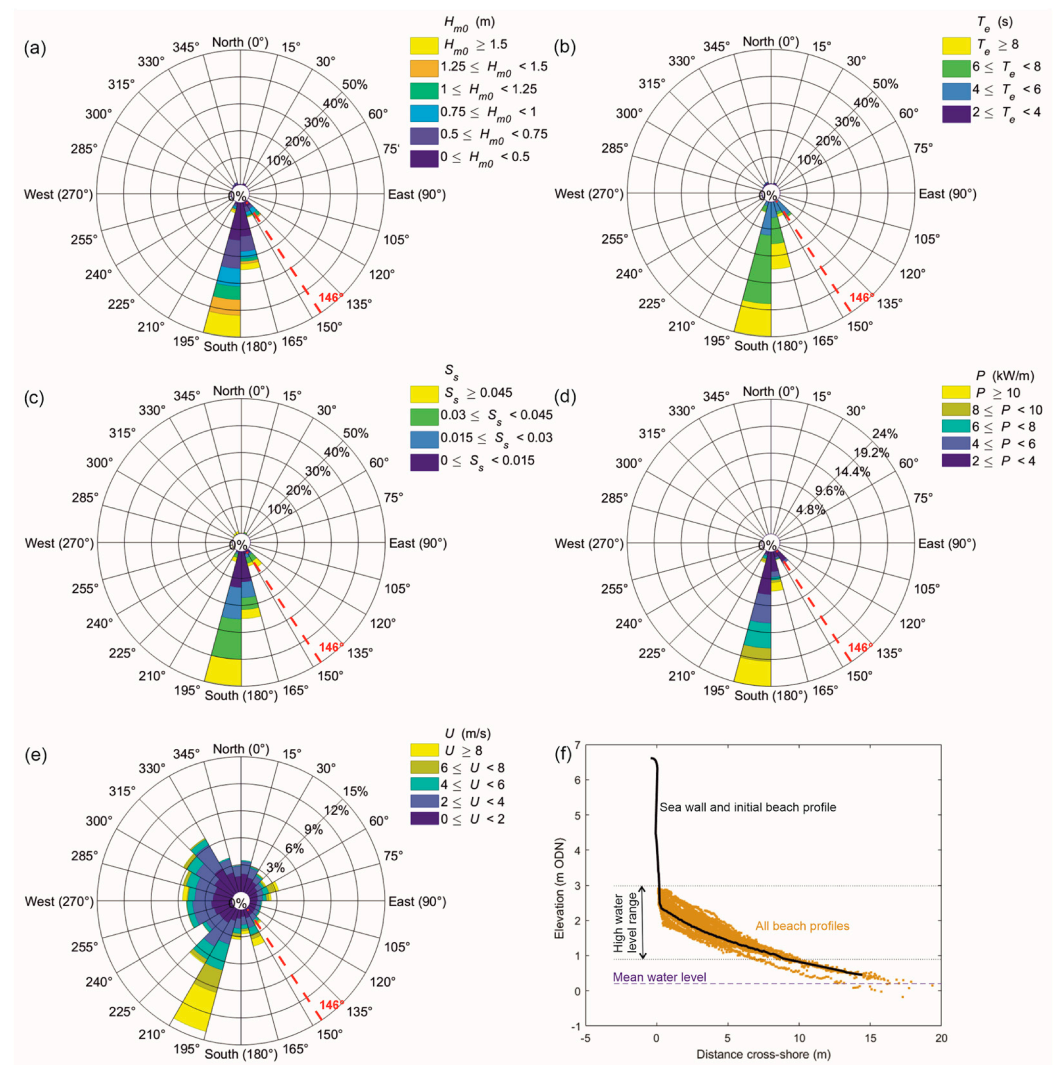


Figure 2. The observed wave–wind climate in Penzance during the 4-month WireWall deployment. The onshore direction in the mid-bay is at an angle of 146° , highlighted in red with a dashed line. Directional roses (made with code from Pereira [29]) show: (a) zero moment wave height, H_{m0} , (m) measured at the wave buoy; (b) wave energy period, T_e , (s) measured at the wave buoy; (c) wave steepness, S_s , measured at the wave buoy; (d) wave power, P , (kW/m) measured at the wave buoy; (e) wind speed, U , (m/s) measured at the harbour; and (f) the sea wall structure and upper beach level variation during the deployment (m ODN), measured by the BScan, with the 4-month mean (total) water level and range in high (total) water levels measured by the Newlyn tide gauge.

The coastal metocean data are used to describe the spectrum of conditions during the winter at Penzance. The study site is characterised by a unidirectional wave climate (Figure 2a–d) due to headland sheltering. There is likely to be a slight discrepancy in the (refracted) wave directions (more southerly/south-westerly directions) impacting the sea wall at the WireWall locations compared with those recorded by the wave buoy due to the positioning of the nearshore buoy to the east of the sea wall (WireWall sites). The waves propagate into the bay from the south, with a SSW dominance at the buoy. The prevailing nearshore wave direction closely aligns with the wind direction (Figure 2e), which is often oblique from the SW. The beach fronting the sea wall is often higher than the winter mean water level (Figure 2f). Mean high water spring tide at the (Newlyn) tide gauge is 2.49 m ODN. BScan recorded the mean upper beach levels close to the structure toe (over ~ 0.5 m from the structure) during the 4 months to vary between 1.85 m ODN and 2.86 m ODN at the Middle location (Figure 2f). The beach levels at the structure toe vary from 2.45 m

ODN to 2.92 m ODN. The BScan data suggest that the (October) beach profile applied in the operational OWWL system may often be lower than the levels observed during the study period.

2.4. Relating Metocean Data to Overtopping

In Section 3, histograms will be used to show the frequency distribution of overtopping relative to the coastal conditions and tidal cycle. The timestamp of the individual wave overtopping events is compared with the time of predicted high tide (Section 3.2). All individual wave overtopping events are included within the histograms, which are limited to the 6 h measurement window centred on predicted high tide. The timestamps of the individual wave overtopping events are also compared with the metocean/BScan data to identify the coastal condition ranges associated with overtopping (Section 3.3). If an overtopping event occurs during the metocean data recording interval or during the two high tides following a BScan, that metocean data record is flagged to be associated with wave overtopping at either the Middle and/or Southwest WireWall locations. The metocean monitoring provides a near-continuous winter record of coastal conditions, but any gaps in the metocean data also impact the overtopping data as the latter cannot be related to the metocean forcing. For metocean data outside the 6 h WireWall monitoring period, there will be no overtopping information recorded. Occasionally, for higher energy wave or onshore wind conditions, wave overtopping was suspected to have started before or continued after the time the WireWalls turned on/off. However, the number of waves overtopping is likely to be low during the lower tidal elevations. For the BScan data, each record may be flagged as associated with overtopping once or twice if overtopping was observed on the first and/or second high tide measurement window following the low tide scan.

3. Results

3.1. Event Summary and Comparison with the OWWL System

During the 4 months, some level of overtopping of the sea wall crest was recorded for 35% and 7% of the high tides at the Middle and Southwest locations, respectively (Figure 3a). The Southwest location required higher waves and water levels than the Middle location for overtopping to occur. At the Middle location, 16,800 overtopping waves were recorded over 81 tides; at the Southwest location, 1190 overtopping waves were recorded over 16 tides. The wave overtopping often occurred when there was an onshore wind (Figure 3b) and due to limited spray events, which were unlikely to be predicted by OWWL. During some tides (32 and 6 tides at the Middle and Southwest locations, respectively), only a few overtopping waves (<5) were recorded, whereas during other tides, many waves overtopped (≤ 1269 and ≤ 670 waves at the Middle and Southwest locations, respectively). During the deployment, the UK experienced six named storms. Of these storms, Atlantic storm 'Barra' caused overtopping on 7th December 2021, and the extratropical cyclone 'Eunice' caused overtopping on 18th February 2022. The storm contributions to the 4-month record (number of individual waves) were 4.3% and 19.1% at the Middle and Southwest locations, respectively, during Barra, and were 0.7% and 1.8% at the Middle and Southwest locations, respectively, during Eunice. The offshore wind component during Eunice reduced wave overtopping by blowing the vertical spray seaward. The relative contribution of storms to the total number of overtopping waves was largest at the Southwest location; however, most overtopping at both sites occurred under typical and relatively modest conditions, although higher waves (>1.5 m, often coincidental with stronger winds, >10 m/s) were associated with overtopping at the Southwest location (Figure 3c). The 0.25-year return period values, defined as the storm and swell wave thresholds by the NNRCMP, for the Penzance wave buoy are $H_{m0} = 3.03$ m and $T_e = 11.80$ s.

Neither Barra nor Eunice exceeded these thresholds. At the Middle location, < 3% of the wave records associated with wave overtopping were characterised by $H_{m0} \geq 3.03$ m and all the wave records associated with overtopping were characterised by $T_e < 10$ s.

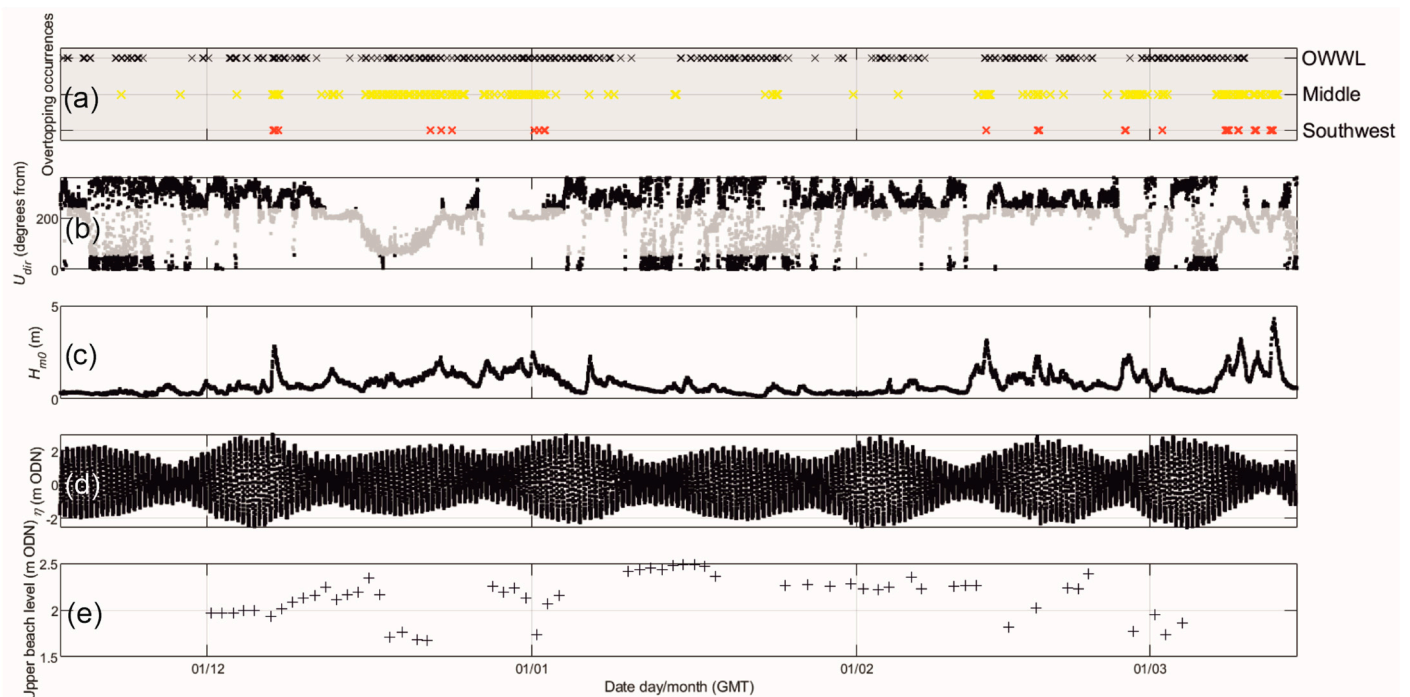


Figure 3. Time series over the winter 2021/2022 period of: (a) when wave overtopping was observed by WireWall (at Middle, yellow, and Southwest, orange, locations) and predicted by OWWL (Middle location, black); (b) the wind direction (degrees from) with grey data points representing onshore winds (56–236°); (c) the wave heights at the buoy (m); (d) the water levels at the tide gauge (m ODN); and (e) the BScan mean upper beach elevations (m ODN, at Middle).

During the study, the OWWL system predicted wave overtopping ~30 m northwest of the Middle WireWall during the 6 h high tide measurement windows for 66.1% of the 230 tides during the deployment (Figure 3a). Occasionally, operational issues prevented data from being received/sent within the coupled Met Office OWWL system. During the study, eight high tide measurement windows were missed, of which one experienced overtopping at the Middle location. Out of the 222 high tides during the deployment when OWWL ran, 51.35% were correctly predicted to experience (27.93%) or have no (23.42%) overtopping. The remaining 48.65% incorrect predictions either missed the occurrence of overtopping (8.11%) or falsely predicted the occurrence of overtopping (40.54%). Overprediction by OWWL often occurred (Figure 3a) when the winds had an offshore component (Figure 3b) or during spring tides (Figure 3d) with high (>2.2 m ODN), probably emergent, beach levels (Figure 3e), e.g., early and mid-January.

3.2. Tidal and Wave Constraints on Wave Overtopping

There is no information about the wave height at the structure toe; therefore, the nearshore wave height is used to categorise the wave conditions associated with observed overtopping over the tidal cycles (Figure 4a,b). At two locations along the sea wall crest (~345 m apart), the total number of waves overtopping during winter can vary by nearly an order of magnitude (Figure 4a,b). At both locations, more waves overtop when the nearshore wave heights exceed 1.1 m. At the Middle location, with a less protective beach, the higher the waves (i.e., >1.1 m), the longer the duration for which they can overtop within the 6 h high tide window (Figure 4a). The wave overtopping distribution (Figure 4a,b)

follows the asymmetric pattern in the water levels (Figure 4c). Higher water levels (>0.5 m ODN) enable more overtopping, and the slow drop in elevation of the falling tide allows more overtopping than on the fast-rising tide. The limited overtopping at the Southwest location (Figure 4b) is likely to be due to the more protective beach. The shift in (medium) waves between 1.1 m and 2 m in height being associated with more overtopping on the rising tide and (large) waves > 2 m being associated with more overtopping on the falling tide at both sites is likely to be related to the timing of the weather/wave conditions relative to high tide.

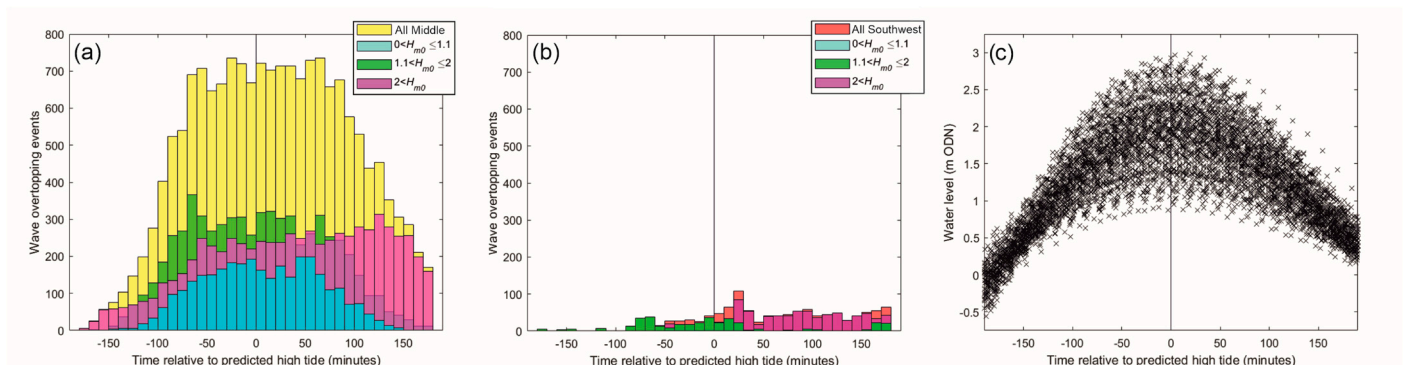


Figure 4. Histograms of ‘All’ overtopping waves during the 4 months, measured by the WireWalls for 6 h centred on predicted high tide (0 min), at the (a) Middle (yellow) and (b) Southwest (orange) locations. ‘All’ the observed data are separated into nearshore wave height categories, H_{m0} (m), using their associated wave buoy measurements. The bar transparency creates some differences in shading to that in the legend where data overlap. (c) The total water levels (m ODN) measured by the Newlyn tide gauge relative to predicted high tide (0 min) during the 4-month period.

3.3. Coastal Conditions Contributing to Wave Overtopping

Wave overtopping occurs due to the combined influence of multiple interactive coastal processes. To identify the range of coastal conditions that contribute most to wave overtopping at Penzance, the distribution of overtopping wave events across a variable’s range (e.g., wave height or water level) is compared with the distribution of the full dataset of that variable. This enables the identification of parameter values that contribute to promoting (or inhibiting) overtopping. The relevant parameters that are investigated here are wave height, period, etc. The overtopping distributions are plotted with a logarithmic y -axis to enable comparison of the distribution for the two measurement locations on the same graphs. If a histogram bar reaches the dashed black line (Figure 5), this means that every data record of that metocean parameter during the 6 h measurement window is associated with observed overtopping. If the value of a bar is less than that of the black line, this means that only a number of the data records for that metocean parameter are associated with observed overtopping. Wave overtopping occurs at the Middle location when $H_{m0} > 0.5$ m and requires larger waves, $H_{m0} > 1.4$, for wave overtopping to occur at the Southwest location (Figure 5a). Wave overtopping at both locations is solely associated with the shorter 4–9 s energy period waves, which are most common in the wave climate, and no overtopping was recorded under swell wave conditions (Figure 5b). For Penzance, wave overtopping is associated with short-crested seas. While the wave climate is unidirectional, there is a bimodal wind sea and swell wave partitioning of the wave spectrum (Figure 5c). Wave overtopping is mainly associated with large wind waves ($H_{m0} > 1.1$ m and $T_e < 9$ s, Figure 5c), i.e., relatively steep waves (Figure 5d), and can occur for waves of any power (Figure 5f). At the Southwest location, the waves that overtop are generally steeper. Overtopping occurs when the waves have an onshore component, 130 – 210° (Figure 5e), which is often the case as the waves are rarely from directions other than 140 – 200° . The Middle

location experiences overtopping from a wider range of nearshore wave directions. The Southwest location experiences wave overtopping when the nearshore waves are from the south. This suggests that the waves that are more closely aligned onshore are often smaller, due to the shorter local fetch, than those from the south.

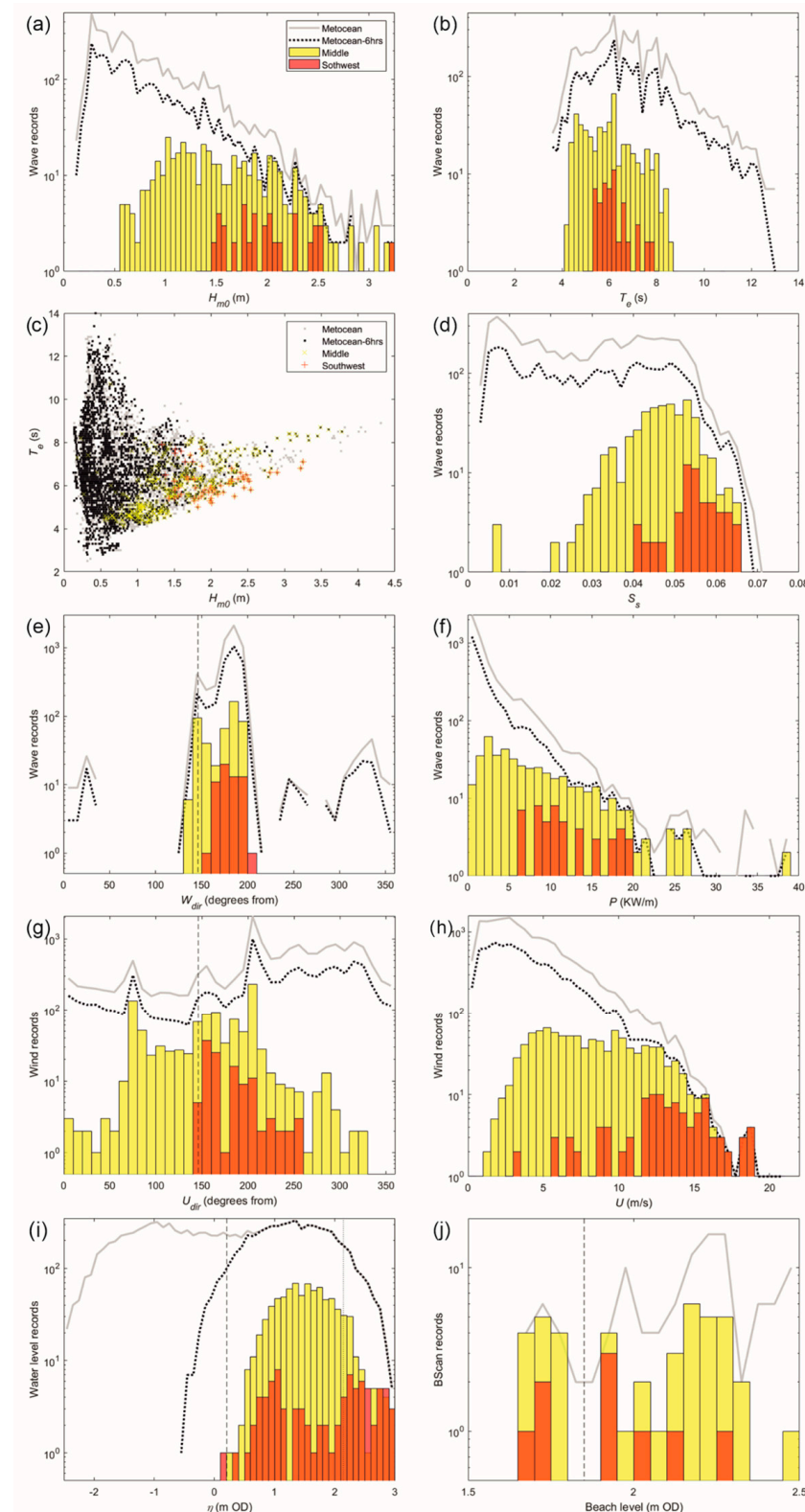


Figure 5. Logarithmic histograms showing the distribution of metocean conditions associated with observed wave overtopping at the Middle (yellow bars) and Southwest (orange bars) locations: (a) wave height, H_{m0} , (m); (b) wave energy period, T_e , (s); (c) scatter plot of the observed H_{m0} against

T_e , colour coded if wave overtopping occurs at the Middle or Southwest location; (d) wave steepness, S_s ; (e) wave direction, W_{dir} , (degrees), with the vertical dashed line indicating the shore normal direction; (f) wave power, P , (kW/m); (g) wind direction, U_{dir} , (degrees), with the vertical dashed line indicating the shore normal direction; (h) wind speed, U , (m/s); (i) water level, η , (m ODN), with the vertical dashed line indicating the mean water level over the 4-month period and the vertical dotted line representing the time mean of the upper beach level; and (j) upper beach level (m ODN), with the vertical dashed line representing the lowest high water level during the deployment. The metocean data are near-continuous for the 4 months (grey line). Only the metocean conditions during the 6 h high tide WireWall measurement windows (black dashed line) are analysed in conjunction with the WireWall overtopping observations.

The wind direction associated with wave overtopping (Figure 5g) is closely aligned with the wave direction. The winds associated with overtopping at the Southwest location are more southerly. In the exposed Middle location, overtopping occurs for most wind speeds (Figure 5h) and is mainly associated with the common mid-range (3.5 m/s to 13 m/s) wind speeds. In the Southwest, the winds need to be stronger (often >11.5 m/s) for overtopping to occur.

Waves can overtop when the water level is above the mean water level for the 4-month period (Figure 5i). Wave overtopping can occur for most beach levels (Figure 5j), even when the upper beach is likely to be dry (emergent), i.e., when the beach level is higher than the tide level (Figure 5i,j). At the Middle location, the number of waves overtopping follows the water level distribution. At the Southwest location, the beach has a greater influence, and the number of waves overtopping does not correlate with the likelihood of a certain tidal level (neap, mean or spring) occurring. At this location, the coincidental wave conditions seem to be more important than at the Middle location in overcoming the protection of the larger beach.

3.4. Beach Influence

The beach levels (Figure 3e) were highest (>2.4 m ODN) when the waves were low (<1.2 m, Figure 3c) or during neap tides (Figure 3d). BScan data during 59 low tide scans are associated with metocean and wave overtopping conditions (Figure 6) during the two-following high tide measurement windows (118 tides). Each BScan represents the first low tide beach level of the day. Conditions during both 6 h high tide windows that follow the scan are associated with the recorded upper beach level. The conditions analysed represent the maximum water level during the 6 h high tide window at the tide gauge, the mean nearshore wave height during the 6 h high tide window at the buoy, and a flag to indicate if overtopping occurred during the 6 h high tide window at the Middle location.

During the winter, the maximum water levels (Figure 6a) were up to 1 m above the mean upper beach profile (averaged across 0.5 m to 3.5 m distance offshore from the toe). At the Middle location, the beach can be emergent, i.e., above the still water level ('dry beach'), when overtopping occurs (Figure 6a, data below the diagonal). Overtopping in this case occurs at some point during the high tide by wave run-up impacting the sea wall. The data, when at least five waves overtop during the high tide measurement window at the Middle location, are isolated (Figure 6b) and separated into emergent and non-emergent beach categories (depending on where the data fall in Figure 6a). When the beach is emergent (dry), overtopping can be associated with low (<1.2 m) mean wave conditions during the high tide measurement window (Figure 6b).

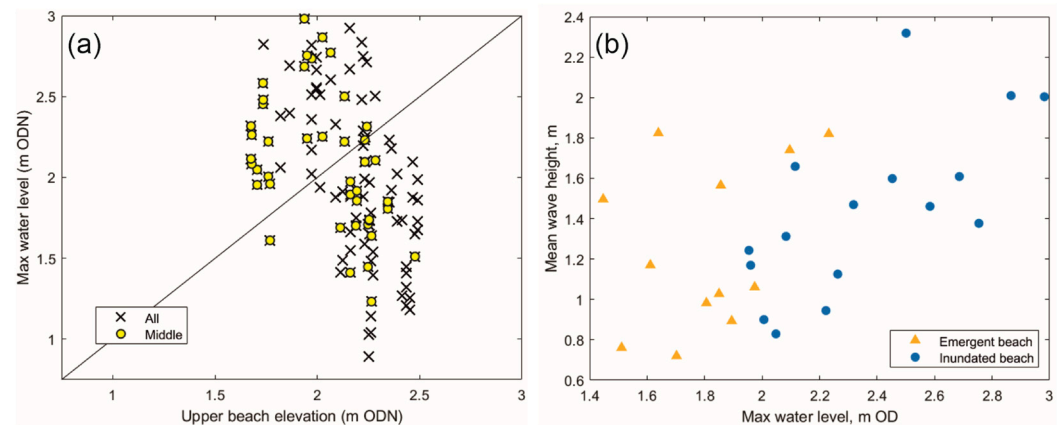


Figure 6. (a) Conditions during the two high tides following each BScan (All, 118 tides) and associated with wave overtopping at the Middle WireWall location (yellow, 44 tides). The diagonal line is the threshold to classify data as an emergent or inundated beach during the 6 h high tide window. (b) Conditions during tides associated with wave overtopping at the Middle WireWall location that have at least five overtopping waves (28 tides): mean wave height, H_{m0} , (m), during the 6 h high tide window and maximum water level (m ODN).

4. Discussion

4.1. Hazard Prediction

Often for larger coastal works, observations of wave overtopping discharge, obtained via physical modelling, are used to calibrate/validate predictive capability. However, this has its own limitations, such as scaling issues and simplification of the complex environment with regard to the wave climate, tidal cycles and bathymetric variation. Ideally, field observations of wave overtopping discharge are required to develop and/or calibrate/validate predictive capability. However, while the WireWall approach is in development, the wave overtopping information in this study is limited to the number of overtopping waves [30]. This is due to uncertainty in the depth measurement of the overtopping waves and, more critically, the inability to measure the horizontal velocity component during large overtopping events due to the spacing between the wire pairs within the WireWall system (which was approximately 40 cm).

Field data on the ranges of coastal conditions associated with overtopping still add value by identifying the local (more typical) conditions to consider in coastal design works and by enabling assessment of operational services. When missed or false alerts occur, conditions can be assessed to identify where additional parameters need to be considered within the approach. The static nature of the beach profile applied for a winter season contributes to over-prediction in this study because the implemented profile is relatively low (Figure 1c, Middle) and will influence the wave breaking/shoaling dynamics and water depths at the structure toe. Sensitivity in the overtopping discharge to beach level has previously been found [21] to potentially modify a forecast hazard category, which is important for hazard management. The greater uncertainty in numerical predictions for less extreme but frequent “nuisance” conditions [19] is likely to increase the sensitivity in hazard ratings for low energy/intensity events, especially where an emergent foreshore has the potential to reduce the wave impact on the structure.

The complex rock-sand foreshore along the sea wall frontage (Figure 1b) noticeably impacts the overtopping exposure (Figure 4). Such a coastline is common for many ocean-exposed shorelines, illustrating the need for high spatial resolution (<350 m here) or alongshore uncertainty information in numerical hazard assessment and alerting tools for beach-fronted structures. Prediction systems can often be established for more vulnerable

locations (e.g., the Middle location), making them less accurate for nearby locations along the same frontage.

4.2. Potential Future Change

To support adaptive coastal management strategies, research into how sea-level rise and beach lowering could change the occurrence of wave overtopping during the tidal cycle, rather than only the overtopping discharge, is needed. The tide-related distribution for wave overtopping (Figure 4a) for this emergent beach-fronted sea wall suggests that higher water elevations (>0.5 m ODN), which reduce depth-limited breaking, will increase both the number of waves overtopping and the duration of overtopping for all nearshore wave height categories.

At this location, wave overtopping is predominantly by the run-up of broken waves or waves breaking on the emergent/shallow foreshore fronting the structure toe¹. It is hypothesised that rising sea levels, which reduce structure freeboard and depth-limited breaking, at emergent beach-fronted structures (i.e., where wave breaking on the foreshore occurs prior to impact with the vertical structure) will increase the number of waves overtopping during a tidal cycle and the number of tides for which wave overtopping can occur. Beach lowering will further increase water depths, but not reduce the freeboard, and may trigger a change in dynamics from a wave breaking regime (at least for smaller waves) to a wave reflecting regime at high water levels. This regime shift could complicate the wave overtopping distribution in future, as illustrated for Dawlish—a beach-fronted vertical structure where the foreshore has minimal influence at high tide and wave overtopping is often caused by waves breaking directly onto the structure [30].

Due to the headland constraints in embayed locations such as Penzance (with a unidirectional wave climate), the impacts of future changes in the wind/wave climate on the overtopping dynamics are likely to be associated with changes in frequency due to the constraints on fetch. The field observations presented illustrate that it is critical for the impact of wind-wave and non-extreme wave conditions, which can be associated with overtopping more often than storms and/or swell at many coastal locations, to be considered in predictive tools for coastal management.

5. Conclusions

Penzance is an example of an emergent beach-fronted vertical sea wall. Headland sheltering and rock outcrops create variable beach levels within the bay, which in turn influence the shallow water wave dynamics and water depths at the structure toe. By observing winter wave overtopping at two locations, with different levels of beach protection, it was found that:

- Vertical sea walls fronted by an emergent (protective) beach can be vulnerable to overtopping by non-storm conditions, even by low waves. Empirical rules to predict overtopping when a broken wave or wave run-up impacts a vertical sea wall are urgently required for hazard forecasting services. The spray nature of overtopping during non-storm conditions requires predictive tools that account for wind influence on overtopping spray.
- Accurate wave overtopping forecasts at emergent beach-fronted sea walls require intra-seasonal variability within the beach profile to be captured.
- Wave overtopping vulnerability can vary substantially within hundreds of metres along a beach-fronted sea wall with varying beach protection. Overtopping thus requires appropriate spatial resolution in hazard forecasting services.
- Storms can have a low contribution to the total number of overtopping waves ($<3\%$ at the Middle location) during certain winters. Although this might not translate into

a low overtopping volume or associated impact contribution, there is still a need for reliable predictions of frequent low-intensity overtopping for coastal management purposes (e.g., public safety).

- Wave overtopping by short-crested wind waves requires more attention to support hazard prediction at locations where the swell wave contribution is small.
- Beach-fronted structures, where the foreshore influences wave breaking, are likely to have a wave overtopping response that follows the trend in sea-level rise, until beach lowering exacerbates the increase in water depth to a point that enables the waves to no longer break and instead reflect. Both future sea-level and beach-level scenarios should be considered in coastal scheme design.

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Note

- ¹ Penzance Wave Conditions, <https://www.youtube.com/watch?v=VLBf7HaJP2I> (accessed on 13 August 2026).

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