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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  $875 \text{ m}^3$ . 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,  $\Omega_0$  is the dimensionless fall velocity as given by Dean (1973); Gourlay (1968) and wave energy is given per metre of wave crest.

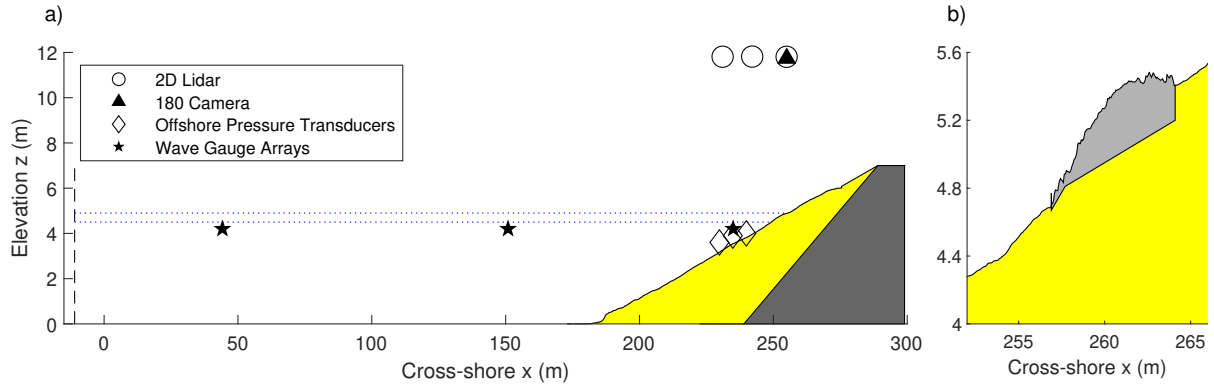
Test	Start (hr)	End (hr)	Duration (hr)	$H_s$ (m)	$T_p$ (s)	Water Level $z_{wl}$ (m)	$\Omega_0$	Energy (MJ)
Beach Equilibrium Approach								
2DR0	-20:00	0:00	20	0.8	6	4.5	3.38	0.78
Revetment Construction								
2DR1	0:00	7:00	7	0.8	6	4.6	3.38	0.78
2DR2	7:00	14:00	7	0.8	6	4.7	3.38	0.78
2DR3	14:00	21:00	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 m<sup>3</sup> 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/m<sup>3</sup>, bulk density 1760 kg/m<sup>3</sup> 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 m<sup>3</sup> 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  $0.1666^\circ$ . A Vivotek MS8391-EV  $180^\circ$  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 m<sup>2</sup> 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.

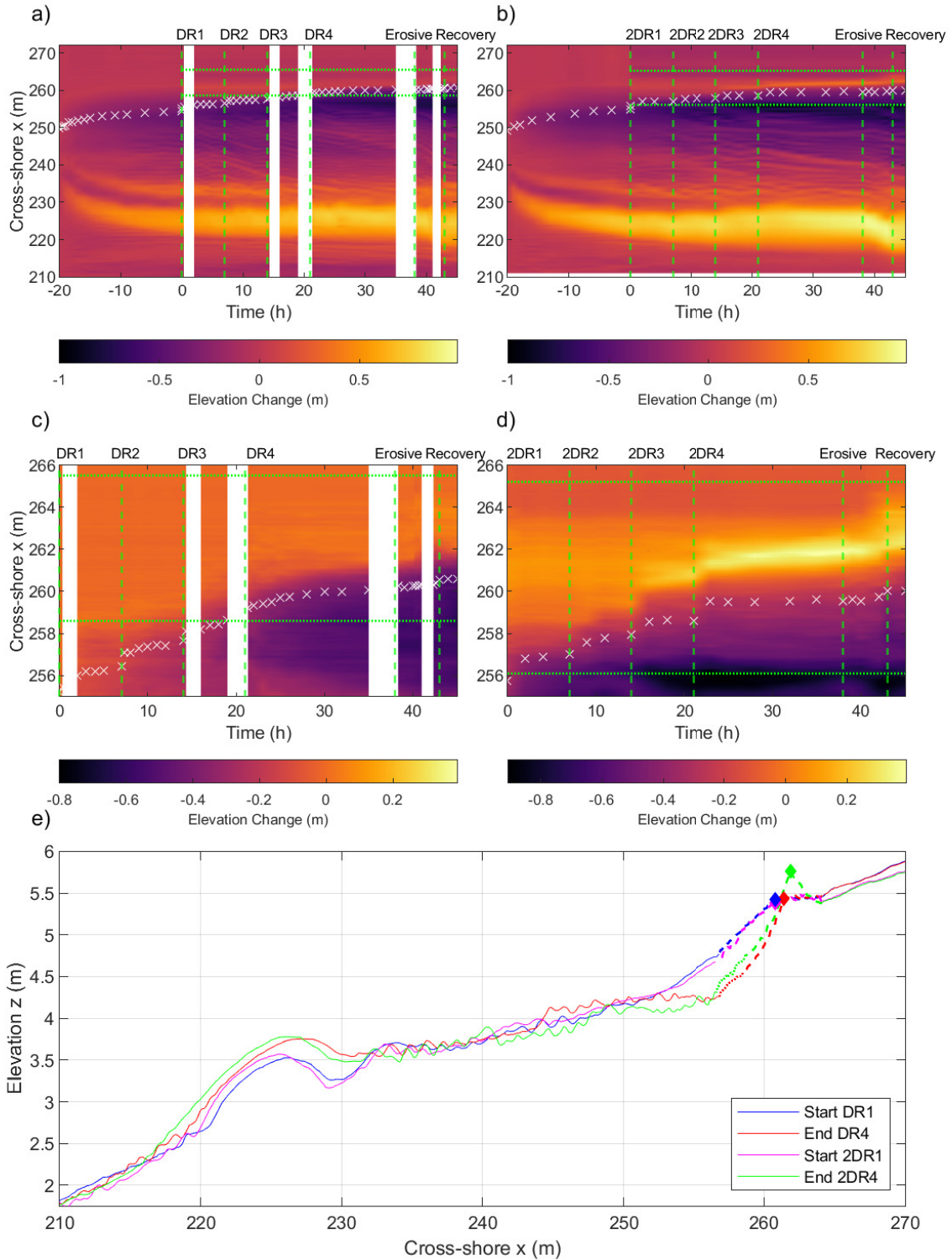
### 326 3.1 Comparison of Morphological Behaviour

#### 327 3.1.1 Evolution of Revetment Shape During the Water Level Tests

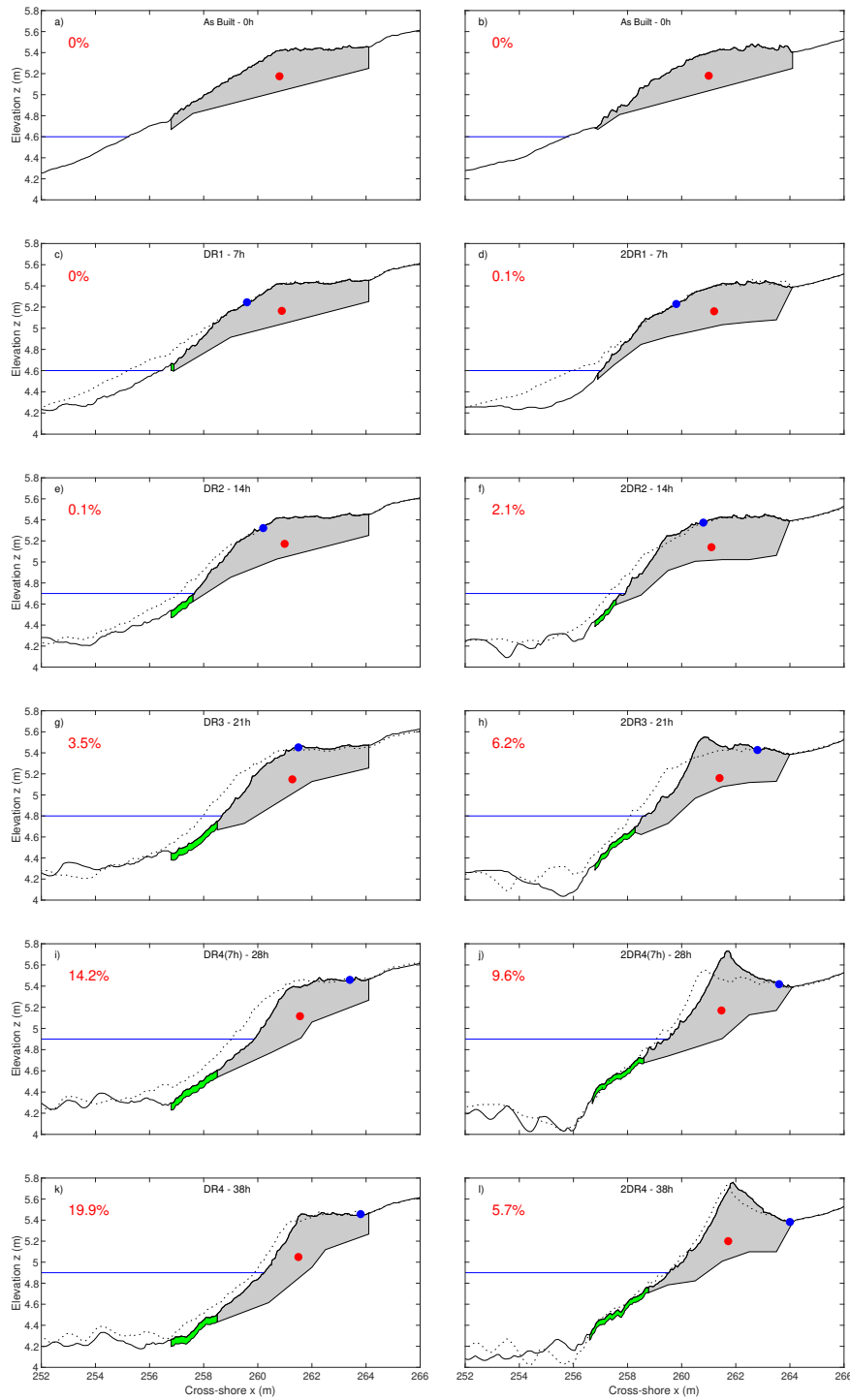
328 The morphological evolution of the revetments and sandy beach immediately seaward of  
329 the revetment for both DynaRev1 and DynaRev2 is presented in Figure 3a,b. Note that  
330 0 h corresponds to the time of revetment installation, explaining the sudden accretion  
331 between  $x = 259$  and  $x = 262.5$ . 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



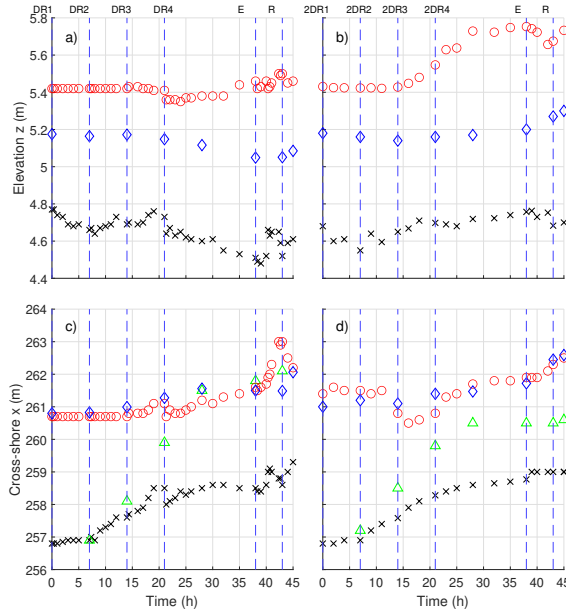
**Figure 3:** Bed elevation change relative to initial beach profile over the entire experiment for a) DynaRev1, well-sorted revetment, b) DynaRev2, poorly-sorted revetment. Revetment surface elevation change relative to installed profile for c) DynaRev1, d) DynaRev2. The dashed green vertical lines 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

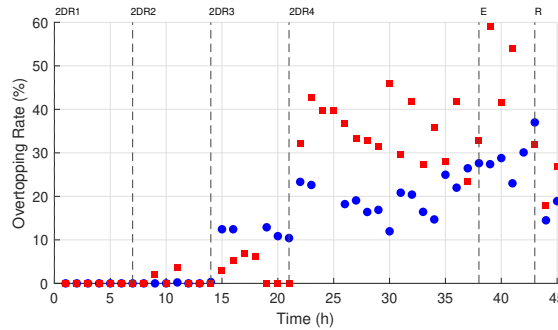
366 original toe position and accounted for just 2% of the revetment’s original volume. By  
 367  $t = 14$  h an intermediate berm formed at  $x = 259.4$  m just below the 2% run-up elevation  
 368 (Figure 4f). The well-sorted revetment in DynaRev1 had a similar response and after 14  
 369 hours of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

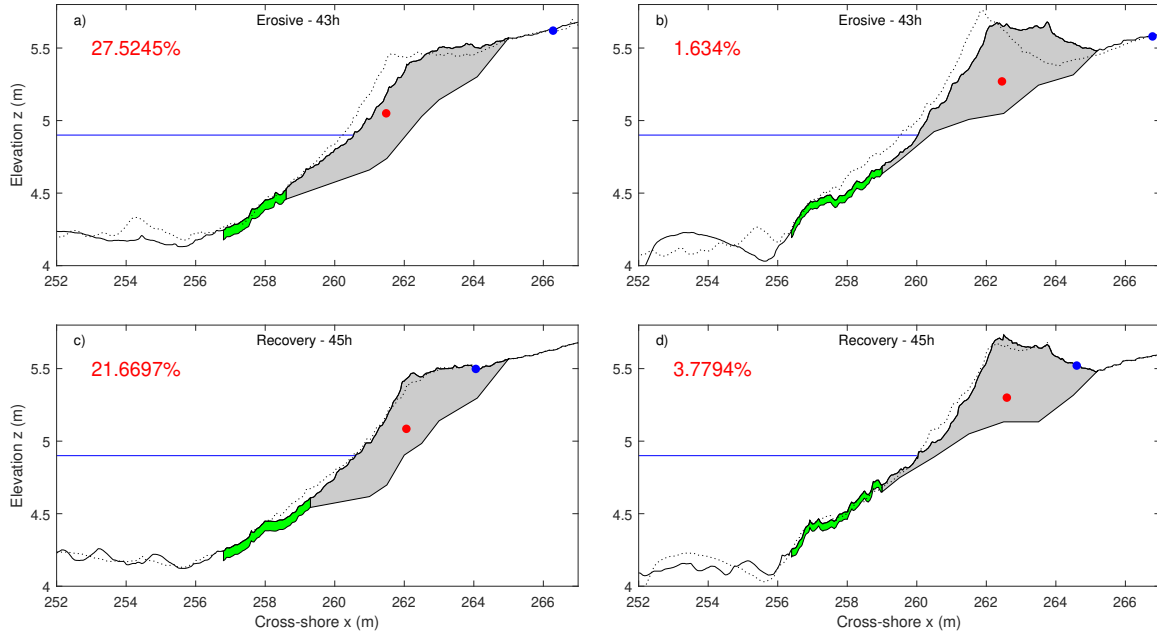
391 change, leading to a 18 cm vertical crest growth and a 90 cm landward retreat. Analysis  
392 of the revetment profiles indicates that much of the material that moved onto the top  
393 of the structure did so during the first hour of the test (21-22 h) and is detectable in  
394 the profile measurement 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



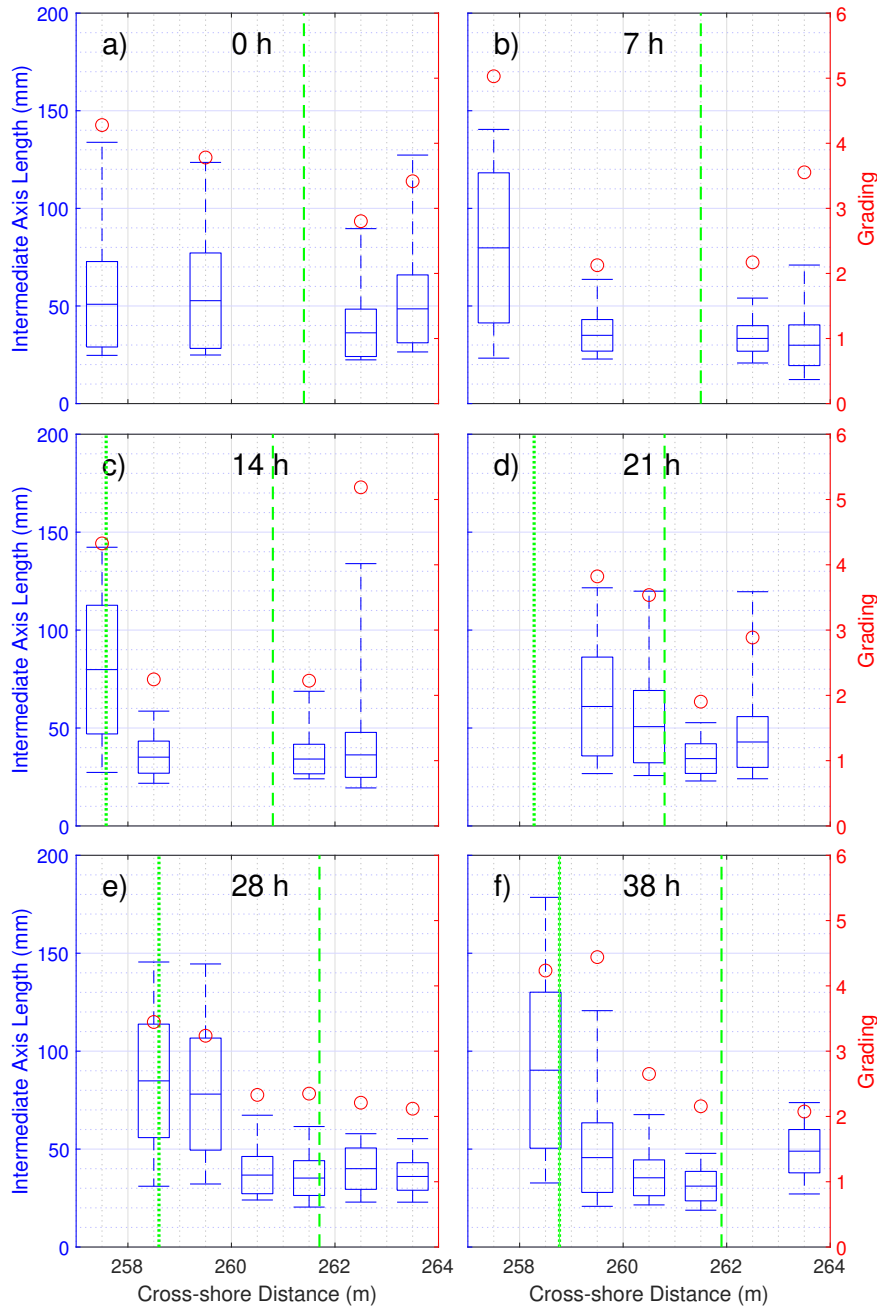
510 the designed crest was infrequent during this time period (Figure 6) and the increased  
 511 horizontal runup excursion between  $t = 7$  h and  $t = 14$  h ( $z_{wl} = 4.7$  m) for DynaRev2  
 512 is explained by the crest being constructed slightly landward of that for DynaRev1 (see  
 513 subsection 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.

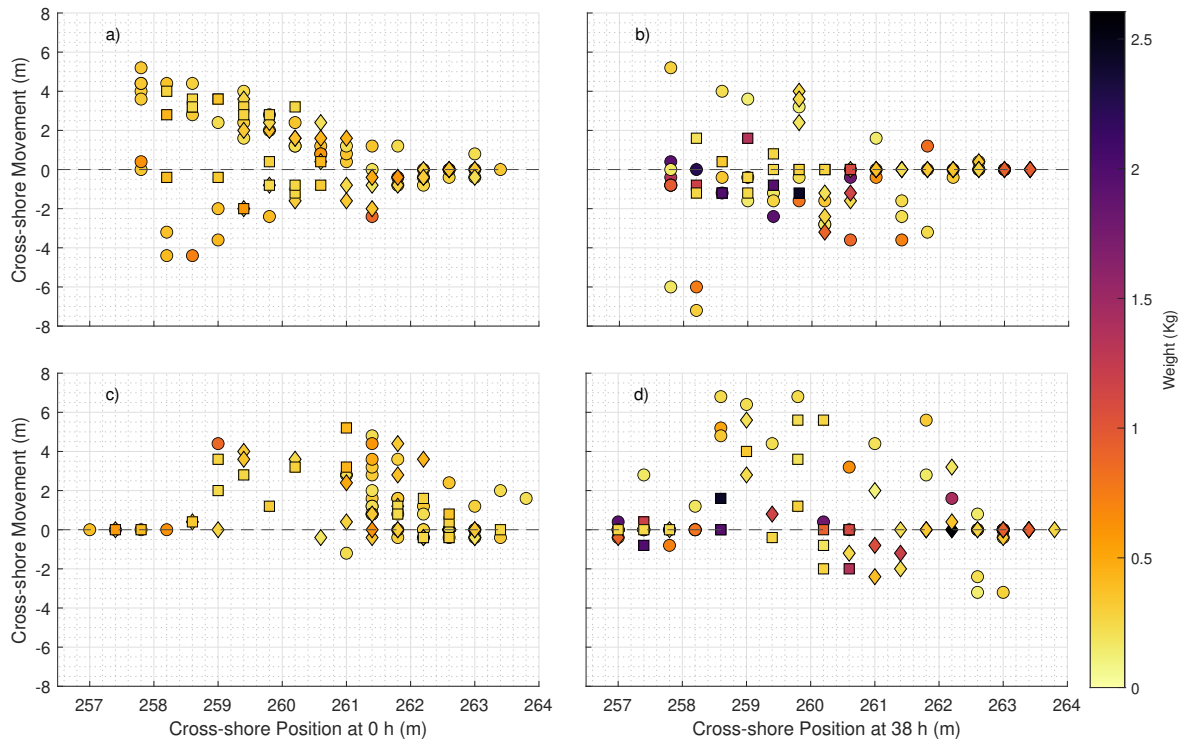
555 The distribution of cobbles on the surface of the poorly-sorted revetment was initially  
 556 very consistent at all cross-shore positions (Figure 8a). Subsequently, the surface cobbles  
 557 underwent a sorting process throughout the experiment as they were mobilised by wave



**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).

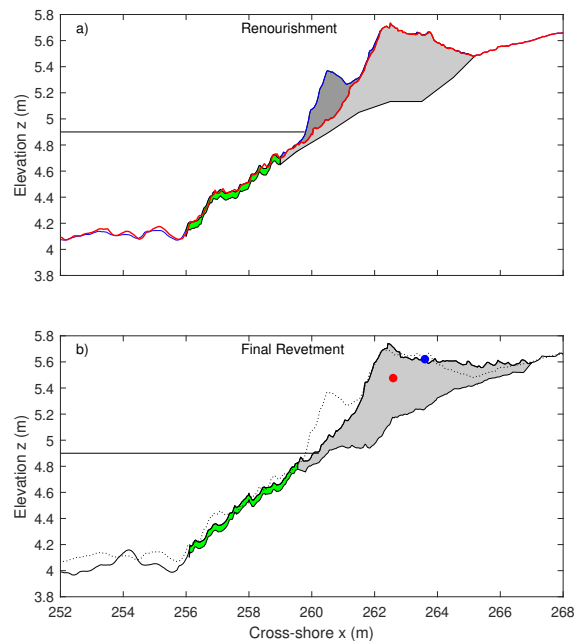
602 Additionally, behaviour of the tagged cobbles varied between the two revetments  
603 depending on the initial placement location (layer and cross-shore location). In both  
604 cases, tagged cobbles placed on the surface and in front of the final crest location for  
605 standard wave conditions ( $x = 261.5$  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  $2.25 \text{ m}^3$  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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