DYNAMIC COASTAL PROTECTION: RESILIENCE OF DYNAMIC REVETMENTS (DYNAREV)

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A large-scale laboratory experiment was completed to investigate the performance of a dynamic cobble berm revetment designed to provide sustainable coastal protection under wave attack and a rising water level. The experiment demonstrated the inherent stability of the dynamic revetment, which was observed to be reshaped by every wave but retained its overall shape throughout the experiment with almost no loss of material. By comparing with a sand beach case, it was found that the revetment reduced shoreline retreat during an erosive wave condition and reduced runup excursions, thus eliminating erosion landward of the revetment. Overall the experiment provided significant new understanding of dynamic revetments and demonstrated the potential for dynamic revetments to provide low cost, robust coastal protection.

1. INTRODUCTION

A recent study by Luijendijk *et al*. (2018) found that 24% of the world's beaches are eroding at rates exceeding 0.5 m/yr. The coastal zone has become heavily populated and developed, and in many countries is of key economic importance. Indeed, fifteen of the world's 20 megacities are located on the coast and, as such, ensuring the sustainability of coastal populations and infrastructure is of critical importance and will become ever more challenging and expensive as sea levels rise and wave conditions change due to the changing climate.

The typical coastal management approach in sensitive or developed areas is to hold the line, and coastal managers have two fundamental options to achieve this:

1. Hard structures (e.g. rock seawalls) which aim to reduce erosive wave energy, compartmentalise beach sediment or provide a barrier at the back of the beach to protect the land from inundation. As sea levels rise most such structures will need to be upgraded in order to maintain their level of protection.
2. "Soft engineering", typically beach nourishment, which aims to maintain the health of the sand buffer by artificially increasing the volume of the beach and/or dunes. This is a commonly used approach to maintain the sand buffer, particularly in areas of high recreational value where there is a desire to retain the natural character of the beach. Realistically, in many areas, the additional volumes of sand required to stabilise the shoreline as sea levels rise is likely to become unsustainable.

While hard engineering protection may well be required in highly developed areas where the economic and social implications of failure are disastrous, in some areas a lower level of protection may be acceptable. A relatively recent and little tested shore protection method is the use of what have been variously termed "dynamic revetments", "cobble berms" or "rubble beaches". This approach involves the construction of a gravel or shingle ridge around the extreme wave runup limit. These structures aim to mimic composite beaches which consist of a lower foreshore of sand and a backshore ridge constructed of gravel or cobbles which stabilises the upper beach and provides overtopping protection to the hinterland. They contrast with static coastal defence structures as they are “dynamic” and are expected to reshape significantly under wave attack.

It is recognised that gravel beaches exhibit a remarkable degree of stability (e.g. Powell, 1988). As a result, the idea to use artificially constructed gravel barriers to provide shore protection can be traced to the 1970’s when an artificial gravel beach was constructed along the entrance to Rotterdam Harbour. Since then, dynamic revetments have been installed in a small number of locations including Cape Lookout State Park, Oregon (Allan & Komar, 2002), Columbia River South Jetty, Oregon (Allan & Gabel, 2016) and North Cove, Washington. While very little information is available about dynamic revetments and composite beaches, the overall conclusion from these installations is that dynamic revetments perform well in terms of limiting wave runup, overtopping and erosion of the hinterland, continuing to provide robust coastal protection through high energy conditions. The major consideration for such structures is the loss of material alongshore and as such, just as with conventional beach nourishment, maintenance work should be expected on a multi-annual basis to maintain levels of protection.

Dynamic revetments potentially have a number of advantages over other forms of coastal protection. It is known that the berm crest of a gravel beach is generally formed just below the maximum level of wave runup (Bradbury and Powell, 1992) and studies have suggested that during severe storms material can be pushed up to or beyond the crest by extreme runup events, causing the berm to gain elevation and roll landwards (Carter and Orford, 1984). Dynamic revetments are expected to respond in a similar way, meaning that overtopping protection would actually improve during storm events as long as the crest is not breached and remains continuous. This process may also mean that the structure adapts to a rising sea level by increasing its crest height and rolling slowly landward, similar to gravel barriers. In addition to the potential adaptive nature of the structure, dynamic revetments are a relatively sustainable approach to coastal defence, suitable for community construction and use in developing nations as they require no foundation preparation, can be constructed through random placement of materials without the need for expensive plant, can make use of inexpensive, low grade, poorly sorted material, and are likely to provide a suitable habitat for beach invertebrates.

2. METHODOLOGY

The DynaRev experiment was designed to investigate the resilience of a dynamic cobble berm revetment structure to wave attack and a rising water level. The experiment took place over a 2-month period from August to September 2017 in the Large Wave Flume (Großer Wellenkanal, GWK), Hannover, Germany. The GWK flume is 309 m long, 7 m deep and 5 m wide with a combined piston-flap type wavemaker. A schematic of the experimental setup is shown in Figure 1. All coordinates are given as the distance from the wave paddle rest position (x = 0 m), elevation above the horizontal flume bed (z = 0 m) and across-flume distance from the centreline (y = 0 m).

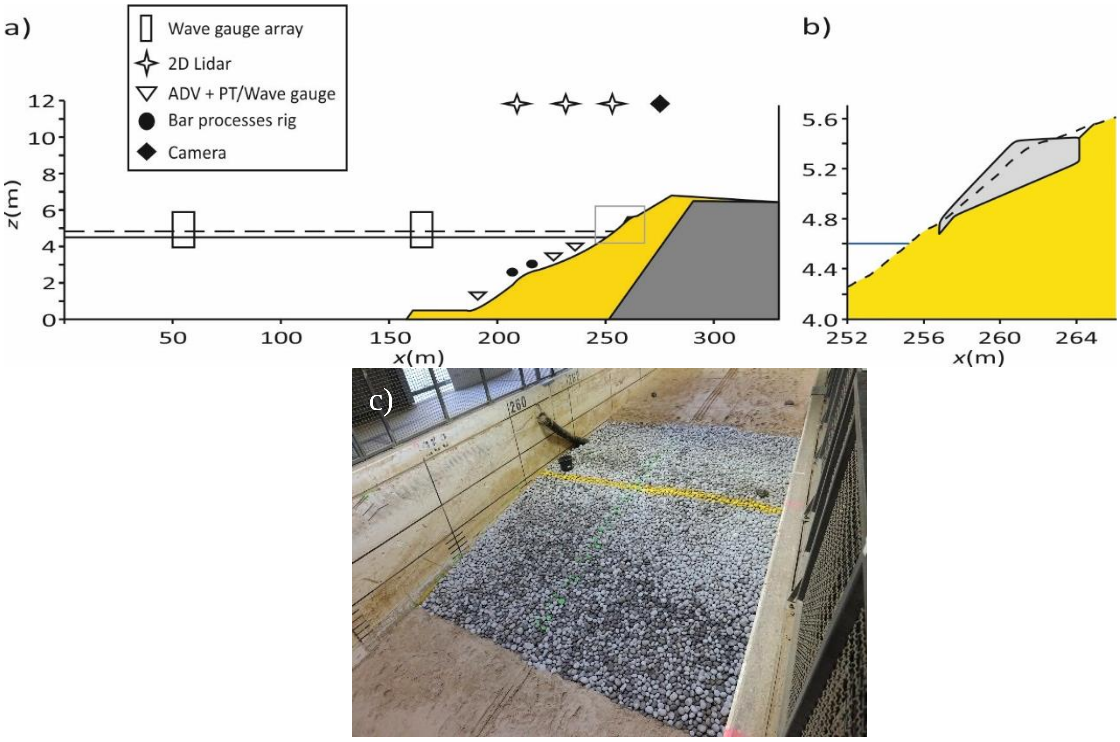

Figure 1. a) Schematic of flume setup showing primary locations (see Table 1). The yellow shaded area represents the sand volume and the dark grey shaded area is the permanent 1:6 impermeable slope. The black solid and dashed horizontal lines indicate the minimum (h = 4.5 m) and maximum (h = 4.9 m) water levels. b) Close up of the dynamic revetment geometry after construction prior to DR1, corresponding to the grey box in (a). The light grey region indicates the dynamic revetment and the dashed line shows the beach profile prior to revetment construction. c) Photograph of the constructed dynamic revetment. The yellow line indicates the line of the front of the crest at x = 260.7 m.

A total of 141.6 hours of testing was completed, divided into two "phases" as detailed below, with each phase being split into a series of "runs" (133 in total across both phases) varying from 20 minutes to 3 hours in duration. The full details of the test program are given in Table 1.

Phase SB - Unmodified sand beach response to a rising water level: Starting with a 1:15 plane slope, the evolution of the beach profile was measured under constant wave forcing (H_s = 0.8 m, T_p = 6.0 s). The mean water level in the flume was then raised by a total of 0.4 m in steps of 0.1 m. Following the completion of the water level rise increments, the short-term response of the beach was measured for a range different wave conditions expected to produce both erosion and accretion. Run names for this phase are given as SB<WL increment>_<Run No.>, where water level (WL) increments are numbered 0 for the initial water level of h = 4.5 m to 4 for h = 4.9 m and run numbering is started from 1 for each WL increment.

Phase DR - Dynamic revetment response to a rising water level: Again starting with a plane slope, a sand beach was measured as it evolved under the same constant wave conditions as used in Phase SB for 20 hours to provide a natural beach profile on which to construct the dynamic revetment. The cobble revetment was installed at the location of the sand beach berm prior to the first water level increment. The revetment was constructed using granite cobbles (D_{50} = 66 mm), had a 1:6.3 front slope and its crest height at the elevation of the $R_{5\%}$ runup level (z = 5.42 m) for the second water level increment to ensure significant overtopping as the water level increased. The sand foreshore and dynamic revetment were then reshaped under constant wave conditions over the remaining water level increments with the test durations at each water level mirroring those in Phase SB. Finally, higher energy storm waves were used at the end of the final water level increment to investigate revetment resilience to higher energy conditions. Run names for this phase are given as DR<WL increment>_<Run No.>. Note that the revetment was constructed prior to the start of DR1.

Table 1. Overview of the test program.

WL increment/Test	Duration (hr)	H_s (m)	T_p (s)	Water level *h* (m)	Number of Runs	Run Durations (minutes)
Phase SB - Morphological response of a sandy beach with a rising water level						
SB0	20	0.8	6	4.5	14	20,20,20,30,30,60,60,60,120,120,120,180,180, 180
SB1	7	0.8	6	4.6	9	20,20,20,30,30,60,60,60,60,60
SB2	7	0.8	6	4.7	7	20,40,60,60,60,60,120
SB3	7	0.8	6	4.8	7	20,40,60,60,60,60,120
SB4	17	0.8	6	4.9	11	20,40,60,60,60,60,120,120,120,180,180
Phase SB – Resilience testing at the maximum water level *h* = 4.9 m						
SBE1	2	1	7	4.9	3	20,40,60
SBE2	4	1.2	8	4.9	5	20,40,60,60,60
SBA1	6	0.6	12	4.9	7	20,40,60,60,60,60,60
Phase DR – Morphological response of a sandy beach with a dynamic revetment to a rising water level						
DR0	20	0.8	6	4.5	14	20,20,20,30,30,60,60,60,120,120,120,180,180, 180
Dynamic revetment installation						
DR1	7	0.8	6	4.6	9	20,20,20,30,30,60,60,60,120
DR2	7	0.8	6	4.7	7	20,40,60,60,60,60,120
DR3	7	0.8	6	4.8	7	20,40,60,60,60,60,120
DR4	17	0.8	6	4.9	11	20,40,60,60,60,60,120,120,120,180,180
Phase DR – Resilience testing at the maximum water level *h* = 4.9 m						
DRE1	2	0.9	6	4.9	3	20,40,60
DRE2	2	1	7	4.9	4	20,20,20,60
DRE3	1	1	8	4.9	3	20,20,20
DRA1	2	0.8	6	4.9	2	60,60
Phase DR – Resilience testing with recharged revetment at the maximum water level *h* = 4.9 m						
DRN1	2	0.8	6	4.9	2	60,60
DRN2	0.66	1.0	8	4.9	2	20,20
DRN3	2	0.8	6	4.9	2	60,60
DRN4	0.66	1.0	9	4.9	2	20,20
DRN5	0.33	1.2	8	4.9	1	20
DRN6	1	0.8	6	4.9	1	60

A large suite of instruments was deployed during the experiment to measure waves, morphology, sediment transport and hydrodynamics (see Figure 1). All instruments were logged to PCs connected to a local area network with a shared time-server to ensure time-synchronisation.

Wave measurements in the horizontal bed section of the flume were obtained using 2 x four wave gauge arrays. High resolution wave data through the surf and swash zones (see Figure 2) was obtained using an array of three roof-mounted (z = 11.8 m) SICK LMS511 2D Lidars (see Martins *et al*., 2017). Additional runup data was obtained using a video camera mounted at z = 11.8 m above the subaerial beach.

Complete beach profile data was obtained intermittently between wave runs using a mechanical profiler. This was complimented by the Lidar array which was able to capture the subaerial beach profile continuously throughout the experiment by separating the stable “bed” from the “swash” using the variance-based method of Almeida *et al.* (2015) as the beach was inundated and exposed in the swash zone.

Hydrodynamics, sediment transport and morphological change during bar formation and migration were measured by two measurement rigs at x = 226.5 and 233.5 m on either side of the predicted sand bar location. Each rig was equipped with a suite of instruments sampled at 25 Hz including 2 optical backscatter sensors (OBS) mounted at 5 and 10 cm from the bed, an acoustic backscatter sensor (ABS), 65 cm above the bed, two electromagnetic current meters at elevations of 5 and 10 cm above the bed, a Nortek Vectrino profiling ADV (Vectrino) mounted 6 cm above the bed and a pressure transducer (PT) mounted 45 cm above the bed. Finally, a ripple profile scanner (RPS) was mounted 75 cm above the bed to obtain local bed profile measurements. The RPS on each rig was sampled alternately for one minute to avoid cross-talk between instruments.

In addition to the rigs, a 3D sector scanning sonar (SSS) which provided measurements of the local bathymetry in a 1 to 2-m diameter circular region centred on the instrument which was located at *x* = 228.8 m. Two Nortek ADVs were located at *x* = 235 and 240 m and maintained at a height 150 mm above the bed.

The movement of individual cobbles within the dynamic revetment was monitored using an RFID tracking system similar to that used by Allan *et al*. (2006). A total of 97 cobbles were fitted with transponders and placed along the centreline of the revetment at the sand interface (20 cobbles), mid depth (30 cobbles) and top layer (47 cobbles). The cobble locations were detected before each water level increment using a radio-based detection system.

Finally, a multibeam echo-sounder was installed to obtain measurements of the bubble clouds generated by wave breaking. These measurements are described in Bryan *et al*. (2019).

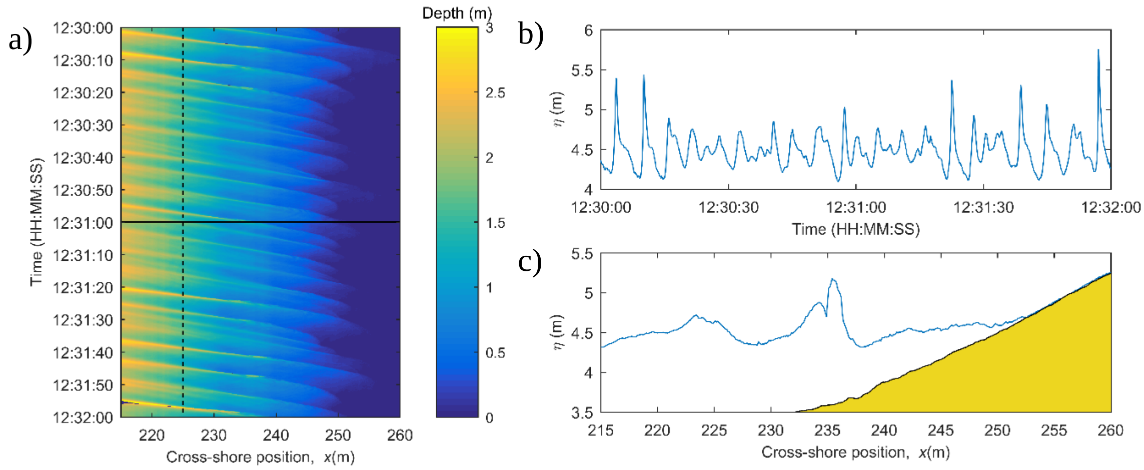

Figure 2. Example wave measurements. a) Timestack of water depth measured by the Lidar throughout the surf and swash zones. b) Timeseries of water surface elevation at x = 225 m as indicated by the vertical dashed line in panel a. c) Measured free- surface profile through the surf and swash zone at the time indicated by the horizontal solid line in a. Note that the measurements capture the splash-up generated by a breaking wave at x = 235.5 m.

3. RESULTS

When installed for coastal protection, dynamic revetments are built above the typical wave runup limit to provide runup and overtopping protection during storms when water levels are super-elevated for an hour or two around high tide. By installing the revetment at the level of the natural berm and undertaking testing over tens of hours using a series of water level increments, it was possible to effectively carry out accelerated testing of the revetment performance at a series of raised water levels. This gives insight into how the revetment responds to a series of high energy events and also provides information about the rollover behaviour of the revetment as sea levels rise.

Figure 3 shows a series of profiles comparing the response of the beach with and without the revetment. It is clear that the evolution of the sandy part of the beach in Phase DR is similar to that for Phase SB. The offshore bar forms at the same location and grows to approximately the same height over the course of the water level increments. During this process, the defined trough and inner bar evident landward of the bar at the start of the first water level increment (SB1, DR1) are smoothed out and becomes less pronounced. Between the shoreline and the sandbar, sand ripples with a wavelength greater than a metre are evident in all profiles. In Phase SB, the bed elevation in this region rises by approximately 0.25 m as the water level increases by 0.4 m. This is not the case for the Phase DR testing and the bed elevation between the revetment toe and the bar remains at approximately the same elevation.

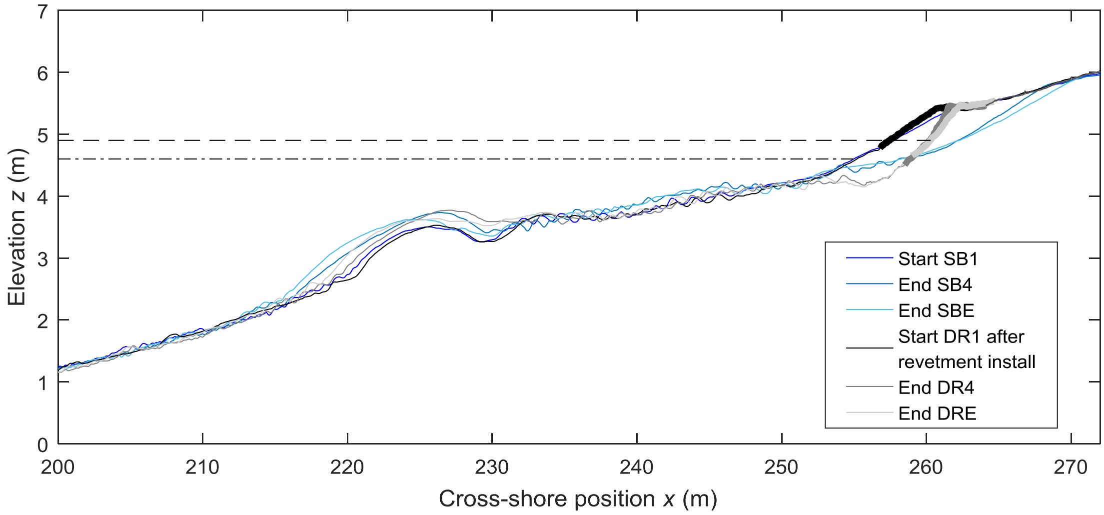

Figure 3. Beach profiles comparing beach response with and without the dynamic revetment. The revetment extent is shown by the thicker line. Phase DR runs are shown in greyscale while Phase SB runs are in blue colours. The dot-dash and dashed horizontal lines show the minimum (SB0, DR0) and maximum water levels (SB4, DR4) respectively.

Significant erosion of the sand beachface is observed during the Phase SB testing. The shoreline retreated (due to both water level rise and sand loss) by 7.5 m over the course of the water level increments and resilience testing, and erosion was observed up to x = 270 m. The presence of the revetment slowed this retreat considerably, with the shoreline retreating by approximately 5 m. Over the course of the water level increment testing, the toe of the revetment retreated by approximately 1.5 m and lowered by 0.3 m due primarily to a loss of sand from beneath the revetment and in front of the toe. This led to an overall steepening of the revetment from 1:6.3 to 1:3.5. The majority of this steepening occurred during DR4 when the percentage of waves overtopping the crest measured using the Lidar was around 50%. By comparison, the crest position was relatively stable throughout the testing. The front of the crest retreated by approximately 0.9 m, and the elevation increased by 0.07 m. Further gains in crest elevation were expected due to the rollover process which was observed throughout the testing; however it was observed that the rollover was approximately balanced by the rate of sand loss from beneath the revetment. As the experiment progressed, the rate of sand loss decreased as the revetment found a more stable configuration with the wave conditions, and crest elevation increase due to rollover became evident. Although the crest of the cobble structure was overtopped completely by multiple waves, the horizontal runup extent was greatly reduced when compared to the SB cases and no beach change is observable in the profile measurements landward of the back of the revetment crest at x = 265 m; thus, the revetment provided good erosion protection to the hinterland behind the structure.

A feature of the revetment performance was the loss of sand from beneath the structure. This is an inevitable consequence of constructing without a filter layer and is clearly a consideration when installing these structures for the purpose of coastal protection. Estimates of the sand beach elevation underlying the revetment through the experiment suggest that it forms a similar profile to the Phase SB case, and would be expected to approach a quasi-stable equilibrium shape in time. Support for this hypothesis comes from sediment balance calculations which showed that the rate of sand loss was reducing with time throughout Phase DR, and observations of natural composite beaches which are known to be highly stable and show no evidence of episodic or continuous sand loss from beneath the cobble ridge. This is further supported by observations from a trial revetment structure at North Cove, Washington, where there was evidence that the sandy beach underlying and seaward of the revetment accumulated sand over time due to Aeolian processes and the armouring effect of the placed coarse material (P. Bayle pers comm.). It is thought that the rates of sand loss during the DynaRev experiment were enhanced due to the fact that the underlying sand profile had to be artificially modified to allow the full revetment volume to be placed at the correct location. This meant that the sand profile underlying the revetment was far from equilibrium and thus prone to rapid change. Despite the observed sand loss in the revetment case, the underlying sand profile was found to retreat at a lower rate during Phase DR than Phase SB as shown in Figure 4.

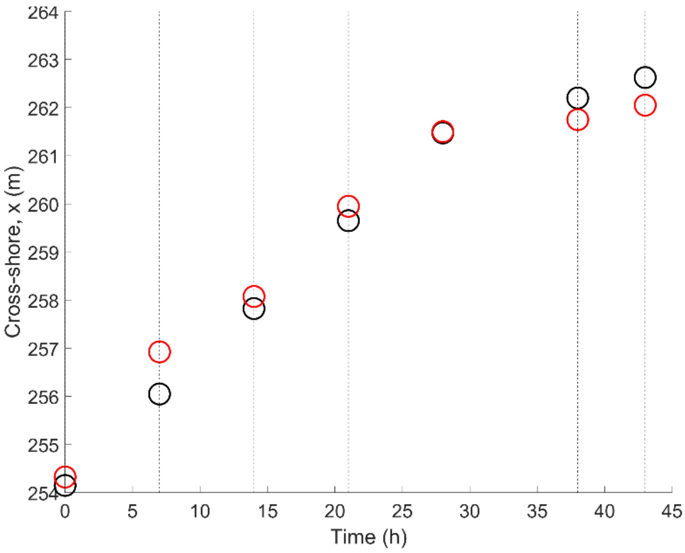

Figure 4. Shoreline position for Phase SB (black circles) and Phase DR (red circles) from the start of water level increment 1 (SB1, DR1). The vertical dashed lines indicate the times at which the water level was increased by 0.1 m and the start of erosive test (38 hours) and the start of recovery test (43 hours). Note that due to the need to artificially modify the underlying beach profile to enable placement of the full revetment volume, the initial sand beach shoreline in the Phase DR case is landward of that for Phase SB, however by the end of the testing it is approximately 1 m seaward.

Throughout all of the Phase DR testing it was evident that the revetment structure was dynamically stable and remained as a coherent structure with a defined toe through all test cases. Other than a few stones in a thin layer extending a few metres landward of the defined revetment toe, no material was lost from the structure throughout the testing, with at least 90% of the total volume of cobbles remaining within the body of the revetment at all times. It was noted that large individual waves could cause significant change to the shape of the revetment, particularly those that completely overtopped the structure. However, within a small number of subsequent waves, the majority of the change had been cancelled out. This observation of large gross change caused by sustained wave action, but minimal net change has also been observed on sand and gravel beaches (Blenkinsopp *et al*., 2011; Masselink *et al.,* 2010).

The evolution of the revetment during the water level increment testing is shown in more detail in Figure 5. The figure demonstrates that the revetment retreats throughout the testing, with the maximum rate of retreat occurring during DR3 when the revetment starts to be overtopped (approximately 8% of waves overtop during DR3). This retreat is caused by loss of sand from beneath the revetment and the overall steepening of the front slope. It is evident that the revetment becomes steeper over time as the toe moves landward and lowers while the crest position only retreats slightly. Careful examination of the profiles indicates that the steepening occurs over the part of the revetment face being influenced by swash motion. During DR1, swash only occurs on the lower part of the revetment and leads to a change in slope at approximately x = 258.5 m with the lower part of the slope having a gradient of 1:4, while the upper part of the slope is 1:6.3. As the water level rises and the runup limit moves landward, the position of the slope change moves up and landward, leading to a greater proportion of the revetment front slope becoming steeper.

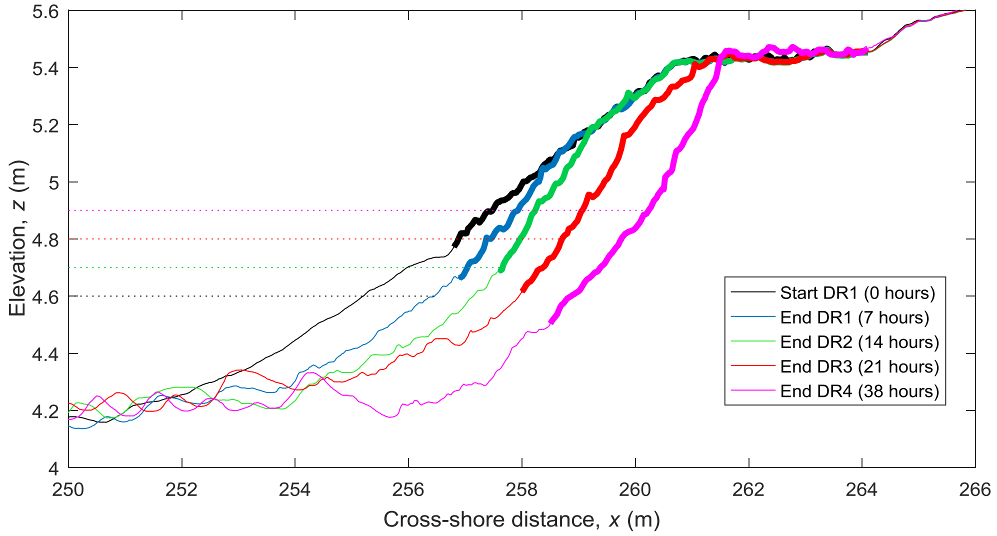

Figure 5. Revetment profiles at the end of each water level increment during Phase DR. The revetment extent is shown by the thicker line. Note that the duration of testing for DR1, 2 and 3 is 7 hours, while the duration of DR4 is 17 hours.

The steepening observed during the Phase DR testing leads to a change in reflection characteristics of the beach. Figure 6a shows the reflection coefficient measured by the wave gauge arrays as a function of time for both Phase SB and DR, starting from the beginning of SB0/DR0. Because Phase SB0 and DR0 both start from a planar sandy beach and use an identical wave time series, the reflection coefficient increases in a similar manner as sediment is transported from the beachface to the bar leading to a steepening of the bar and beachface. After construction of the dynamic revetment (20 hours in Figure 6), the reflection behaviour of the beaches diverges. For Phase DR, the value of K_r gradually increases as the slope of the revetment front face increases. Conversely, during Phase SB the reflection coefficient gradually decreases as the profile (separation between bar crest and shoreline) lengthens and mean surf/swash zone slope decreases with increasing water level. Figure 6b presents the reflection coefficient as a function of the deepwater Irribarren number for both phases. There is a clear relationship between Irribarren number and K_r as suggested by Battjes (1974), and the results for both phases demonstrate similar behaviour despite the complex nature of the beach profiles and the large differences in swash zone slope.

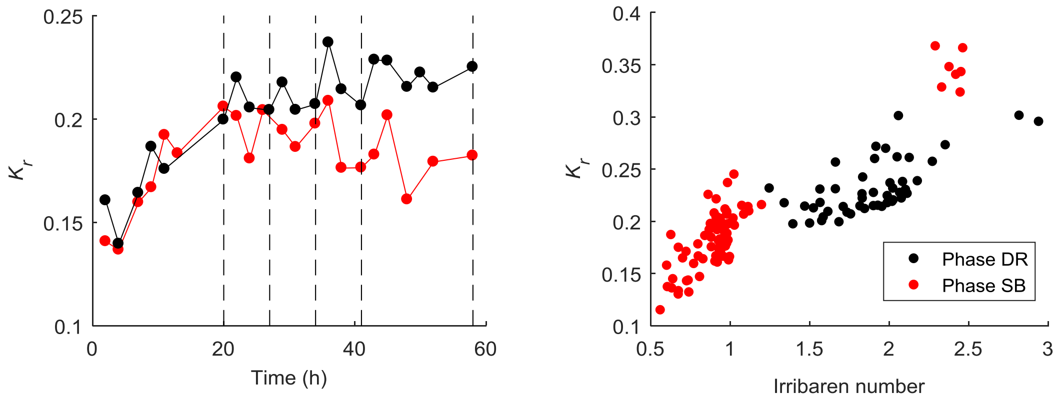

Figure 6. a) Reflection coefficient calculated every 2 hours as a function of time during Phases SB (red) and DR (black). The time axis starts at the beginning of SB0/DR0 unlike Figure 4 in which zero hours represents the time of revetment construction. b) Reflection coefficient for every run as a function of deepwater Irribarren number.

The results from the RFID cobble tracking give additional insight into the behaviour of the dynamic revetment during testing. Figure 7 presents the movement of the 97 instrumented cobbles throughout tests DR1 to DRR (Table 1). The main conclusion from this analysis is that the vast majority of the detected cobbles remain within the main body of the revetment, and only 4 of the 97 instrumented cobbles move seaward of the original revetment toe (x = 256.8 m). Of the remaining cobbles the majority finish landward of their original position and landward movements outnumber seaward movements by approximately 2 to 1. It is evident that the number of landward movements increases significantly during the first 7 hours of DR4 as the percentage of waves overtopping increases from approximately 8% during DR3 to 50% during DR4 and the rollover process becomes more obvious. As the revetment steepens and becomes narrower in cross-shore extent, it is evident that the instrumented cobbles bunch up between *x* = 260 m and *x* = 262.5 m by the end of DR4, with many of these cobbles having been transported onto the revetment crest. The majority of seaward movements occur during DR1, 2 and 3 as cobbles positioned in the upper swash zone are moved seaward by the backwash of the larger swash events, but there is insufficient energy in the uprush to move them back up the slope. The number of seaward movements decreases significantly during DR4 when the overtopping rate becomes large.

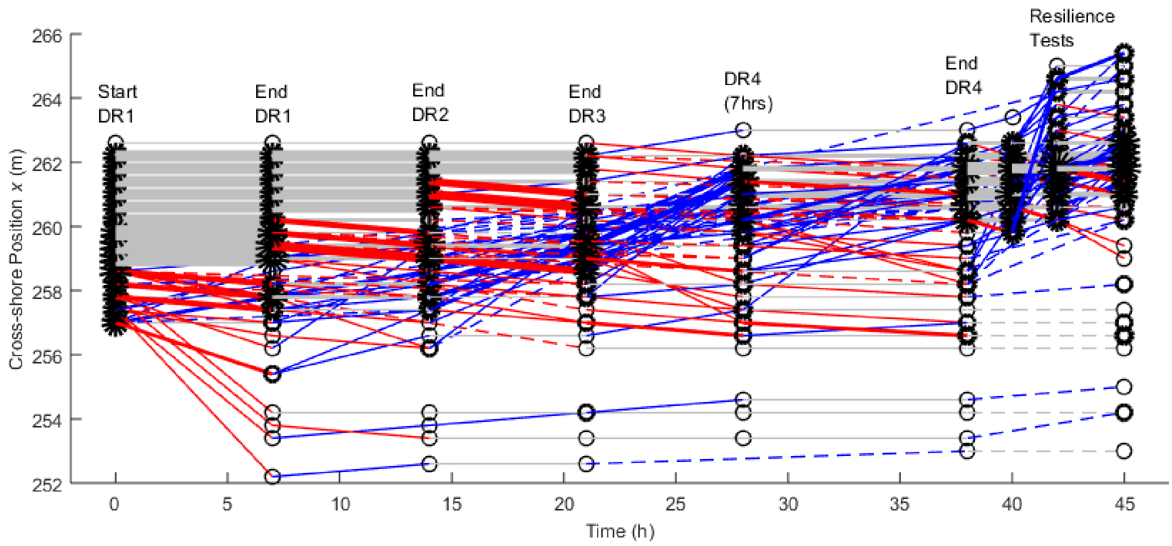

Figure 7. Cross shore position of the 97 tagged cobbles as a function of time. The position of the cobbles was measured to the nearest 0.4 m in the cross-shore direction at the end of every water level increment and after each resilience test. The black circles represent the instrumented pebbles at each 0.4 m cross-shore increment and the thickness of the circle is relative to the number of cobbles at each location. Plain red lines correspond to seaward transport. Plain blue lines correspond to landward transport. Plain grey lines correspond to no transport. The thickness of the lines is relative to the number of cobbles moving along a particular path. The dashed lines indicate that a cobble was not detected for at least one detection survey, but was found again later. The same colour and thickness principles apply for the dashed lines.

4. CONCLUSIONS

A large-scale laboratory experiment was completed to investigate the performance of a dynamic revetment designed to provide sustainable coastal protection under wave attack and a rising water level. Testing was undertaken in 2 phases, first with an unmodified sand beach and subsequently with a cobble revetment constructed around the natural berm location. Long test durations were used in an attempt to approach profile equilibrium at each water level and to investigate the revetment resilience over many hours of wave attack.

Throughout all revetment testing, the revetment remained as a coherent cobble berm structure with minimal loss of cobbles. Thus, while the individual cobbles moved with every wave, continuously reshaping the revetment as overtopping rates increased with increasing water level, the overall structure was dynamically stable and overtopping and erosion protection to the hinterland was maintained. The movement of individual cobbles during the experiment was monitored using an RFID-based cobble tracking system. This demonstrated that 95% of the tagged cobbles originally placed in the revetment remained within the structure throughout testing.

Comparison with the sand beach case demonstrated that the revetment structure led to a reduction in the rate of shoreline retreat and reduced runup excursions, thus eliminating erosion landward of the revetment. While the revetment slowed shoreline retreat compared to the sand beach case, the structure was observed to retreat continuously throughout the experiment due to a loss of sand from beneath and an overall steepening of the front face. The retreat of the revetment crest was significantly slower than the shoreline and the crest height was maintained throughout. Indeed, at the highest water level when around 50% of waves overtopped the crest, there was evidence of rollover transport leading to a small increase in crest elevation. The observations of rollover transport indicate that a sustained increase in crest height could be expected in the event of multiple large storms or a sea-level rise scenario.

The evolution of the sand beach profile was similar with and without the revetment, with the offshore bar forming in approximately the same location and growing to a similar height. In both cases, the bar crest elevation increased as the water level was increased in line with the Bruun Rule concept.

While the results of the experiment are promising, additional research will be required before dynamic revetments could be widely adopted. The loss of sand from beneath the revetment must be better understood because if the structure can only retreat, with no mechanism for the revetment to recover after a storm it may be unsustainable. Observations of composite beaches and a small number of dynamic revetments in the USA suggest that natural and artificial cobble berms are stable in the field with no evidence of continuous retreat. This suggests that once the beach/revetment system approaches an equilibrium condition, its stability greatly increases and the observed recession will slow or stop. Another consideration will be the influence of longshore transport which will inevitably require dynamic revetments to be regular inspected and maintained. With improved understanding of these issues, the testing presented here indicates that dynamic revetments could provide a feasible alternative to traditional hard engineering structures in some locations as they provide low cost, robust overtopping and erosion protection to the hinterland while maintaining some natural character.

ACKNOWLEDGEMENTS

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 654110, HYDRALAB+. P. Bayle and G. Hennessey are supported by a PhD scholarship through the EPSRC CDT in Water Informatics: Science & Engineering (WISE). A. Hunter and O. Bryan were supported by a University of Bath Alumni Fund grant.

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