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Comparison of Dynamic Cobble Berm Revetments with Differing Cobble Characteristics

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Abstract

Pressure on the coastline is escalating, this is leading to a rise in sea-levels and intensifying storminess. Consequently, many regions of the coast are at increased risk of erosion and flooding. In response there is a growing use of nature-based coastal protection which aim to be sustainable, effective and adaptable. An example of a nature-based solution is a dynamic cobble berm revetment: a cobble berm constructed at the high tide wave runup limit. These structures limit wave excursion protecting the hinterland from inundation, stabilise the upper beach and adapt to changes in water level. Recent experiments and field applications have shown the suitability of these structures for coastal protection, however many of the processes and design considerations are poorly understood. This study directly compares two prototype scale laboratory experiments which tested dynamic cobble berm revetments constructed with approximately the same geometry but differing cobble characteristics; well-sorted rounded cobbles (DynaRev1) and poorly-sorted angular cobbles (DynaRev2). In both cases the structures were tested using identical wave forcing including incrementally increasing water level and erosive wave conditions. The results presented in this paper demonstrate that both designs responded to changing water level and wave conditions by approaching a dynamically stable state, where individual cobbles are mobilised under wave action but the geometry remains approximately constant. Further, both structures acted to reduce swash excursions compared to a pure sand beach. However, their morphological behaviour in response to wave action varied considerably. Once overtopping of the designed crest occurred, the poorly-sorted revetment developed a peaked crest which grew in elevation as the water level or wave height increased, further limited overtopping. By comparison, the well-sorted revetment was characterised by a larger volume of submerged cobbles and a lower elevation flat crest

42 which responded less well to changes in conditions. This occurred due to two processes:
43 (1) for the poorly-sorted case, cobble sorting processes moved small to medium cobble
44 material ($D_{50} < 70mm$) to the crest and (2) the angular nature of the poorly-sorted
45 cobble material promoted increased interlocking. Both of these processes led to a cobble
46 matrix that is more resistant to wave action and gravitational effects. Both revetments
47 experienced some sinking due to sand erosion beneath the front slope. The rate of sink-
48 ing for the well-sorted case was larger and continued throughout due to the large pore
49 spaces within the cobble matrix. For the poorly sorted revetment in DynaRev2, sand
50 erosion ceased after approximately 28 h due to the development of a filter layer of small
51 gravel at the sand-cobble interface, hence a larger volume of sand was preserved beneath
52 the structure. Both designs present a low-cost and effective solution for protecting sandy
53 coastlines but from an engineering viewpoint it appears better to avoid well-sorted cobble
54 material and greater cobble angularity has been seen to increase crest stability.

55 1 Introduction

56 Globally, anthropogenic pressure on the coastline is escalating, leading to an increased
57 threat from sea-level rise (SLR) as well as increasing severity and frequency of storms
58 (DeConto and Pollard (2016)). It is estimated if current coastal defences are not up-
59 graded, global flood losses could exceed US\$1 trillion per year by 2050 (Hallegatte et al.
60 (2013)). Therefore new coastal management strategies and structures are required to
61 mitigate the increased coastal hazards. Often it is preferable to do this at a local level,
62 taking into account the ecological, environmental and economic concerns of the region.
63 Dynamic cobble berm revetments which mimic naturally occurring composite beaches
64 are a promising coastal intervention to reduce erosion of the beach face and inundation
65 of the hinterland. The structure can be comprised of low-cost material such as quarry
66 spall and requires no specialist equipment to install, making it well-suited to a localised
67 approach to coastal protection. Such a solution may be particularly appropriate in areas
68 where composite beaches naturally occur as the structure can be designed based on these
69 beaches, leading to a defence that is in-fitting with the local environment, potentially
70 using locally sourced materials.



Figure 1: Left) The poorly-sorted revetment. Right) The well-sorted revetment

71 Traditional coastal protection techniques can be divided into two broad groups (Cartwright
72 et al. (2008)). The first is hard engineering solutions often referred to as grey structures
73 (Morris et al. (2018)), these consist of fixed structures such as seawalls and artificial
74 reefs. They are designed to provide a fixed barrier and are typically expensive to install

75 (Howe and Cox (2018a,b)). Additionally, many existing hard engineering schemes were
76 not designed for the current and predicted wave climates and therefore require upgrading
77 or replacing. For example, it is common for sea walls to have a fixed crest height which
78 was designed without consideration of sea level rise. Increasing the elevation of these
79 structures risks failure due to the capacity of the foundations to bear additional load.

80 The second group are soft engineering solutions such as beach, dune or submerged
81 nourishment (Kana et al. (2018)). As the drivers of coastal erosion are site specific, the
82 lifespan of such schemes are unpredictable although these can often be re-implemented
83 as required (Cartwright et al. (2008); French (2001); Ludka et al. (2018)). Additionally,
84 many regions have strict environmental laws that make sourcing of appropriate sediment
85 difficult (Pranzini (2018)). Further, such schemes are often ecologically destructive (Sey-
86 mour et al. (1996)), in the case of dune nourishment this problem is further exacerbated by
87 the complex nature of ecosystem diversity in dune systems (Cooper and Jackson (2021)).
88 An alternative is nature based solutions that focus on the restoration of natural habitats
89 such as salt marshes and mangroves (Morris et al. (2018)), but the long term effectiveness
90 of such schemes has not been established and they are not appropriate for high energy
91 coastlines. A more extreme option is managed retreat (Hino et al. (2017)), where the
92 coastline is left to develop naturally. However, this has socio-political difficulties due to
93 impact on local communities.

94 Most shoreline protection schemes utilise hard engineering, soft engineering, managed
95 retreat or a combination of these dependent on environmental and community pressures.
96 As the impact of climate change becomes progressively worse these schemes will increase
97 in cost. There is an urgent need for new coastal protection methods and structures to
98 deal with future environmental demands.

99 Composite Beaches are identified by Jennings and Schulmeister (Jennings and Shul-
100 meister (2002)) as a beach type with bi-modal sediment composition, sand and gravel,
101 separated into two distinct zones. The foreshore of the beach is composed of sand and
102 the backshore ridge, normally located at the high tide shoreline, is composed of gravel.
103 The combination of dissipative sand foreshore and reflective cobble ridge is considered an
104 effective natural form of coastal protection (Allan and Gabel (2016)), providing stability
105 to the upper beach and protecting the hinterland from overtopping. The cobble ridge
106 reshapes in response to wave attack, maintaining the ridge's elevation relative to the
107 water level with minimal loss of gravel material. During this process, gravel sediments
108 move constantly under wave forcing but the ridge responds as a single coherent body,
109 this is referred to as dynamic stability in this paper. The cobble ridge is most commonly
110 exposed to swash processes during energetic wave conditions and spring high tides leading
111 to infrequent overtopping of the ridge (Everts et al. (2002); Allan and Komar (2004)).
112 At present, composite beaches are under represented in the academic literature and there
113 is a lack of numerical, laboratory and field studies investigating their behaviour. Recent
114 research from Matsumoto (Matsumoto and Young (2018); Matsumoto et al. (2020a,b))
115 has investigated seasonal behaviour of composite beaches in Southern California and an
116 early review is provided by Mason et al. (Mason and Coates (2001)).

117 In engineering terms dynamic cobble berm revetments are artificially constructed
118 berms of gravel sediments, placed at or near the high tide berm of a sandy beach. A
119 review of these structures is provided by Bayle et al. (2020) and surmised here. They
120 are designed to mimic naturally occurring composite beaches, providing erosion control,
121 stability for the upper beach and protection to the hinterland. Due to this they are
122 considered a nature based solution for coastal protection. The DynaRev1 large-scale
123 laboratory experiment (Bayle et al. (2020)) compared the resilience and morphological
124 response of a dynamic cobble berm revetment constructed using well-sorted, rounded

125 cobbles to that of a sand beach under both wave forcing and increasing water level. [Bayle](#)
126 [et al. \(2020\)](#) found that installation of a dynamic cobble berm revetment led to reduced
127 erosion and inundation of the upper beach. Furthermore, the experiment demonstrated
128 the dynamic stability of such structures, which allowed them to adjust to changing wave
129 conditions and water-level rise while maintaining a coastal defence function with minimal
130 cross-shore loss of gravel, similar to composite beach ridges. This suggests that they have
131 the potential to be a climate adaptive coastal intervention. Field applications are rare
132 with only a few small scale or trial structures installed, primarily in North America.
133 The most recent and directly comparable dynamic cobble berm revetment design is that
134 installed at North Cove, Washington in 2018 ([Weiner et al. \(2019\)](#)). The coastline at
135 this location had been suffering rapid erosion since records were started in 1871 ([Phipps](#)
136 [and Smith \(1978\)](#)), with a shoreline retreat of approximately 4 km over the historical
137 record, leading to the moniker Washaway Beach. A 2 km stretch of the coastline was
138 protected using a dynamic cobble berm revetment constructed between February 2017
139 and January 2019 using poorly-sorted quarry spall. The monitoring report over the
140 first set of winter storms states that the uplands were protected from significant erosion
141 ([Weiner et al. \(2019\)](#)). Further, although sand was eroded from the lower beach face over
142 the winter, the sand volume at the site had rebounded by March due to deposition at
143 the toe. A recent field experiment conducted over a spring tidal cycle with high energy
144 waves (H_s up to 6 m) observed that the revetment underwent large fluctuations in both
145 elevation and volume due to the combined behaviour of the gravel berm and underlying
146 sand. However, over an entire spring tidal cycle overall change in volume was small ([Bayle](#)
147 [et al. \(2021\)](#)) and the structure displayed a dynamic stability comparable to a composite
148 beach.

149 At present, dynamic cobble berm revetments designed using non-sorted gravels are
150 effective at protecting their respective coasts. This current study examines the differences
151 in morphological response of revetments designed using differing cobble populations. It is
152 then contextualised in consideration of coastal protection techniques. It follows that pub-
153 lished by [Bayle et al. \(2020\)](#) which reported on the ‘DynaRev’ experimental
154 investigation of a dynamic cobble berm revetment constructed using well-sorted, rounded
155 cobbles (hereafter called DynaRev1). This work presents a comparable large-scale ex-
156 periment (DynaRev2), designed similar to the DynaRev1 experiment to investigate the
157 performance of a different dynamic cobble berm revetment under the same conditions.
158 It was constructed with approximately the same geometry as the original revetment, but
159 comprised of poorly-sorted, angular material equivalent to quarry run that would be ex-
160 pected to be widely available throughout the developed and developing world. This work
161 compares the results from both experiments (see [Figure 1](#) for comparative photo of the
162 two revetment structures).

163 The paper is structured as follows: This section provides a background and shortened
164 overview of the existing studies pertaining to dynamic cobble berm revetments. [Section 2](#)
165 details the methodology of the prototype-scale flume testing of the structure constructed
166 using poorly-sorted angular material. [Section 3](#) presents a thorough comparison of the
167 morphodynamic response of the structures under testing and investigates their potential
168 as coastal defence. [Section 4](#) discusses the results in the wider context of coastal protection
169 and highlights the limitations of the structures. [Section 5](#) presents a conclusion for the
170 study.

2 Methodology

2.1 Experimental Facility

The DynaRev2 experiment was designed to repeat DynaRev1 (discussed in Section 2), but with a revetment constructed using poorly-sorted angular cobbles instead of well-sorted rounded material. DynaRev2 was completed in the same facility as DynaRev1, the Großer Wellenkanal large wave flume (GWK) located in Hanover during November and December 2019. The flume is 309 m long, 7 m deep and 5 m wide and utilises a combined piston-flap-type wave paddle with automatic reflection compensation (ARC).

The revetment was constructed on a 1:15 sandy beach. The sand used during the experiment was the same as that for DynaRev1 and had the following grain size characteristics; $D_{50} = 0.33$ mm, $D_{10} = 0.20$ mm and $D_{90} = 0.65$ mm. The total volume of sand used for the beach construction was 875 m^3 . The entire beach profile including the revetment was constructed 11 m further from the wave paddle than in DynaRev1 and is shown in Figure 2b. This shift is not expected to influence the results as it simply increased the length of the deepwater section of the flume. To aid comparison between the two experiments, an adjusted 2-dimensional co-ordinate system was defined for DynaRev2, with the cross-shore origin located in front of the wave paddle such that the wave paddle is located at $x = -11$ m and continues in the positive direction towards the beach. The vertical elevation from the base of the flume defines the z -direction such that 0 m represents the floor of the flume as shown in Figure 2.

2.2 Experimental Procedure

The experiment was split into a series of twelve ‘tests’, where a test represents a change in conditions, such as water level increase (see Table 1 for full details). Each test was split into a series of runs with varying length after which the waves were stopped and the beach profile measured using a mechanical profiler described in Section 2.3.1. After each run neither the beach or revetment were reset giving each test a unique antecedent morphology. Note that the DynaRev2 runs do not align with those for the DynaRev1 experiment, however the experimental conditions and total experiment time for each test are identical. Here we avoid using run names and instead reference the experimental time from revetment installation.

To ensure the revetment was installed on a “realistic” beach profile, the planar beach slope detailed in subsection 2.1 was allowed to evolve naturally under 20 hours of wave forcing ($H_s = 0.8$ m, $T_p = 6.0$ s) with a constant water level ($z_{wl} = 4.5$ m). Upon this developed profile the poorly-sorted revetment was installed such that the crest elevation corresponded to the predicted value of $R_{2\%}$ for a water level of $z_{wl} = 4.8$ m (Table 1; for further details on the revetment geometry see subsection 2.3). After revetment installation, a series of four long tests were completed using the standard wave conditions with a 0.1 m incremental water level increase for each test from $z_{wl} = 4.6$ m to $z_{wl} = 4.9$ m. The tests are named using the following notation 2DR(E,R)<WL increment> where a WL increment of 0 refers to $z_{wl} = 4.5$ m and increases by 1 for each subsequent 0.1 m water level rise. For example, the Test 2DR3 refers to the fourth test with water level $z_{wl} = 4.8$ m, this would have identical testing conditions to the Test DR3 from the DynaRev1 experiment.

Following the water level rise testing a series of ‘resilience tests’ were completed, during which the wave energy was increased and the water level remained constant ($z_{wl} = 4.9$ m). This was then followed by a final test which used the standard irregular wave conditions to encourage recovery of the structure. The tests had varying duration’s and are denoted

Table 1: The testing conditions for DynaRev2. H_s is the significant wave height, T_p is the peak wave period, Ω_0 is the dimensionless fall velocity as given by Dean (1973); Gourlay (1968) and wave energy is given per metre of wave crest.

Test	Start (hr)	End (hr)	Duration (hr)	H_s (m)	T_p (s)	Water Level z_{wl} (m)	Ω_0	Energy (MJ)
Beach Equilibrium Approach								
2DR0	-20:00	0:00	20	0.8	6	4.5	3.38	0.78
Revetment Construction								
2DR1	0:00	7:00	7	0.8	6	4.6	3.38	0.78
2DR2	7:00	14:00	7	0.8	6	4.7	3.38	0.78
2DR3	14:00	21:00	7	0.8	6	4.8	3.38	0.78
2DR4	21:00	38:00	17	0.8	6	4.9	3.38	0.78
Resilience Tests								
2DRE1	38:00	40:00	2	0.9	6	4.9	3.69	0.99
2DRE2	40:00	42:00	2	1	7	4.9	3.51	1.23
2DRE3	42:00	43:00	1	1	8	4.9	3.08	1.23
2DRR1	43:00	45:00	2	0.8	6	4.9	3.38	0.78
Re-nourishment Tests								
2DRN1	45	47	2	0.8	6	4.9	3.38	0.78
2DRN2	47	47.40	0.66	1	9	4.9	2.73	1.23
2DRN3	47.40	49.40	2	0.8	6	4.9	3.38	0.78

218 using the naming convention 2DR(E,R)<test number> where E and R refer to erosive
219 and recovery tests respectively.

220 The ‘Re-nourishment Tests’ examined the process of recharging the revetment, see
221 Table 1. An additional 1.5 m³ of cobbles were placed on the front face of the revetment.
222 This was forced using a mixture of both the standard irregular wave conditions and a
223 shortened high energy wave test (Table 1). These are denoted using the naming con-
224 vention DRN<test number>. Due to restricted experimental time this was a shortened
225 process and is not considered directly comparable to the DynaRev experiment.

226 2.3 Revetment Installation and Characteristics

227 The poorly-sorted revetment used in DynaRev2 was designed with the same geometry as
228 the well-sorted revetment from DynaRev1. Prior to installation, the revetment location
229 was flattened to a 1:15 slope to allow sufficient cobble placement at the design slope of
230 1:6.3 (this was also done for the well-sorted case). Construction was carried out using
231 a front end loader to dump the cobbles at the approximate location and then manually
232 reshaped to match the profile of the well-sorted revetment. Due to difficulties in shaping
233 angular cobbles, the profile of the revetment differed slightly to that in DynaRev1, with
234 a less well-defined crest (Figure 2 b). The revetment was constructed using poorly-sorted
235 granite cobbles with density 2700 kg/m³, bulk density 1760 kg/m³ and a porosity of 0.35.
236 The intermediate axis characteristics were as follows; $D_{10} = 23$ mm, $D_{90} = 123$ mm,
237 $D_{50} = 44$ mm with a grading value of $D_{85}/D_{15} = 3.79$ (see Equation 1 in subsection 2.4
238 for details). The front slope had an incline of 1:6.3 and the toe was located at $x = 256.9$
239 m and $z = 4.67$ m. Using the runup equation for gravel beaches developed by Poate
240 et al. (2016) the 2 % exceedance runup elevation was predicted to be 0.72 m, therefore
241 the crest was constructed at $x = 260.8$ m and $z = 5.42$ m corresponding to the predicted
242 $R_{2\%}$ for a water level $z_{wl} = 4.7$ m. Behind the crest, the poorly-sorted revetment was
243 approximately horizontal and intersected the sand beach at $x = 264.1$ m. The total
244 volume of placed cobbles was 9.375 m³ and weighed 16.5 t.

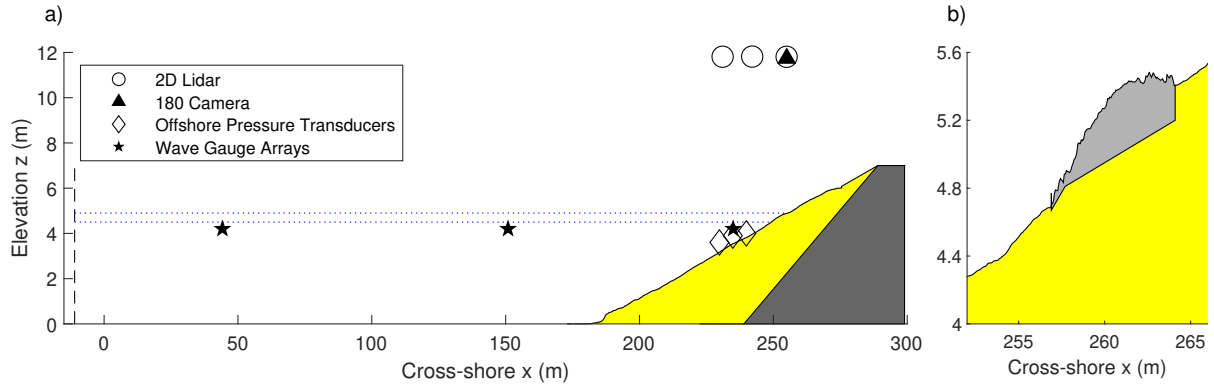


Figure 2: a) Schematic of initial experiment setup including instrument locations and profile of the placed beach. The vertical dashed line indicates the location of the wave paddle and the horizontal dotted lines give the lowest and highest water level during the experiment. b) Close-up schematic of the initial poorly-sorted revetment placement. The grey box is the placed revetment shape.

2.3.1 Instrumentation and Data Acquisition

The instrumentation used to monitor the response of the sand beach and poorly-sorted revetment was the same as that for DynaRev1. Beach profiles were taken at the end of each run using a mechanical profiler which provided measurements of the bed elevation at approximately 2 cm vertical accuracy. Three Sick LMS511 Lidar scanners at $x = 241$ m, $x = 253$ m and $x = 266$ m with elevation $z = 11.8$ m provided continuous measurement of the water surface and exposed beach face morphology over an 80 m transect along the flume centreline. These instruments were sampled at 25 Hz with an angular resolution of 0.1666° . A Vivotek MS8391-EV 180° camera was mounted in the flume roof at $x = 253$ m with elevation $z = 11.85$ m. Once calibrated using ground control points this enabled the generation of timestack imagery of the swash zone which was used for continuous verification of the shoreline position estimated using data from the most landward Lidar (see section 3.4.2).

To track the movement of individual cobbles within the revetment, a radio frequency identification tracking system (RFID) was used as during DynaRev1. A total of 99 cobbles were fitted with 23 mm Passive Integrated Transponder tags (PIT). These were placed in groups of three cobbles along the bottom, middle and top layers of the revetment at 0.4 m cross-shore intervals. At the revetment toe, an additional group of eight cobbles was placed and are considered part of the top layer. The top layer of 48 cobbles was placed along the surface of the revetment from $x = 257.8$ m to $x = 263.0$ m. The middle layer of 30 cobbles was placed from $x = 259.8$ m to $x = 263.4$ m. The bottom layer of 21 cobbles was positioned along the sand-cobble interface between $x = 258.2$ m and $x = 260.6$ m. The cross shore position of each cobble was recorded within 0.2 m accuracy at the end of each test. Due to the size of the PIT tags, only cobbles with an intermediate diameter size greater than 40 mm were able to be tagged and included in the analysis.

2.4 Data Processing

2.4.1 Revetment Volume and Sand Cobble Interface Elevation

The thickness of the revetment down to the underlying sand beach was recorded at 1 m cross-shore intervals along the centreline after each test. This was achieved by driving a thin serrated pole through the structure, the serrated edge would capture sand once through the revetment body and allowed measurements with approximately 2 cm accuracy. The impact on the revetment was minimal and no restorative action was necessary

277 to repair the revetment surface. The sand cobble interface profile was estimated through
278 linear interpolation of these elevations under the assumption that the revetment sand in-
279 terface could not rise during the experiment. Combined with the profiler measurements
280 of the bed elevation, this allowed estimation of both the revetment volume and shape. At
281 the end of the experiment, a channel was excavated along the centreline of the revetment.
282 This exposed the sand cobble interface and was measured by the mechanical profiler.

283 2.4.2 Swash Detection

284 High frequency measurements of the exposed beach profile and water surface were ob-
285 tained using the Lidar array. Each Lidar detects the nearest surface: either the water
286 surface or exposed beach face without distinction between the two. To generate a time
287 series for the beach profile and swash separately, first, a 0.1 m horizontally gridded sub-
288 sample was created and all measurements were processed with a moving-average 2 s win-
289 dow with a mean variance threshold. Then the data were separated into a stationary
290 bed elevation and a swash surface elevation time series using the method presented by
291 Almeida et al. (2015). The continuous shoreline position was extracted by finding the
292 most landward position of the swash at all time steps. These were validated by plotting
293 the continuous shoreline time series over rectified stacks from the 180-camera (see sec-
294 tion 3.3.1) for every run. The difference between the stack imagery and the continuous
295 shoreline position was less than 0.1 m for all tests.

296 2.4.3 Cross-Shore Grain Size Distribution

297 The cross-shore variation in surface grain size distribution over the dynamic cobble berm
298 revetment was estimated using a digital point count technique which utilised downward
299 looking images of the revetment surface captured using a digital single-lens reflex (SLR)
300 camera. Photos were taken at 1 m cross-shore increments along a line offset 0.5 m
301 from the flume centreline between $x = 257.5$ m and $x = 264.5$ m immediately after
302 revetment installation and after each test (Table 1). The photographs adhere to the rules
303 of appropriate grain size imagery as presented by Buscombe (2013).

304 The digital point count software (Buscombe (2010)) estimates the size distribution
305 curve of the intermediate axis length which is considered representative of cobble size
306 (Bunte et al. (2009)) and used to estimate D_{15}, D_{50} and D_{85} . Grading was calculated
307 using the equation presented by van der Meer (1988),

$$Grading = D_{85}/D_{15}, \quad (1)$$

308 and is considered a good estimate for the spread of the cobble population. An additional
309 measure of spread is provided by the median absolute deviation which is more robust
310 for skewed data. The cobble size distributions obtained from the digital point count
311 software were validated against manual measurements of 100 cobbles randomly selected
312 from within a 1 m² at two locations. This procedure was repeated twice and agreed
313 closely with the image-based results.

314 3 Results

315 This section explores the general and morphodynamic behaviour of the beach and dy-
316 namic cobble berm revetment constructed from poorly-sorted, angular material during
317 DynaRev-2. These are compared with results presented for the dynamic cobble berm

318 revetment constructed using well sorted, rounded cobbles during the DynaRev1 exper-
319 iment (Bayle et al. (2020)) and put in the context of coastal protection. It focuses
320 on both revetment’s physical evolution and stability in response to wave attack. Ad-
321 ditional analysis of the behaviour of cobbles within the poorly sorted revetment is also
322 presented, including the movement of individual cobbles using the radio frequency iden-
323 tification tracking system (RFID) and the sorting of cobbles over the exposed surface of
324 the revetment, see section 4.1.4 for details. Further, results capturing the wave run-up
325 and shoreline retreat are presented.

326 3.1 Comparison of Morphological Behaviour

327 3.1.1 Evolution of Revetment Shape During the Water Level Tests

328 The morphological evolution of the revetments and sandy beach immediately seaward of
329 the revetment for both DynaRev1 and DynaRev2 is presented in Figure 3a,b. Note that
330 0 h corresponds to the time of revetment installation, explaining the sudden accretion
331 between $x = 259$ and $x = 262.5$. Negative times correspond to test DR0/2DR0 (see
332 Table 1) before revetment installation, when only the sand beach was present. In both
333 experiments the beach behaved in a similar manner during the 20 h of wave action prior
334 to revetment installation (-20 h to 0 h). The geometry of the revetment at the end of each
335 test is shown in Figure 4 to aid interpretation of Figure 3.

336 The poorly-sorted revetment in DynaRev2 underwent significant morphological change
337 during the 38 h of standard wave conditions with a rising water level (Table 1). This
338 included both landward retreat of the toe of the main cobble body (hereafter toe) by
339 2 m and an increase in crest elevation of 0.38 m (Figure 3e; Figure 5b), approximately
340 corresponding to the 0.4 m applied rise in water level. Further, the exposed surface of
341 the revetment changed from a convex profile to a profile with a defined crest and concave
342 front face Figure 4. This evolution differed for the well-sorted revetment (DynaRev1)
343 which was characterised by a sinking of the front face and a more consistent shape that
344 retreated under wave attack (Figure 3e). This was driven by differing rates in the pri-
345 mary modes of cobble transport; landward cobble transport which was induced by wave
346 action on individual cobbles and seaward cobble transport where cobbles rolled down the
347 revetment under gravitational forces. Note that Bayle et al. (2020) defined crest height
348 for the well-sorted revetment in DynaRev1 as the mean elevation of the flat revetment
349 crest area landward of the front slope and cross-shore crest position as the seaward limit
350 of this area. Due to the more defined crest in the poorly-sorted revetment case, these
351 definitions were updated as follows; For the first 14 hours before overtopping occurred
352 and the defined crest developed, the crest was taken at the designed crest’s horizontal
353 position. For the rest of the experiment this was defined as the apex of the peaked crest
354 immediately behind the front slope of the revetment, Figure 3e shows the location of the
355 crest for the revetments in DynaRev1 and 2 respectively, both as designed and at the end
356 of water-level tests.

357 The crest was rarely overtopped during the first 14 hours of testing during DynaRev2
358 (tests 2DR1 and 2DR2, 0 to 14 h), see Figure 6. The swash zone was limited to the
359 front face of the cobble body and morphological change was confined to this region.
360 Water infiltration into and through the structure eroded sand beneath the front face,
361 reducing the elevation of both the toe and centre of mass of the revetment (red dots in
362 Figure 4, blue diamonds in Figure 5). A single layer of sparse cobbles mixed with sand
363 was formed at the front of the revetment, termed the sparse cobble layer (marked in green
364 in Figure 4). This layer was formed from cobbles at the larger end of the size range, was
365 approximately 1 m in cross-shore extent by $t = 14$ h, did not extend seaward of the

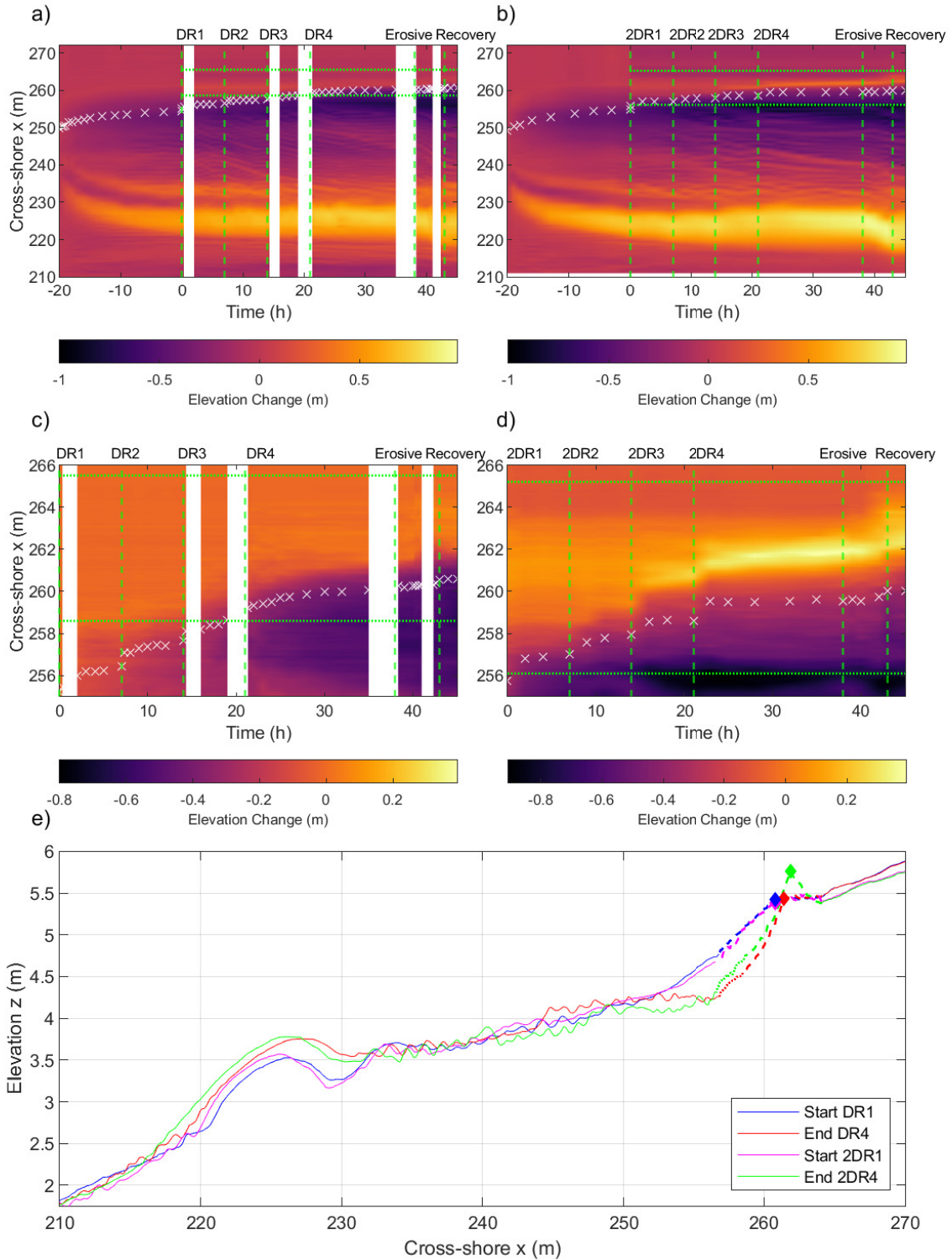


Figure 3: Bed elevation change relative to initial beach profile over the entire experiment for a) DynaRev1, well-sorted revetment, b) DynaRev2, poorly-sorted revetment. Revetment surface elevation change relative to installed profile for c) DynaRev1, d) DynaRev2. The dashed green vertical lines represent the time of a 0.1 m water level rise, and the dotted horizontal lines denote the maximum seaward and landward extent of the revetment during the experiment. The white crosses represent the shoreline position at the end of each run. e) Profile at the start and end of the 38 h of standard wave conditions for both the well-sorted revetment (DynaRev1) and poorly-sorted revetment (DynaRev2). The dashed line represents the cobble body, the dotted line represents the sparse cobble layer and the diamonds gives the crest location (see section 3.1.1).

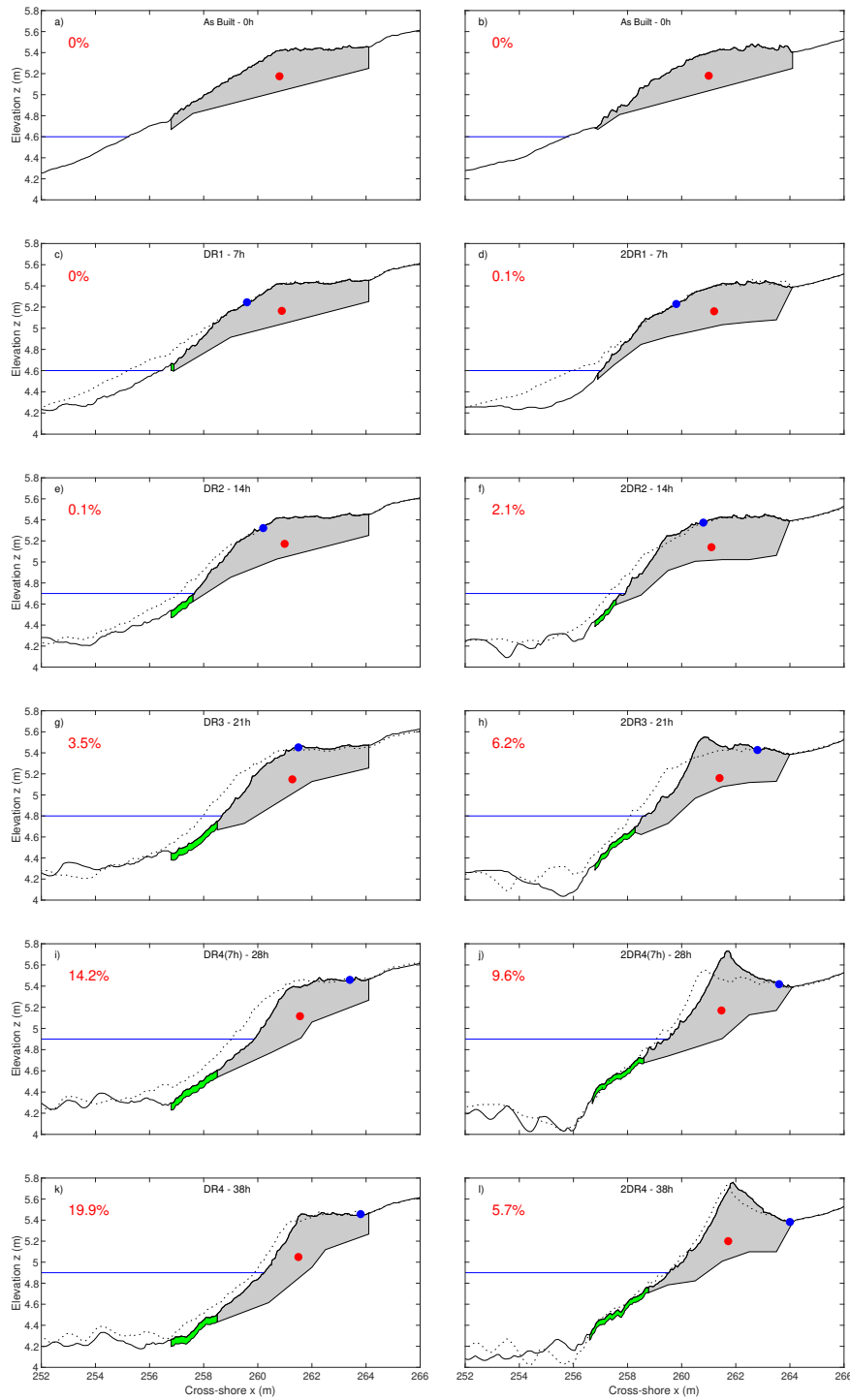


Figure 4: Revetment shape as-built and at the end of each indicated test for the well-sorted revetment (DynaRev1, left) and poorly-sorted revetment (DynaRev2, right). The grey area represents the cobble only portion of the revetment. The green area represents the sparse cobble layer. The blue dot indicates the cross-shore position that was exceeded by 2% of wave run-up events, the red dot indicates the centre of mass of the revetment and the dashed line is the revetment surface from the previous panel. The red value gives the percentage of the main cobble body below the still water level

366 original toe position and accounted for just 2% of the revetment’s original volume. By
 367 $t = 14$ h an intermediate berm formed at $x = 259.4$ m just below the 2% run-up elevation
 368 (Figure 4f). The well-sorted revetment in DynaRev1 had a similar response and after 14
 369 hours of tests and the geometry of the two revetments at this time was quite similar.

370 Tests DR3 and 2DR3 ($z_{wl} = 4.8$ m; $t = 14$ to 21 h) resulted in the divergence in the
 371 response of the two revetments (Figure 4g and h). The new water level led to an increased
 372 rate of overtopping for both revetments driving morphological change, see Figure 6 for
 373 further details. Landward transport of cobbles driven by overtopping events led to the
 374 development of a very peaked crest behind the initial crest location for the poorly-sorted

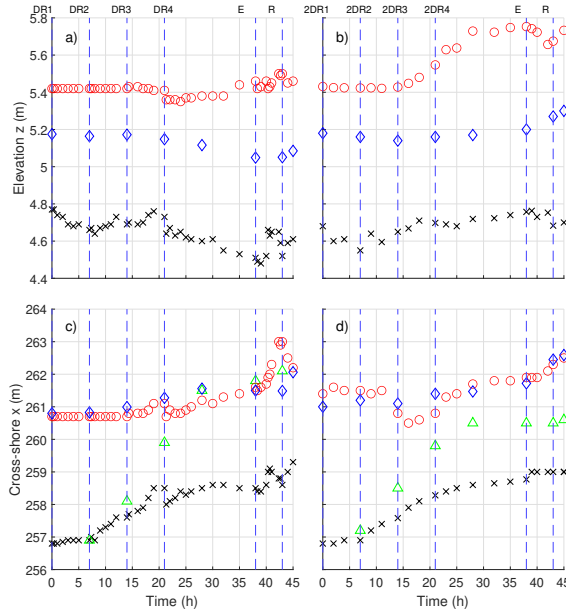


Figure 5: Vertical elevation of the toe (black crosses), centroid of the cross-sectional area (blue diamonds) and crest (red circles) for a) DynaRev1 and b) DynaRev2. Cross-shore location for the toe of the main cobble body (black crosses), the location of the intersection between the still water level and the sand-cobble interface beneath the revetment (green triangles), centroid of the cross-sectional area (blue diamonds) and crest (red circles) for c) DynaRev1 and d) DynaRev2.

375 revetment (Figure 4h) and a toe retreat of 1 m (Figure 5d). This resulted in an increase in
 376 structure height and the front slope changed from a convex to a concave shape (Figure 4h).
 377 Conversely, the well-sorted revetment (DynaRev1) showed similar crest and toe retreat
 378 but the shape remained consistent with no crest growth (Figure 4g; Figure 5a and c). The
 379 development of the peaked crest feature for the poorly-sorted revetment in DynaRev2 is
 380 a result of the cobble population characteristics. Firstly, highly angular cobbles interlock
 381 better, reducing the frequency of seaward cobble transport due to increased stability
 382 under wave attack. Secondly, the wide size range of the poorly-sorted cobbles leads to
 383 size sorting on the revetment surface, with larger cobbles accumulating near the toe and
 384 primarily smaller cobbles being transported landward to form the peaked crest feature
 385 (see section 4.3 for further analysis of surface cobble size distributions). This process
 386 results in the elevation gain and landward movement of the crest feature for the poorly-
 387 sorted revetment in DynaRev2 as it develops under wave forcing.

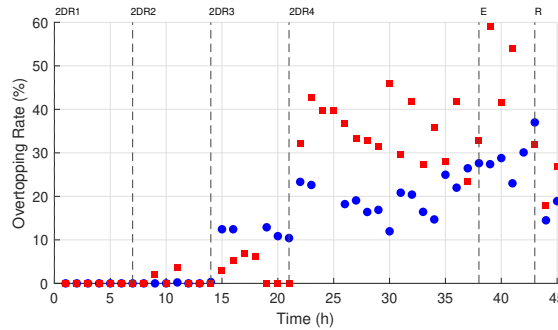


Figure 6: Hourly overtopping rate for the poorly-sorted revetment (blue) and the well-sorted revetment (red).

388 Tests DR4 and 2DR4 ($z_{wl} = 4.9$ m; $t = 21$ to 38 h) were the longest (17 hours)
 389 and experienced the highest overtopping rates (see Figure 6). During the first seven
 390 hours the poorly-sorted revetment (DynaRev2) experienced accelerated morphological

391 change, leading to a 18 cm vertical crest growth and a 90 cm landward retreat. Analysis
392 of the revetment profiles indicates that much of the material that moved onto the top
393 of the structure did so during the first hour of the test (21-22 h) and is detectable in
394 the profile measurement taken at 23 hours (Figure 3d). The toe of the main cobble
395 body continued to retreat (Figure 5d) and the sparse cobble layer occupied the free
396 space in front of the structure (Figure 4j), this was composed of larger cobbles which
397 are less mobile under wave action (see subsection 3.3). The well-sorted revetment in
398 DynaRev1 continued to retreat during hours 21 to 28 ($z_{wl} = 4.9$ m) and began to develop
399 a more prominent crest (Figure 4i), however this did not result in vertical growth of
400 the structure. The rate of morphological change decreased for both revetments over the
401 next ten hours (Figure 4k and l; Figure 5) suggesting they were approaching a dynamic
402 stability. In this state individual cobbles are transported both landward and seaward
403 but the overall shape remains consistent. It is clear that the poorly-sorted revetment
404 was more dynamically stable than the well-sorted revetment between hours 28 and 28
405 as shown by the consistent location of geometric features such as crest, toe and centre
406 of mass (Figure 5). Therefore, it can be concluded that the poorly-sorted revetment
407 is prone to a more rapid morphological stabilisation as forcing conditions change, with
408 initial wave overtopping promoting the formation of a more substantial and stable crest
409 that subsequently reduces overtopping of the structure, and therefore decreases cobble
410 transport up and over the crest. Both revetments had a final front face slope of 1:3.9,
411 but the centre of mass for the poorly-sorted revetment in DynaRev2 was 0.2 m landward.
412 However this is mainly caused by the formation of the substantial crest feature and is
413 not necessarily indicative of a greater rate of landward retreat. The main cobble body
414 of the poorly-sorted revetment was slightly shorter in cross-shore extent than that of the
415 well-sorted revetment, 5.3 m and 5.6 m respectively.

416 The cross-shore extent of the main cobble body of both revetments reduced under
417 the standard wave conditions (Figure 4) and are similar throughout the experiment.
418 Because the landward limit of the revetment did not move under stand wave testing, this
419 can be attributed to the retreat of the toe. However, whereas the toe of the well-sorted
420 revetment sank as it retreated due to loss of sand volume beneath the structure, the toe of
421 the poorly-sorted revetment retreated up the beach profile (Figure 5c and d). Therefore,
422 taking the elevation change between the toe and crest as the height of the revetment it
423 appears that both revetments grew rapidly in height under the highest water level ($z_w =$
424 4.9), but for the poorly-sorted revetment this is due to upward growth of the structure
425 as opposed to the sinking of the sand-cobble interface for the poorly-sorted revetment,
426 leading to a larger elevation change over the body (Figure 4). As noted earlier the well-
427 sorted revetments crest only shows minimal (0.04 m) of growth over the entire standard
428 wave conditions (Figure 5a).

429 3.1.2 Revetment Response to Erosive and Recovery Wave Tests

430 In both experiments the water level rise testing was followed by 5 h of erosive wave con-
431 ditions with increased wave energy at the highest water level, $z_{wl} = 4.9$ m (see section
432 3.2 for details, Table 1) which resulted in increased overtopping in both DynaRev1 and
433 DynaRev2 (Figure 6). This led to a landward retreat of the centre of mass, flattening
434 of the crest and reducing the front face gradient to 1:3.6 for the poorly-sorted revetment
435 (see Figure 7 a and b). For the well-sorted revetment, the primary response was the
436 retreat of the crest leading to an even lower front face gradient of 1:3.15. For both struc-
437 tures, cobbles were transported beyond the landward limit of the structure (overwash)
438 leading to an increase in the revetment cross-shore extent of 0.8 m (DynaRev1) and 0.9

439 m (DynaRev2). The length of the well-sorted revetment was more variable during the
 440 erosive wave testing due to the more changeable cobble toe location (Figure 5c and d).
 441 The increased stability of the toe in the poorly-sorted revetment is due to the fact that
 442 the toe contained many large cobbles which were not mobilised by the increased wave
 443 energy (subsection 3.3).

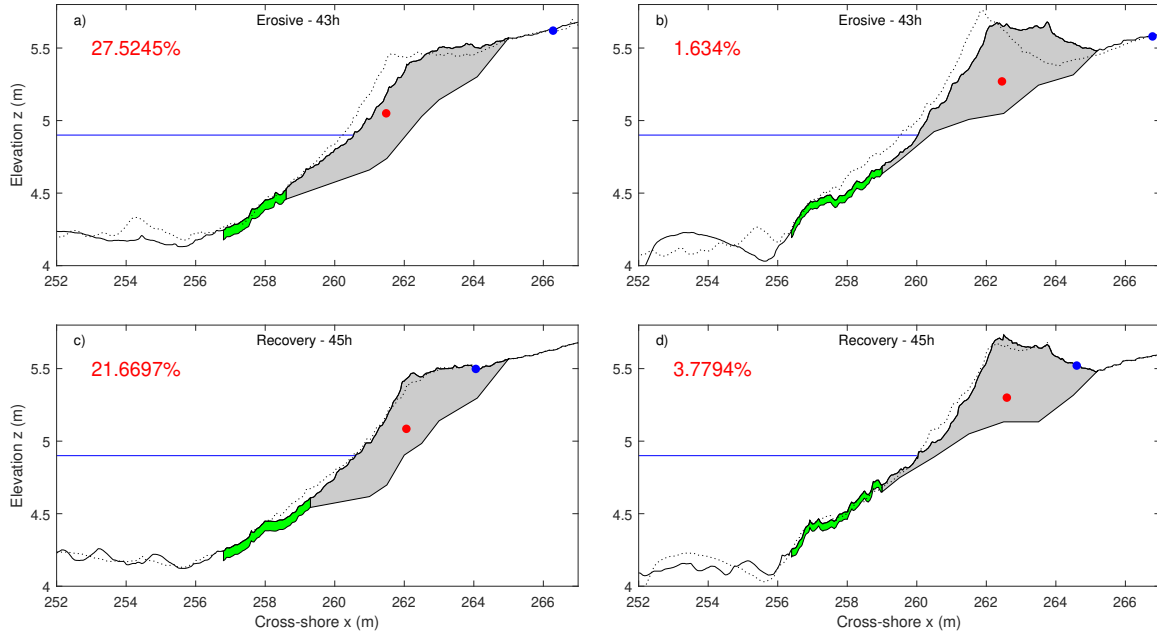


Figure 7: Revetment shape at the end of erosive (2DRE3, 38 to 43 h) and recovery (2DRR1, 43 to 45 h) wave conditions for the well-sorted revetment (left) and poorly-sorted revetment (right). The grey area represents the cobble only portion of the revetment. The green area represents the sparse cobble layer (see subsection 3.1.1). The blue dot gives the cross-shore position which was exceeded by 2% of wave run-up events, the Red dot indicates the centre of mass and the dashed line is the revetment surface from the previous panel for the respective design.

444 The final stage of the revetment testing consisted of 2 h of recovery wave conditions
 445 with the same characteristics as the standard wave conditions ($t = 43$ to 45 h). During
 446 this period, the poorly-sorted revetment began to reform the very peaked crest, but
 447 landwards of its position at the end of the standard wave conditions ($x = 261.9$ m, $t = 38$
 448 h), see Figure 7d. This resulted in the centre of mass being elevated by 0.05 m and
 449 moved landward by 0.2 m compared to the end of the erosive wave conditions (43 h). It is
 450 suggested that the structure would return to approximately the previous shape ($t = 38$ h)
 451 had this test been longer. The well-sorted revetment also began to rebuild a crest similar
 452 to that at the end of standard wave conditions ($t = 38$ h). Overall, both revetments could
 453 be described as showing a general retreat under erosive wave conditions and both were
 454 beginning to reshape under the recovery wave conditions, but with the revetment mass
 455 slightly further landward, however the poorly-sorted revetment in DynaRev2 reformed
 456 above the still water level.

457 3.1.3 Evolution of the Sandy Beach and Revetment Sinking

458 Both beaches were considered to be approaching an equilibrium state and presented
 459 similar morphologies (Figure 3). The notable difference being the slightly larger and
 460 further seaward outer bar in DynaRev2 prior to the installation of the poorly-sorted
 461 revetment. Over the main region of interest between $x = 210$ m and $x = 270$ m the root
 462 mean square difference between the beach profiles at $t = 0$ h was just 0.3 m. This agrees

463 with the previous finding by Bayle et al. (2020) that laboratory experiments exploring
464 morphological change are repeatable at this scale.

465 After installation of the poorly-sorted revetment in DynaRev2, the outer bar accu-
466 mulated sand resulting in a vertical and predominantly seaward growth of the outer bar
467 (Figure 3). The source of this sand is from three primary processes; sand erosion beneath
468 the revetment, the development of a trough immediately seaward of the revetment struc-
469 ture and smoothing out of the smaller inner bar. Morphological changes are strongest in
470 the two hours immediately following the third and fourth water level rise ($z_{wl} = 4.8$ and
471 4.9 m), the same period in which the revetment and trough underwent significant mor-
472 phological change. The well-sorted revetment in DynaRev1 showed a similar accretion of
473 sand in the outer bar driven by the same processes. Less sand erodes immediately seaward
474 of the well-sorted revetment leading to a smaller trough, indicating that sand erosion from
475 beneath the structure contributes more for the well-sorted revetment in DynaRev1. The
476 sand erosion beneath the revetment leads to a sinking effect for both revetments. This
477 process can be tracked throughout the experiment by comparing the approximate loca-
478 tion that the still water level intercepts the sand-cobble interface beneath the revetment
479 (green triangles in Figure 5). For both revetments this is a continuing process throughout
480 the first three water level tests ($z_{wl} = 4.6$ to 4.8 $0 - 27$ h). If water level rise is discounted
481 the During the fourth water level test ($27 - 38$ h) this process halted for the poorly-sorted
482 revetment in DynaRev2 but continued at a reduced rate for the well-sorted revetment
483 in DynaRev1. This results in a significantly less of the poorly sorted revetments main
484 cobble body being below the still water level at the end of the water level tests (19.9 %
485 in DynaRev1 vs 5.71 % in DynaRev2, Figure 2k and l).

486 3.1.4 Shoreline Evolution

487 The shoreline, considered as the intersection between the still water level and seaward
488 facing limit of the poorly-sorted revetment was initially located at $x = 255.8$ m (see
489 Figure 4 b). Over the course of the experiment the shoreline retreated at an average
490 rate of 0.01 m/hour, with a total retreat of 3.7 m although a large degree of this can be
491 attributed to the 0.3 m rise in water level over tests (0-38 h). If there were no changes
492 in the morphology the final shoreline would be expected to be at $x = 258$ m (a retreat
493 of 2.2 m). The final shoreline was located at $x = 259.5$ m giving a true retreat of 1.5
494 m when discounting water-level rises, which was under half the true retreat of 3.7 m for
495 the well-sorted revetment (see Figure 4 k,l). A major reason for lesser retreat in the
496 poorly-sorted case is the reduced loss of sand from beneath the revetment and hence
497 reduced sinking of the front face of the revetment. This can be seen clearly in the retreat
498 of the sand water interfaces (SWI) for the revetments (see Figure 5 c,d), the location
499 where the still water line intercepts the interpolated surface beneath the revetment. The
500 final SWI location for the poorly-sorted revetment was 260.5 m at the end of standard
501 wave conditions (38 h), which is 1.3 m further seaward than for the well-sorted revetment
502 (see Figure 5). The poorly-sorted revetment preserves up to 52% more sand above the
503 still water level under the structure. This reduced sand loss has the advantage of better
504 preserving the revetment height compared to the still water level improving the ability
505 to reduce overtopping.

506 3.2 Overtopping Rates

507 A comparison of the overtopping rates on an hour by hour basis using the Lidar array
508 during both experiments is provided in Figure 6. The values for both experiments are
509 similar between $t = 0$ h and $t = 14$ h ($z_{wl} = 4.6$ m and $z_{wl} = 4.7$ m). Overtopping of

510 the designed crest was infrequent during this time period (Figure 6) and the increased
 511 horizontal runup excursion between $t = 7$ h and $t = 14$ h ($z_{wl} = 4.7$ m) for DynaRev2
 512 is explained by the crest being constructed slightly landward of that for DynaRev1 (see
 513 subsection 2.3 for details of the construction). As the water level increased further, the
 514 crest of both revetments began to be regularly overtopped (0-8 % DynaRev1, 11-13%
 515 DynaRev2) (Figure 6) and this led to substantial crest growth for the poorly-sorted
 516 revetment (DynaRev2). Despite the large crest growth in DynaRev2, the revetment
 517 experienced higher overtopping rates than for DynaRev1 at $z_{wl} = 4.8$ m. This may
 518 be due to the fact that the crest of the revetment in DynaRev2 is 0.3 m seaward of
 519 the DynaRev1 crest and it was demonstrated by Blenkinsopp et al (Blenkinsopp et al.
 520 (2022)) that overtopping rates decay rapidly with cross-shore distance. Alternatively, the
 521 water depth seaward of the revetment is consistently larger for DynaRev2, allowing more
 522 wave energy to reach the shoreline and drive runup (Blenkinsopp et al. (2022)). After
 523 increasing the water level to $z_{wl} = 4.9$ m, the overtopping rates increased again. This led
 524 to rapid crest growth during the first hour at the new water level for DynaRev2 which
 525 acted to limit overtopping to 23%, compared to 31% in DynaRev1 where crest growth
 526 was minimal. It is noted that there is substantial variability in the overtopping rates
 527 during both experiments and this is thought to be due to the fact that the geometry of
 528 the structures is constantly evolving, meaning that the instantaneous crest elevation is
 529 varying and provides variable rates of overtopping protection.

530 The overtopping rate in both experiments increased further during the erosive tests
 531 (38-43 h; Table 1). For the poorly-sorted revetment in DynaRev2, the overtopping rate
 532 increased by less than 10% compared to the final hour of wave testing under standard
 533 wave conditions (28%, 37-38 h in Figure 6) and at no point was the structure's crest
 534 overtopped by more than 38% of the waves in any given hour. Conversely, overtopping of
 535 the well-sorted DynaRev1 revetment was very variable and reached as high as 59% (38-39
 536 h in Figure 6), this is 26% larger than the final value under standard wave conditions
 537 (33%, 37-38 h in Figure 6). Overall, the ability of a revetment constructed from poorly-
 538 sorted, angular material to form an elevated crest is beneficial as it reduces overtopping
 539 of the structure and provides increased resilience under energetic wave conditions. The
 540 poorly-sorted revetment's ability to rapidly develop a significant crest feature suggests
 541 that it is highly adaptable to a rising water level.

542 3.3 Cobble Transport and Surface Sorting

543 For both experiments cobbles tagged with passive RFID transmitters were placed along
 544 the cross shore centreline of the revetment in three layers; On the surface (top), at half
 545 the revetment depth (middle) and along the cobble-sand interface (bottom). Figure 9
 546 details the movement of the cobbles for both the poorly-sorted (DynaRev2) and well-
 547 sorted revetment (DynaRev1) by placement layer, Table 2 provides further details on the
 548 quantity of tagged cobbles transported and direction of travel. This was supported by
 549 an analysis of the surface cobble size distribution (intermediate axis length) along the
 550 central axis of the poorly-sorted revetment using a digital cobble count method (Figure 8,
 551 see section 3.4.4 for methodological details). Photos of the toe and crest of the poorly-
 552 sorted revetment at the end of the standard wave conditions are provided in Figure 10,
 553 these give a visual reference for the results presented. The well-sorted revetment had a
 554 consistent grading and a small range of cobble sizes and so no size sorting was observed.

555 The distribution of cobbles on the surface of the poorly-sorted revetment was initially
 556 very consistent at all cross-shore positions (Figure 8a). Subsequently, the surface cobbles
 557 underwent a sorting process throughout the experiment as they were mobilised by wave

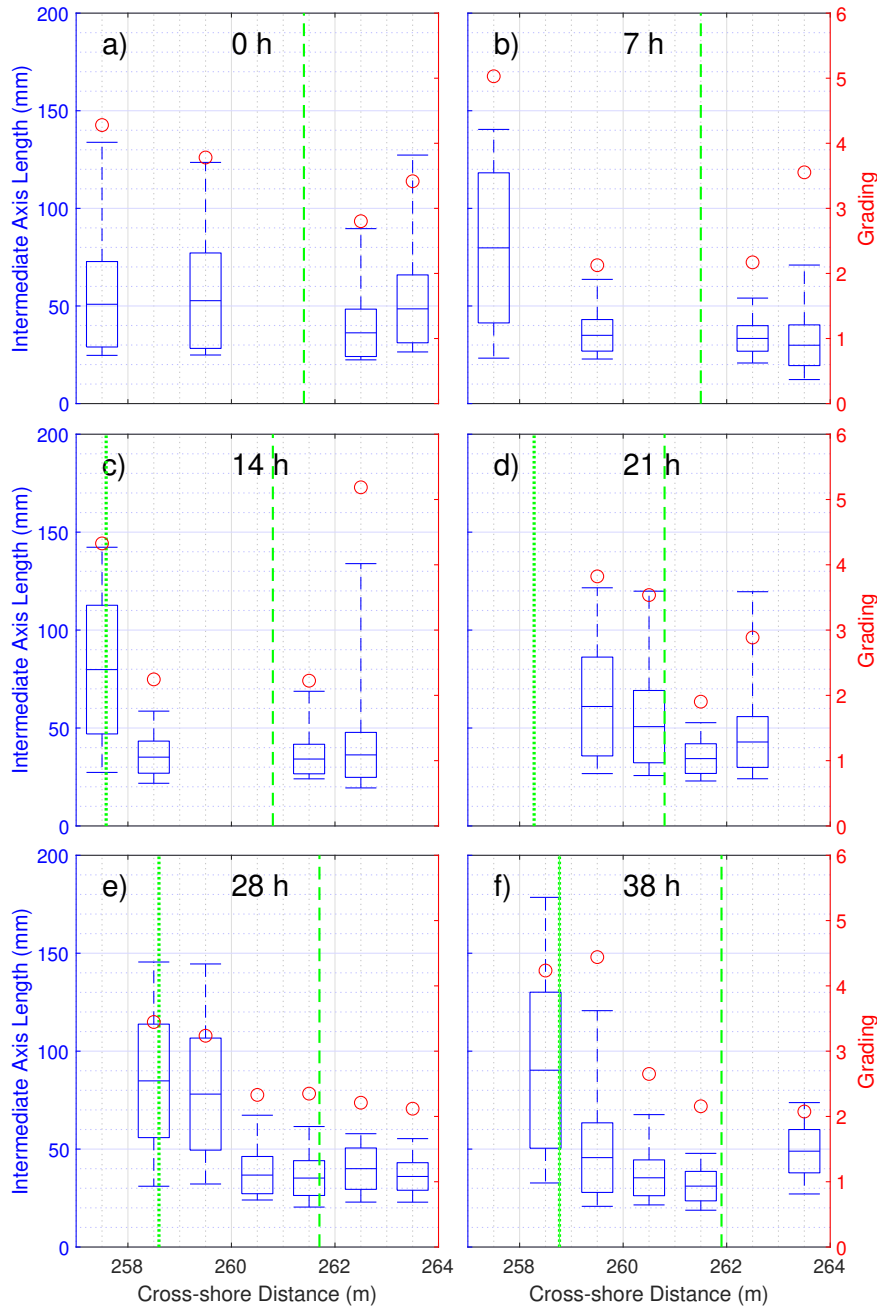


Figure 8: Surface grain size distribution across the poorly-sorted revetment at the end of each test ($t = 0, 7, 14, 21, 28, 38$). The left hand y-axis corresponds to a box plot centred over the median intermediate axis length with inner bounds provided by the median absolute deviation and branches reaching D_{90} and D_{10} . The right hand y-axis and red circles indicate the grading value at each location (Grading = D_{85}/D_{15}). Dotted green line represents the toe location and dashed green line represent crest location.

558 forcing. This sorting process led to the median cobble size decreasing landward of the
 559 toe, combined with a smaller grading value (Figure 8), indicative of better sorted cobbles
 560 moving landwards. This sorting was limited to the seaward limit of the revetment during
 561 test 2DR1 (0-7 h, $z_{wl} = 4.6$ m) when no overtopping occurred (see Figure 8b). Over-
 562 topping appears to accelerate this process by transporting smaller, more easily mobilised
 563 cobbles onto and landward of the crest during uprush where they become stranded and
 564 bury existing larger cobbles. This sorting is most evident during the final water level
 565 test 2DR4 (21-38 h, $z_{wl} = 4.9$ m; see Figure 8 e,f) and is visible in the images shown in

566 **Figure 10** for both the toe and crest of the revetment. Throughout the experiment both
 567 the smallest range of cobble sizes and smallest median cobble sizes were detected at the
 568 crest of the structure (see **Figure 8**). Note, the RFID-tagged cobbles had a minimum
 569 size of 40 mm and therefore this trend is not evident in **Figure 9** because the majority of
 570 cobbles forming the crest are smaller than 40 mm. Conversely, the toe of the revetment
 571 and the sparse cobble layer became less sorted with a higher median cobble size than was
 572 initially present (see **Figure 8**). The median cobble size at the toe increased from 51 mm
 573 at 0 h to 90 mm at 38 h. This is caused by a high proportion of smaller cobbles being
 574 transported landward from the toe, leaving the larger, less easily mobilised cobbles to
 575 form a stable toe for the revetment. Notably, no tagged cobble of weight greater than 2
 576 kg was detected more than 40 cm landward of its initial position by the end of standard
 577 wave testing (38 h, see **Figure 9** b). Some cobbles larger than 2 kg were detected seaward
 578 of their initial position. These are primarily from the surface and middle layer of the
 revetment and have rolled down the front face of the revetment. A comparison of the

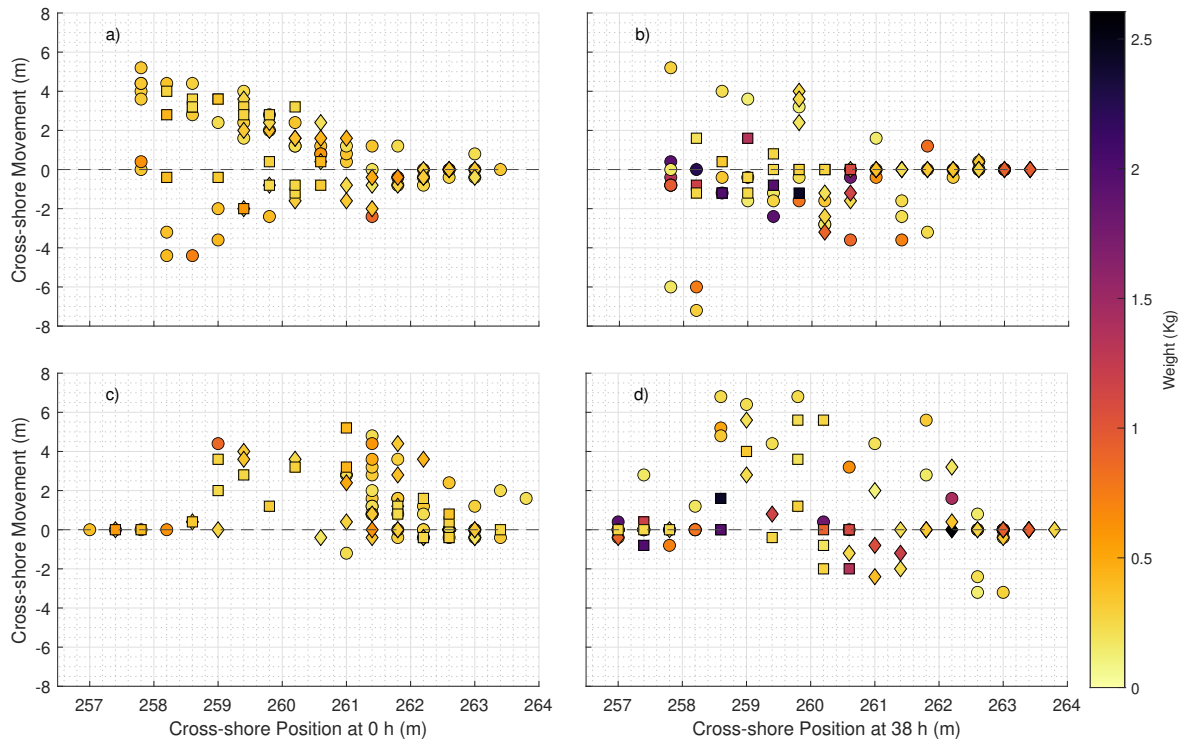


Figure 9: Absolute cross-shore distance travelled by tagged cobbles from their initial position, where positive is landward and negative is seaward for the a) well-sorted revetment (DynaRev1) and b) poorly-sorted revetment (DynaRev2) after 38 h of standard wave conditions. Absolute distance travelled by tagged cobbles from their detected position at 38h for the c) well-sorted revetment and d) poorly-sorted revetment during the erosion and recovery tests. The colour of each marker relates to the cobble weight as shown by the colour bar (left). The cobbles were distributed in three layers; revetment surface (circles), middle layer (diamonds) and sand-cobble interface (squares).

579 transport of tagged cobbles by layer for both the poorly and well-sorted revetments is
 580 shown in **Table 2**. At the end of standard wave testing ($t = 38$ h) only 54% were moved
 581 from their initial position for the poorly-sorted revetment (DynaRev2), predominantly in
 582 the seaward direction (see **Table 2** and **Figure 9** b). The cobbles forming the well-sorted
 583 revetment were more mobile, with 87% displaced from initial position, primarily in the
 584 landward direction (see **Table 2** and **Figure 9** a). It is important to note however that
 585 the largest tagged cobbles for the well-sorted revetment had an intermediate axis size
 586 (D_{50}) less than 100 mm, meaning that the whole tagged cobble population was more
 587

Table 2: Percentage of cobbles displaced from initial position by cross-shore direction at the end of standard wave conditions (38 h) and the end of recovery test (45 h) for the well-sorted revetment (WS, DynaRev1) and poorly-sorted revetment (PS, DynaRev). This is further broken down by placement layer of cobbles and several size categories

Cobbles Displaced from Initial Position		Total (%)		Landward (%)		Seaward (%)		Not Detected (%)		Average Landward Transport (m)	
		WS	PS	WS	PS	WS	PS	WS	PS	WS	PS
38 h	All	87	54	52	15	35	39	7	6	0.88	-0.45
	Surface	85	68	57	14	28	54	4	12	1.05	-0.65
	Middle	79	30	34	13	44	17	17	0	0.31	0.08
	Bottom	100	57	64	19	34	38	0	0	1.52	-0.3
45 h	All	80	60	60	27	20	33	16	21	2.08	0.69
	Surface	85	65	66	33	19	32	10	20	2.38	0.80
	Middle	70	43	43	16	27	27	30	30	1.54	0.18
	Bottom	85	71	75	28	10	43	10	9	2.87	0.93

588 susceptible to mobilisation by wave action. The movement of the tracked RFID cob-
589 bles was markedly different between the two experiments. For the well-sorted revetment
590 (DynaRev1) the cobbles showed a cyclic pattern of being dragged down to the toe when
591 exposed, these were then transported up and over the crest by overtopping events where
592 they were swiftly reburied by cobbles. For the poorly-sorted revetment (DynaRev2), the
593 cobbles were either dragged down into the toe of the revetment ($D_{50} > 100$) or trans-
594 ported over the crest upon being exposed ($D_{50} < 75$). At the end of the poorly-sorted
595 revetment testing ($t = 45$ h), the quantity of tagged cobbles displaced from their initial
596 position increased and the primary direction of travel became landward with an average
597 displacement of 0.69 m (see Table 2 and Figure 9 d). The erosive testing ($t = 38$ to
598 43h) was characterised by increased wave energy resulting in a greater ability to trans-
599 port heavier cobbles landward, combined with the exposure of tagged cobbles that were
600 initially deeper within the revetment. This led to an increase in the proportion of tagged
601 cobbles being displaced (Table 2).

602 Additionally, behaviour of the tagged cobbles varied between the two revetments
603 depending on the initial placement location (layer and cross-shore location). In both
604 cases, tagged cobbles placed on the surface and in front of the final crest location for
605 standard wave conditions ($x = 261.5$ m for DynaRev1 and $x = 261.9$ m for DynaRev2)
606 were most mobile. Cobble displacement in the middle layer was low for both revetments
607 due to the placement starting at $x = 259.4$ m. The bottom layer of cobbles were highly
608 mobile for DynaRev1. This suggests that overall, the poorly-sorted revetment is less
609 morphologically active at vertical depth than the well-sorted revetment, this is due to
610 the strong interlocking nature of poorly-sorted cobbles.



Figure 10: Photo of surface cobbles for the poorly-sorted revetment after standard wave conditions (38 h) at left) the toe of the revetment and right) the crest of the revetment. The total length of the scale bar is 198 mm.

611 3.4 Renourishment

612 Following the erosive and recovery wave conditions (38-45 h, Table 2) the thickness of
613 the poorly-sorted revetment on the seaward slope had thinned substantially and the
614 revetment consisted of a large crest feature with the majority of volume above the SWL,
615 with a thin layer of larger stones extending to the original toe location ($x = 256.9$ m)
616 (see Figure 4). An opportunistic nourishment of the front slope was carried out where
617 an additional 2.25 m^3 of material was added by simply dumping it on the front face
618 (Figure 11a). Additional erosive test were then carried out, these are not comparable
619 to those carried out for the well-sorted revetment due to a shortened testing regime and
620 different placement method - for the well-sorted revetment the renourishment was added
621 as a constant thickness layer over the front face. The material added to the poorly-
622 sorted revetment in DynaRev2 was quickly reshaped by waves and integrated into the
623 revetment. This had the primary effect of increasing the cobble depth of the front face but
624 some material was transported beyond the landward limit of the revetment, increasing its
625 length by 2 m. During these tests the toe retreated by a further 0.5 m but the crest was
626 stabilised at the pre-nourishment location ($x = 262.45$ m). The renourished revetment
627 preserved its centre of mass beneath the peak of the crest and 0.22 m higher than the
628 end of the resilience tests (38 h, 2DDR1) suggesting this is the most stable shape for
629 these cobble characteristics. The overall effect of the added material was to increase the
630 thickness of the front slope without affecting the overall behaviour of the revetment which
631 continued to reshape rapidly in response to changing conditions.

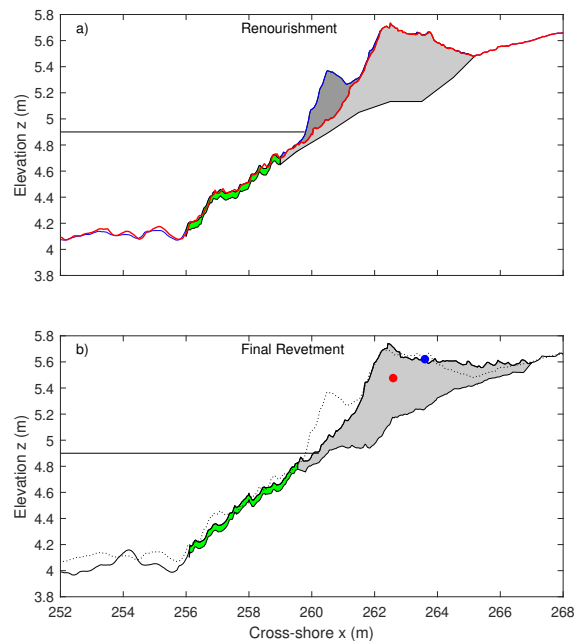


Figure 11: a) Renourished revetment where the light grey area outlined in red shows revetment cross-shore profile at the end of recovery wave conditions (2DDR1, 45 h, Table 1) and the dark grey area outlined in blue indicates the added material. b) The final shape of the revetment after 2 h 40 m of additional tests, the blue dot indicates the runup location under standard wave conditions. The dotted line indicates the revetment profile immediately following renourishment

632 4 Discussion

633 This section presents the current work wider context of both composite beaches and
634 dynamic revetments. It further comments on the application of these structures as coastal

635 protection.

636 The majority of revetment response in DynaRev2 happened within the first seven
637 hours of test 2DR4 (21 – 28 h), after this the retreat slowed (Figure 5) and the degree of
638 morphological change greatly reduced during the final 10 hours of standard wave condition
639 testing (28–38 h), Figure 3) was reduced. This suggests that the revetment moves towards
640 an equilibrium state within approximately 7 hours after each rise in water level. The
641 ability of the revetment to rapidly reshape towards a new equilibrium condition is also
642 seen in Figure 7 which shows that the revetment responds quickly to erosive conditions
643 but is already re-establishing the peaked revetment crest after only 2 h of low energy
644 recovery conditions. As the bulk of material remains part of the main cobble body and the
645 geometry remains approximately constant, the revetment can be considered dynamically
646 stable even though cobbles are moving with every wave. Further investigation involving
647 longer testing at each water level, as well as larger water level increases is suggested to
648 give additional insight into the time for a stable geometry to be reached and the level of
649 coastal protection provided.

650 The behaviour of the cobble body for the poorly-sorted revetment in DynaRev2 under
651 wave attack is that of a coherent structure, see Figure 4. The location of the toe, crest
652 and centre of gravity retreat in unison under standard wave conditions (Figure 5), which
653 can be viewed as a retreat of the whole body. Further, the cobble body of the revetment
654 is estimated to contain up to 97% of the original material at the end of the testing ($t = 45$
655 h). The rapid development of a peaked crest constructed from smaller angular cobbles
656 acted to limit overtopping to a greater degree than that shown in DynaRev1. Overtopping
657 was highest after the revetment crest was pushed over landward by a series of energetic
658 overtopping events, reducing the effective crest height (see 41-43 h in Figure 5 b). This
659 highlights the importance of the crest for protecting the upper beach and hinterland from
660 wave inundation.

661 The lack of variation in cobble size and the rounded nature of the cobbles for the
662 well-sorted revetment are the primary reasons for the different morphological responses
663 observed and are thought to be responsible for the large loss of sand and sinking of the
664 structure. Loss of sand beneath the revetment and associated sinking was much reduced
665 for the well-sorted revetment and this is thought to be due to the development of a layer
666 of small gravels at the sand-cobble interface which acts as a filter layer and prevents sand
667 from escaping. The material for existing dynamic cobble berm revetments is often poorly-
668 sorted local material (Komar and Allan (2010); Weiner et al. (2019)) and sinking has not
669 been reported at these sites. Bayle et al. (2021), reported a similar "natural filter layer" of
670 small gravel at the sand-cobble interface of a poorly-sorted revetment at North Cove and
671 they reported short term sand accumulation and loss within the cobble matrix driven by
672 both wave and aeolian processes, but no evidence of sinking. It is suggested therefore that
673 a wide size grading of gravel material should be used when constructing dynamic cobble
674 berm revetments. The results presented here also suggest that angular cobbles increase
675 interlocking and hence the stability of the revetment crest, which provides overtopping
676 protection to the back of the revetment and hinterland.

677 Similarly the wide size distribution and lower mobility of the interlocking angular
678 cobbles in the poorly-sorted revetment (DynaRev2) meant that the average landward
679 movement of cobbles during the erosive wave conditions was substantially smaller than
680 for the well-sorted case (DynaRev1): 0.69 m and 2.08 m respectively. This meant that
681 the tagged cobble population was far less mobile during DynaRev2 despite the degree
682 of morphological change presented. In the analysis, a cobble was only categorised as
683 displaced if it was detected at the end of the given test, while cobbles that were not
684 detected at all were categorised as 'not detected'. The decrease in the total number of

685 displaced cobbles for the well-sorted revetment during the erosion and accretion testing
686 (87% to 80%) is therefore explained by the greater number of non-detected cobbles and
687 not an indication of a reduced quantity of transported tagged cobbles. As a result, it
688 is probable that the displacement of tagged cobbles during both experiments is under
689 represented.

690 Overall, given the differing morphological response of the two revetments, it is arguable
691 that the new design for DynaRev2 performed better. The development of the filter
692 layer prevented the structure from sinking. When combined with the crest growth it
693 maintained the majority of the main cobble body above the water level till the end
694 of the experiment (96.2 %, 2DDR1, 45 h). Additionally, the structure maintained a
695 significant difference in height between the crest peak and still water level. This reduced
696 overtopping providing better protection to the upper beach. This suggests that a key
697 consideration for dynamic cobble berm revetment design is the characteristics of the
698 cobbles used for construction. As a result it may be desirable to use angular, or at least
699 sub-angular material when constructing dynamic cobble berm revetments, though this
700 has implications for the recreational function of the beach and is not in keeping with the
701 natural character of composite beaches.

702 Maintenance of dynamic cobble berm revetments is vital to their long-term efficacy.
703 The renourishment of the structure suggests that there is no need to carefully place the
704 renourishment material. It is sufficient to simply dump the material on the revetment
705 front face where it will be rapidly reshaped by wave action. It is likely in fact that a
706 revetment could be initially constructed by simply dumping material around the high
707 tide line and allowing wave action to shape the berm, however this has not been tested.

708 The 2D nature of wave flume experiments has limitations which were present in the
709 current study. Primarily, longshore transport cannot be represented in laboratory envi-
710 ronments. While cross-shore processes are expected to primarily influence the revetment
711 during storm conditions and be the major driver of morphological change, the long term
712 impact of longshore cobble transport could influence the lifespan of the structure. Future
713 field studies of dynamic cobble berm revetments and composite beaches should inves-
714 tigate longshore processes including longshore cobble transport. The resulting findings
715 will better inform re-nourishment schemes for dynamic cobble berm revetments. One
716 approach currently being tested at North Cove, USA is a sacrificial feeder bluff of cobbles
717 updrift of the dynamic cobble berm revetment however the efficacy of this is not yet clear.

718 A further issue in terms of the design and analysis of dynamic cobble berm revetments
719 is the lack of numerical modelling tools. An investigation by McCall et al. [McCall et al.](#)
720 (2019) found that although the Xbeach-G gravel beach model accurately reproduced
721 morphology changes in some cases, it couldn't represent the sand erosion beneath the
722 revetment structure and associated lowering of the sand-cobble interface observed during
723 the DynaRev experiment. As noted above, it is likely that this effect was enhanced due to
724 the use of very well-sorted round cobbles and was much less evident during the DynaRev2
725 experiment and on composite beaches and dynamic revetments in the field. As a result
726 DynaRev1 may not be an ideal validation case and additional testing of DynaRev2 in
727 XBeach-G is recommended.

728 5 Conclusions

729 The purpose of a dynamic revetment is to provide protection to the hinterland as well as
730 reducing erosion of the upper beach face. It is clear that both the well and poorly-sorted
731 revetments are appropriate for this purpose based on the experimental results, with the
732 caveat that the observed sinking process needs to be better understood. Both revetments

733 reduced the horizontal runup excursion compared to a sand beach only case (see [Bayle](#)
734 [et al. \(2020\)](#)) and the erosion of the beach face is significantly less than during the sand-
735 only case measured during the DynaRev experiment. Further, both revetments remained
736 dynamically stable and maintained the majority of their cobble mass during testing.

737 For both revetment designs wave overtopping of the crest location is required for
738 morphological change. As overtopping greatly increased after each water level increase
739 so did the rate of morphological change. However, this morphological change reduces as
740 both designs move towards a new dynamic stability, where cobbles are free to move under
741 wave action but the structure maintains a consistent shape. The revetment in DynaRev1
742 constructed using well-sorted, rounded cobble material developed a low flat crest with
743 sinking beneath the seaward face of the revetment throughout the entire experiment.
744 Conversely the poorly-sorted angular revetment in DynaRev2 gained elevation through
745 the development of a peaked crest due to both the strong interlocking nature of the cobbles
746 used and the sorting effect sending smaller cobbles up the front face of the revetment under
747 wave action. A sinking effect was only observable up to $28h$ and slowed substantially after
748 $14h$. It is hypothesised that this is due to the ability of poorly-sorted material to form
749 a filter layer at the intersection between the sand and the structure, this reduces water
750 percolating into the sand preventing its erosion. It is estimated that cobbles will become
751 rounded in 2 to 5 years when placed in the structure ([Allan and Gabel \(2016\)](#)) however
752 the fragmented gravels will maintain the filter layer. The revetment in DynaRev2 gave a
753 better reduction in the amount of overtopping but both designs limited wave excursion
754 to the landward limit of the structure for all but the largest runup events.

755 Long-term studies of dynamic cobble berm revetments in the field are now required to
756 ascertain their long term viability, however some re-nourishment of the structures is likely
757 to be needed in most locations either through periodic renourishment or installation of
758 an updrift feeder bluff. If direct renourishment is required, this can be done by simply
759 dumping stone on the front face and allowing wave action to reshape the material.

760 The uptake of these structures is dependent on more than just their coastal protection
761 performance. Many coastal protection schemes are concerned with the ecological impact,
762 environmental impact, aesthetics and cost of any proposed coastal works. The ecological
763 impact of these structures is yet to be determined. However, the two designs provide a
764 more aesthetic but costly solution in DynaRev1 and a cheaper but less aesthetic solu-
765 tion in DynaRev2. Further, if constructed using locally sourced material the cost and
766 environmental impact would be low compared to more substantial coastal works such as
767 sea walls, due to the ease of construction (simple dumping of stone) and reduced need
768 to transport material. The final consideration is that many coastal protection bodies are
769 looking to create more ‘natural’ defences for preservation of the coastline ([Pye and Blott](#)
770 [\(2018\)](#)), dynamic cobble berm revetments fulfill this requirement.

771 **Declaration of competing interests**

772 The authors declare that they have no known competing financial interests or personal
773 relationships that could have appeared to influence the work reported in this paper.

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