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Comparison of dynamic cobble berm revetments with differing gravel characteristics

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ABSTRACT

Pressure on the coastline is escalating due to the impacts of climate change, 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. Therefore coastal protection schemes will increase in cost and scale. 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 berm constructed from cobble and other gravel sediments 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 gravel characteristics; well-sorted rounded gravel (DynaRev1) and poorly-sorted angular gravel (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 gravel is 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 is 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 gravel and a lower elevation flat crest which responded less well to changes in conditions. This occurred due to two processes: (1) for the poorly-sorted case, gravel sorting processes moved small to medium gravel material ($D_{50} < 70$ mm) to the crest and (2) the angular nature of the poorly-sorted gravel material promoted increased interlocking. Both of these processes led to a gravel matrix that is more resistant to wave action and gravitational effects. Both revetments experienced some sinking due to sand erosion beneath the front slope. The rate of sinking for the well-sorted case was larger and continued throughout due to the large pore spaces within the gravel matrix. For the poorly sorted revetment in DynaRev2, sand erosion ceased after approximately 28 h due to the development of a filter layer of small gravel at the sand-gravel interface reducing porosity at this location, hence a larger volume of sand was preserved beneath the structure. Both designs present a low-cost and effective solution for protecting sandy coastlines but from an engineering viewpoint it appears better to avoid well-sorted gravel material and greater gravel angularity has been seen to increase crest stability.

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1. Introduction

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

Traditional coastal protection techniques can be divided into two broad groups (Cartwright et al., 2008). The first is hard engineering solutions often referred to as grey structures (Morris et al., 2018), these consist of fixed structures such as seawalls and artificial reefs. They are designed to provide a fixed barrier and are typically expensive to install (Howe and Cox, 2018a,b). Additionally, many existing hard engineering schemes were not designed for the current and predicted wave climates and therefore require upgrading or replacing. For example, it is common for sea walls to have a fixed crest height which was designed without consideration of sea level rise. Increasing the elevation of these structures risks failure due to the capacity of the foundations to bear additional load.

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

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

The use of gravel structures in coastal protection is well documented. While many differ to the presented dynamic cobble berm revetments they often demonstrate similar design ethos and behaviour. Artificial gravel beaches, often referred to as 'dynamic revetments', have been constructed in the great lakes and other locations, these are reviewed in detail by Bayle et al. (2020) but surmised here. Lorang (1991) details the constructions of a gravel perch beach at Flathead Lake in Montana where a stable base of boulders was overlain with a layer of gravel material. It was shown to reduce erosion but was lost material due to long shore currents. Another example is the gravel beach installed by Allan at Yaquina Bay, Oregon (Allan et al., 2012). It stabilised the shoreline protecting a foot path located behind the beach. Occasionally these have been installed as part of hybrid structures. The port of Rotterdam was protected by a gravel beach fronted by an artificial reef acting as a breakwater (Loman et al., 2010), this was also utilised on the Adriatic coast of Italy (Tomasicchio et al., 2010). In both cases the breakwater decreases the wave energy reaching the coastline, while the gravel beach dissipates the swash energy.

Artificial gravel beaches have been tested in laboratory wave flumes (Van Hijum and Pilarczyk, 1982; Pilarczyk and Den Boer, 1983). For example, Van der Werf and Van Gent (2011) examined the influence of infiltration into the gravel matrix on the dynamic response of such structures, this was done using an impermeable bed beneath the gravel and introducing sand into the structure. They found that dynamic behaviour reduced as sand was incorporated into the structure and that premixing the two sediments yielded a different dynamic response. A structure consisting of small rocks covering a concrete slope was tested by Ahrens (1990). It was shown that the gravel slope was dependent on wave conditions and not the initial slope of the structure. Ahrens also introduced the concept of critical mass, the mass of stones required to maintain the stability of the structure for given wave conditions. van der Meer (1988) completed a substantial investigation into the response of an artificial gravel beach to varying parameters including gravel characteristics and wave conditions . Notably, it was found that grain size had a significant effect on the slope stability but shape and grading did not.

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

In engineering terms dynamic cobble berm revetments are artificially constructed berms of cobble and other gravel sediments, placed at or near the high tide berm of a sandy beach. In this paper the use of gravel shall refer to all sediments that form the berm including the cobbles. A review of these structures is provided by Bayle et al. (2020) and surmised here. They are designed to mimic naturally occurring composite beaches, providing erosion control, stability for the upper beach and protection to the hinterland. Due to this they are considered a nature based solution for coastal protection. However, unlike composite beaches these structures are not supplied by a natural source of gravel sediment and generally require periodic renourishment to balance longshore losses and maintain their volume. The DynaRev1 large-scale laboratory experiment (Bayle et al., 2020) compared the resilience and morphological response of a dynamic cobble berm revetment constructed using well-sorted, rounded gravel to that of a sand beach under both wave forcing and increasing water level. Bayle et al. (2020) found that installation of a dynamic cobble berm revetment led

Fig. 1. (Left) The poorly-sorted revetment. (Right) The well-sorted revetment.

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

At present, dynamic cobble berm revetments designed using non-sorted gravel sediments are effective at protecting their respective coasts. This current study examines the differences in morphological response of revetments designed using differing gravel populations. It is then contextualised in consideration of coastal protection techniques. It follows that published by Bayle et al. (2020) which reported on the 'DynaRev' experimental investigation of a dynamic cobble berm revetment constructed using well-sorted, rounded gravel (see Table 1, hereafter called DynaRev1), data from the DynaRev1 experiment is available in Blenkinsopp et al. (2021).

This work presents a comparable large-scale experiment (DynaRev2), designed similar to the DynaRev1 experiment to investigate the performance of a different dynamic cobble berm revetment under the same conditions. It was constructed with approximately the same geometry as the original revetment, but comprised of poorly-sorted, angular material equivalent to quarry run that would be expected to be widely available throughout the developed and developing world. This work also compares the results from both DynaRev1 and DynaRev2 experiments (see Fig. 1 for comparative photo of the two revetment structures), highlighting the difference in their respective responses to wave attack. Further, it draws out many key considerations that may be useful to the design of dynamic cobble berm revetments. This includes the formation of a filter layer to prevent sinking and the importance of crest height to reducing overtopping rates. The paper also provides future consideration for further study that will increase the deployment of such structures.

The paper is structured as follows: This section provides a background and shortened overview of the existing studies pertaining to dynamic cobble berm revetments. Section 2 details the methodology of the prototype-scale flume testing of the structure constructed using poorly-sorted angular material. Section 3 presents a thorough comparison of the morphodynamic response of the structures under testing and investigates their potential as coastal defence. Section 4 discuses the results in the wider context of coastal protection and highlights the limitations of the structures. Section 5 presents a conclusion for the 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 gravel instead of well-sorted rounded material, see Table 1. 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 Fig. 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 Fig. 2.

Table 1
Table comparing gravel characteristics for DynaRev1 and DynaRev2. Roundness and sphericity were estimated using the comparison chart given by Powers (1953). Sediment was classified according to the Wentworth scale (Tomasicchio et al., 2013; Wentworth, 1922).

Experiment	D_{10}	D_{50}	D_{90}	Sediment classification	Grading	Roundness	Sphericity
DynaRev1	52	63	99	gravel	1.32	Well Rounded	Medium
DynaRev2	23	44	123	gravel	3.79	Angular	Low

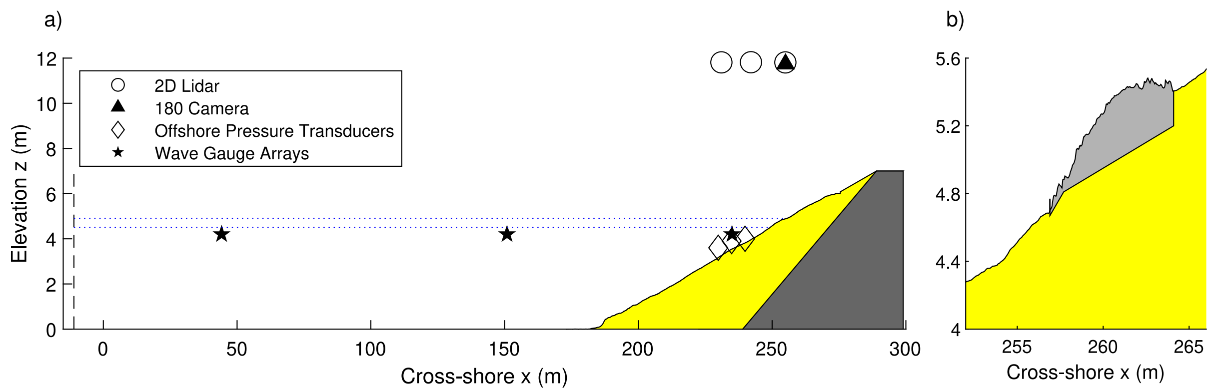

Fig. 2. (a) Schematic of initial experiment setup including instrument locations and profile of the placed beach. The vertical dashed line indicates the location of the wave paddle and the horizontal dotted lines give the lowest and highest water level during the experiment. (b) Close-up schematic of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

2.2. 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 2 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 2.4. 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 as given by Bayle et al. (2020), 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 Section 2.1 was allowed to evolve naturally under 20 h 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 2; for further details on the revetment geometry see Section 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 (see Table 2).

Following the water level rise testing a series of ‘resilience tests’ were completed, these were designed using the dimensionless fall velocity (see Table 2, Gourlay, 1968; Dean, 1973) for erosive and accretive wave conditions on the underlying sand beach. The first set referred to as erosive testing conditions had increased wave energy and a constant water level (z_{wl} = 4.9 m, see Table 2). This was then followed by a final ‘recovery’ test which used the standard irregular wave conditions to encourage recovery of the structure. The tests had varying duration’s and are denoted using the naming convention 2DR(E,R)<test number> where E and R refer to erosive and recovery tests respectively.

The ‘Re-nourishment Tests’ examined the process of recharging the revetment, see Table 2. An additional 2.25 m^3 of gravel were placed on the front face of the revetment, this volume was governed by the remaining available material at the time of the experiment. This was forced using a mixture of both the standard irregular wave conditions and a shortened high energy wave test (Table 2). These are denoted using the naming convention DRN<test number>. Due to restricted experimental time this was a shortened process and is not considered directly comparable to the DynaRev experiment.

2.3. Revetment installation and characteristics

The poorly-sorted revetment used in DynaRev2 was designed with the same geometry as the well-sorted revetment from DynaRev1. Prior to installation, the revetment location was flattened to a 1:15 slope to allow sufficient gravel placement at the design slope of 1:6.3 (this was also done for the well-sorted case). Construction was carried out using a front end loader to dump the gravel at the approximate location and then manually reshaped to match the profile of the well-sorted revetment. Due to difficulties in shaping angular gravel, the profile of the revetment differed slightly to that in DynaRev1, with a less well-defined crest (Fig. 2b). The revetment was constructed using poorly-sorted granite gravel with density 2700 kg/m^3, bulk density 1760 kg/m^3 and a porosity of 0.35. The intermediate axis characteristics were as follows; D_{10} = 23 mm, D_{90} = 123 mm, D_{50} = 44 mm with a grading value of D_{85}/D_{15} = 3.79 (see Table 1 for comparison to DynaRev1 and Eq. (1) in Section 2.5 for details of grading). The front slope had an incline of 1:6.3 and the toe was located at x = 256.9 m and z = 4.67 m. Using the runup equation for gravel beaches developed by Poate et al. (2016) the 2% exceedance runup elevation was predicted to be 0.72 m, therefore the crest was constructed at x = 260.8 m and z = 5.42 m corresponding to the predicted $R_{2\%}$ for a water level z_{wl} = 4.7 m. Behind the crest, the poorly-sorted revetment was approximately horizontal and intersected the sand beach at x = 264.1 m. The total volume of placed gravel was 9.375 m^3 and weighed 16.5 t.

2.4. 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

Table 2
The testing conditions for DynaRev1 and DynaRev2 (denoted by the prefix '2') . 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								
DR0/2DR0	−20:00	0:00	20	0.8	6	4.5	3.38	0.78
Revetment Construction								
DR1/2DR1	0:00	7:00	7	0.8	6	4.6	3.38	0.78
DR2/2DR2	7:00	14:00	7	0.8	6	4.7	3.38	0.78
DR3/2DR3	14:00	21:00	7	0.8	6	4.8	3.38	0.78
DR4/2DR4	21:00	38:00	17	0.8	6	4.9	3.38	0.78
Resilience Tests								
DRE1/2DRE1	38:00	40:00	2	0.9	6	4.9	3.69	0.99
DRE2/2DRE2	40:00	42:00	2	1	7	4.9	3.51	1.23
DRE3/2DRE3	42:00	43:00	1	1	8	4.9	3.08	1.23
DRR1/2DRR1	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

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

2.5. Data processing

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

2.5.2. Swash detection

High frequency measurements of the exposed beach profile and water surface were obtained using the Lidar array. Each Lidar detects the nearest surface: either the water surface or exposed beach face without distinction between the two. To generate a time series for the beach profile and swash separately, first, a 0.1 m horizontally gridded sub sample was created and all measurements were processed with a moving-average 2 s window with a mean variance threshold. Then the data were separated into a stationary bed elevation and a swash surface elevation time series using the method presented by Almeida et al. (2015). The continuous shoreline position was extracted by finding the most landward position of the swash at all time steps. These were validated by plotting the continuous shoreline time series over rectified stacks from the 180-camera (see Section 2.4) for every run. The difference between the stack imagery and the continuous shoreline position was less than 0.1 m for all tests.

2.5.3. Cross-shore grain size distribution

The cross-shore variation in surface grain size distribution over the dynamic cobble berm revetment was estimated using a digital point count technique which utilised downward looking images of the revetment surface captured using a digital single-lens reflex (SLR) camera. Photos were taken at 1 m cross-shore increments along a line offset 0.5 m from the flume centreline between $x = 257.5$ m and $x = 264.5$ m immediately after revetment installation and after each test (Table 2). The photographs adhere to the rules of appropriate grain size imagery as presented by Buscombe (2013).

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

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

and is considered a good estimate for the spread of the gravel population. An additional measure of spread is provided by the median absolute deviation which is more robust for skewed data. The gravel size distributions obtained from the digital point count software were validated against manual measurements of 100 individual gravel particles randomly selected from within a 1 m^2 at two locations. This procedure was repeated twice and agreed closely with the image-based results.

3. Results

This section explores the general and morphodynamic behaviour of the beach and dynamic cobble berm revetment constructed from poorly-sorted, angular material during DynaRev2. These are compared with results presented for the dynamic cobble berm revetment constructed using well sorted, rounded gravel during the DynaRev1 experiment (Bayle et al., 2020) and put in the context of coastal protection. It focuses on both revetment's physical evolution and stability in response to wave attack. Additional analysis of the behaviour of gravel within the poorly sorted revetment is also presented, including the movement of individual gravel particles using the radio frequency identification tracking system (RFID) and the sorting of gravel over the exposed surface of the revetment, see Section 2.4 for details. Further, results capturing the wave run-up and shoreline retreat are presented.

3.1. Comparison of morphological behaviour

3.1.1. Evolution of revetment shape during the water level tests

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

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

The crest was rarely overtopped during the first 14 h of testing during DynaRev2 (tests 2DR1 and 2DR2, 0 to 14 h), see Fig. 6. The swash zone was limited to the front face of the gravel body and morphological change was confined to this region. Water infiltration into and through the structure eroded sand beneath the front face, reducing the elevation of both the toe and centre of mass of the revetment (red dots in Fig. 4, blue diamonds in Fig. 5). A single layer of sparse gravel mixed with sand was formed at the front of the revetment, termed the sparse gravel layer (marked in green in Fig. 4). This layer was formed from gravel at the larger end of the size range, was approximately 1 m in cross-shore extent by $t = 14$ h, did not extend seaward of the original toe position and accounted for just 2% of the revetment's original volume. By $t = 14$ h an intermediate berm formed at $x = 259.4$ m just below the 2% run-up elevation (Fig. 4f). The well-sorted revetment in DynaRev1 had a similar response and after 14 h of tests and the geometry of the two revetments at this time was quite similar.

Tests DR3 and 2DR3 ($z_{wl} = 4.8$ m; $t = 14$ to 21 h) resulted in the divergence in the response of the two revetments (Fig. 4g and h). The new water level led to an increased rate of overtopping for both revetments driving morphological change, see Fig. 6 for further details. Landward transport of gravel driven by overtopping events led to the development of a very peaked crest behind the initial crest location for the poorly-sorted revetment (Fig. 4h) and a toe retreat of 1 m (Fig. 5d). This resulted in an increase in structure height and the front slope changed from a convex to a concave shape (Fig. 4h). Conversely, the well-sorted revetment (DynaRev1) showed similar crest and toe retreat but the shape remained consistent with no crest growth (Figs. 4g; 5a and c). The development of the peaked crest feature for the poorly-sorted revetment in DynaRev2 is a result of the gravel population characteristics. Firstly, highly angular gravel particles interlock better, reducing the frequency of seaward gravel transport due to increased stability under wave attack. Secondly, the wide size range of the poorly-sorted gravel leads to size sorting on the revetment surface, with larger gravel accumulating near the toe and primarily smaller gravel being transported landward to form the peaked crest feature (see section 4.3 for further analysis of surface gravel size distributions). This process results in the elevation gain and landward movement of the crest feature for the poorly-sorted revetment in DynaRev2 as it develops under wave forcing.

Tests DR4 and 2DR4 ($z_{wl} = 4.9$ m; $t = 21$ to 38 h) were the longest (17 h) and experienced the highest overtopping rates (see Fig. 6). During the first seven hours the poorly-sorted revetment (DynaRev2) experienced accelerated morphological change, leading to a 18 cm vertical crest growth and a 90 cm landward retreat. Analysis of the revetment profiles indicates that much of the material that moved onto the top of the structure did so during the first hour of the test (21–22 h) and is detectable in the profile measurement taken at 23 h (Fig. 3d). The toe of the main gravel body continued to retreat (Fig. 5d) and the sparse gravel layer occupied the free space in front of the structure (Fig. 4j), this was composed of larger gravel particles which are less mobile under wave action (see Section 3.3). The well-sorted revetment in DynaRev1 continued to retreat during hours 21 to 28 ($z_{wl} = 4.9$ m) and began to develop a more prominent crest (Fig. 4i), however this did not result in vertical growth of the structure. The rate of morphological change decreased for both revetments over the next ten hours (Figs. 4k and l; 5) suggesting they were approaching a dynamic stability. In this state individual gravel are transported both landward and seaward but the overall shape remains consistent. It is clear that the poorly-sorted revetment was more dynamically stable than the well-sorted revetment between hours 28 and 28 as shown by the consistent location of geometric features such as crest, toe and centre of mass (Fig. 5). Therefore, it can be concluded that the poorly-sorted revetment is prone to a more rapid morphological stabilisation as forcing conditions change, with initial wave overtopping promoting the formation of a more substantial and stable crest that subsequently reduces overtopping of the structure, and therefore decreases gravel transport up and over the crest. Both revetments had a final front face slope of 1:3.9, but the centre of mass for the poorly-sorted revetment in DynaRev2 was 0.2 m landward. However this is mainly caused by the formation of the substantial crest feature and is not necessarily indicative of a greater rate of landward retreat. The main gravel body of the poorly-sorted revetment was slightly shorter in cross-shore extent than that of the well-sorted revetment, 5.3 m and 5.6 m respectively.

The cross-shore extent of the main gravel body of both revetments reduced under the standard wave conditions (Fig. 4) and are similar throughout the experiment. Because the landward limit of the revetment did not move under stand wave testing, this can be attributed

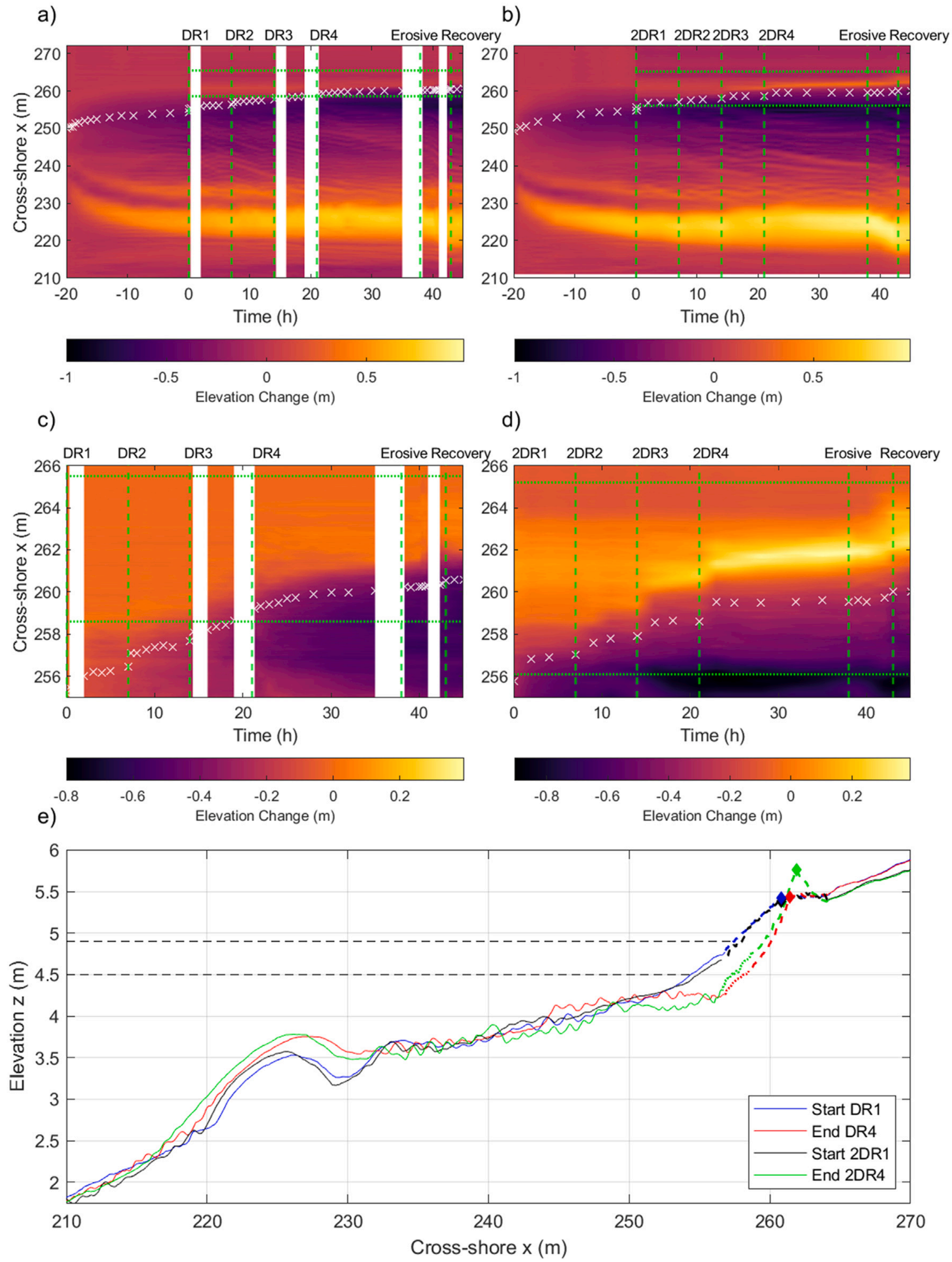

Fig. 3. Bed elevation change relative to initial beach profile over the entire experiment for (a) DynaRev1, well-sorted revetment, (b) DynaRev2, poorly-sorted revetment. Revetment surface elevation change relative to installed profile for (c) DynaRev1, (d) DynaRev2. The dashed green vertical lines represent 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 gravel body, the dotted line represents the sparse gravel layer and the diamonds gives the crest location (see Section 3.1.1). The vertical lines indicate the initial and final water levels.

to the retreat of the toe. However, whereas the toe of the well-sorted revetment sank as it retreated due to loss of sand volume beneath the structure, the toe of the poorly-sorted revetment retreated up the beach profile (Fig. 5c and d). Therefore, taking the elevation change between the toe and crest as the height of the revetment it appears that both revetments grew rapidly in height under the highest water level (z_w = 4.9), but for the poorly-sorted revetment this is due to upward growth of the structure as opposed to the sinking of the sand-gravel interface

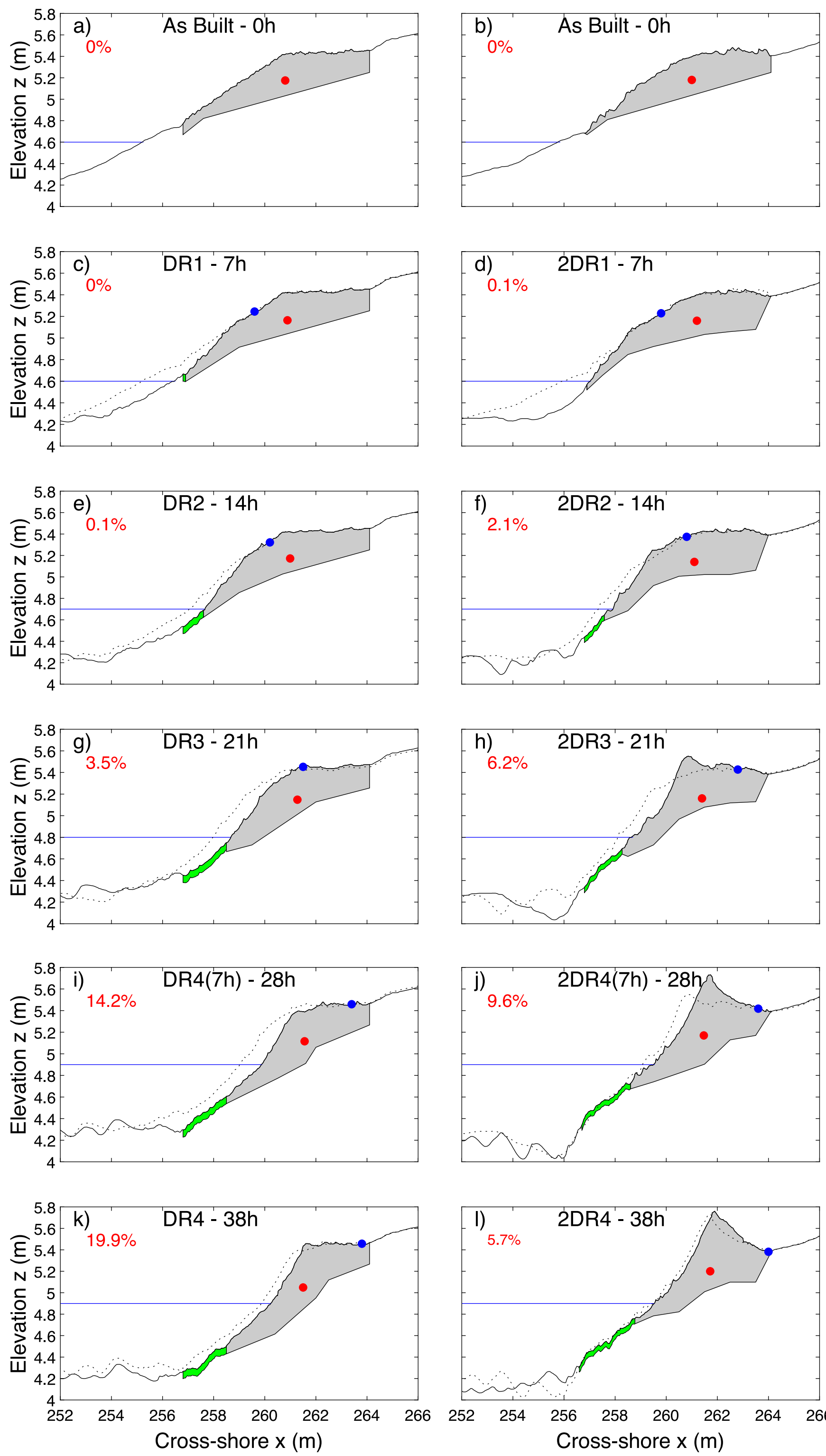

Fig. 4. Revetment shape as-built and at the end of each indicated test for the well-sorted revetment (DynaRev1, left) and poorly-sorted revetment (DynaRev2, right). The grey area represents the gravel only portion of the revetment. The green area represents the sparse gravel layer. The blue dot indicates 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 gravel body below the still water level.

for the poorly-sorted revetment, leading to a larger elevation change over the body (Fig. 4). As noted earlier the well-sorted revetments crest only shows minimal (0.04 m) of growth over the entire standard wave conditions (Fig. 5a).

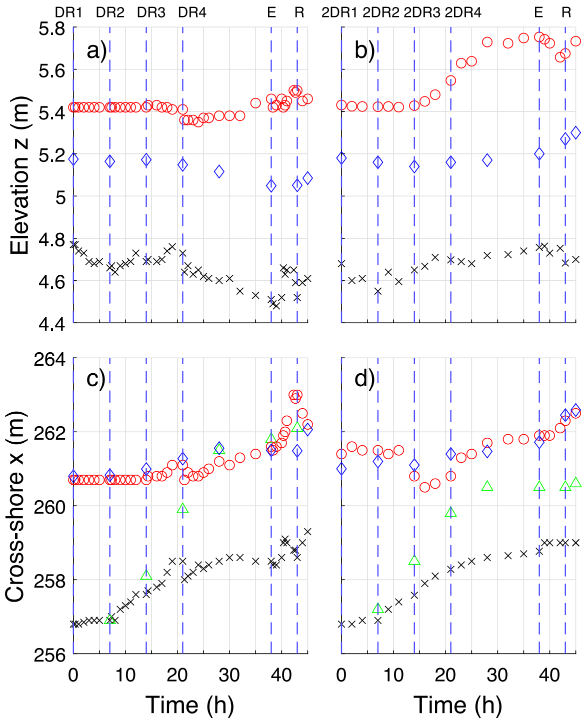

Fig. 5. Vertical elevation of the toe (black crosses), centroid of the cross-sectional area (blue diamonds) and crest (red circles) for (a) DynaRev1 and (b) DynaRev2. Cross-shore location for the toe of the main gravel body (black crosses), the location of the intersection between the still water level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

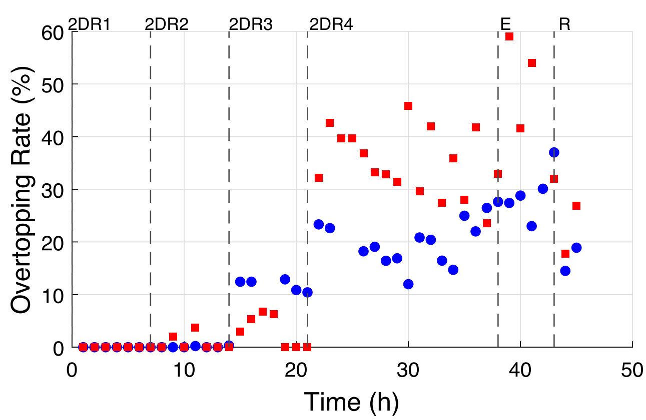

Fig. 6. Hourly overtopping rate for the poorly-sorted revetment (blue) and the well-sorted revetment (red).

3.1.2. Revetment response to erosive and recovery wave tests

In both experiments the water level rise testing was followed by 5 h of erosive wave conditions with increased wave energy at the highest water level, z_{wl} = 4.9 m (see Section 3.2 for details, Table 2) which resulted in increased overtopping in both DynaRev1 and DynaRev2 (Fig. 6). This led to a landward retreat of the centre of mass, flattening of the crest and reducing the front face gradient to 1:3.6 for the poorly-sorted revetment (see Fig. 7a and b). For the well-sorted revetment, the primary response was the retreat of the crest leading to an even lower front face gradient of 1:3.15. For both structures, gravel particles were transported beyond the landward limit of the structure (overwash) leading to an increase in the revetment cross-shore extent of 0.8 m (DynaRev1) and 0.9 m (DynaRev2). The length of the well-sorted revetment was more variable during the erosive wave testing due to the more changeable gravel toe location (Fig. 5c and d). The increased stability of the toe in the poorly-sorted revetment is due to the fact that the toe contained many large gravel particles which were not mobilised by the increased wave energy (Section 3.3).

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

3.1.3. Evolution of the sandy beach and revetment sinking

Both beaches were considered to be approaching an equilibrium state and presented similar morphologies (Fig. 3). The notable difference being the slightly larger and further seaward outer bar in DynaRev2 prior to the installation of the poorly-sorted revetment. Over the main region of interest between x = 210 m and x = 270 m the root mean square difference between the beach profiles at t = 0 h was just 0.3 m. This agrees with the previous finding by Bayle et al. (2020) that laboratory experiments exploring morphological change are repeatable at this scale.

After installation of the poorly-sorted revetment in DynaRev2, the outer bar accumulated sand resulting in a vertical and predominantly seaward growth of the outer bar (Fig. 3). The source of this sand is from three primary processes; sand erosion beneath the revetment, the development of a trough immediately seaward of the revetment structure and smoothing out of the smaller inner bar. Morphological changes are strongest in the two hours immediately following the third and fourth water level rise (z_wl = 4.8 and 4.9 m), the same period in which the revetment and trough underwent significant morphological change. The well-sorted revetment in DynaRev1 showed a similar accretion of sand in the outer bar driven by the same processes. Less sand erodes immediately seaward of the well-sorted revetment leading to a smaller trough, indicating that sand erosion from beneath the structure contributes more for the well-sorted revetment in DynaRev1. The sand erosion beneath the revetment leads to a sinking effect for both revetments. This process can be tracked throughout the experiment by comparing the approximate location that the still water level intercepts the sand-gravel interface beneath the revetment (green triangles in Fig. 5). For both revetments this is a continuing process throughout the first three water level tests (z_{wl} = 4.6 to 4.8 0–27 h). If water level rise is discounted the During the forth water level test (27–38 h) this process halted for the poorly-sorted revetment in DynaRev2 but continued at a reduced rate for the well-sorted revetment in DynaRev1. This results in a significantly less of the poorly sorted revetments main gravel body being below the still water level at the end of the water level tests (19.9% in DynaRev1 vs 5.71% in DynaRev2, Fig. 2k and l).

3.1.4. Shoreline evolution

The shoreline, considered as the intersection between the still water level and seaward facing limit of the poorly-sorted revetment was initially located at x = 255.8 m (see Fig. 4b). Over the course of the experiment the shoreline retreated at an average rate of 0.01 m/hour, with a total retreat of 3.7 m although a large degree of this can be attributed to the 0.3 m rise in water level over tests (0–38 h). If there were no changes in the morphology the final shoreline would be

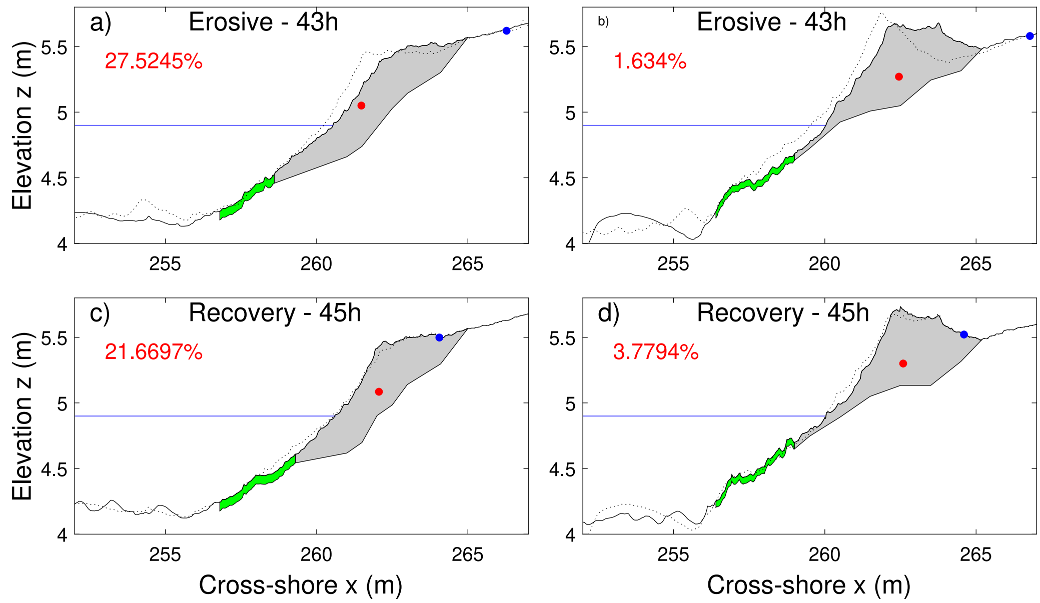

Fig. 7. Revetment shape at the end of erosive (2DRE3, 38 to 43 h) and recovery (2DRR1, 43 to 45 h) wave conditions for the well-sorted revetment (left) and poorly-sorted revetment (right). The grey area represents the gravel only portion of the revetment. The green area represents the sparse gravel layer (see Section 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.

expected to be at $x = 258$ m (a retreat of 2.2 m). The final shoreline was located at $x = 259.5$ m giving a true retreat of 1.5 m when discounting water-level rises, which was under half the true retreat of 3.7 m for the well-sorted revetment (see Fig. 4k,l). A major reason for lesser retreat in the poorly-sorted case is the reduced loss of sand from beneath the revetment and hence reduced sinking of the front face of the revetment. This can be seen clearly in the retreat of the sand water interfaces (SWI) for the revetments (see Fig. 5c,d), the location where the still water line intercepts the interpolated surface beneath the revetment. The final SWI location for the poorly-sorted revetment was 260.5 m at the end of standard wave conditions (38 h), which is 1.3 m further seaward than for the well-sorted revetment (see Fig. 5). The poorly-sorted revetment preserves up to 52% more sand above the still water level under the structure. This reduced sand loss has the advantage of better preserving the revetment height compared to the still water level improving the ability to reduce overtopping.

3.2. Overtopping rates

A comparison of the overtopping rates on an hour by hour basis using the Lidar array during both experiments is provided in Fig. 6. The values for both experiments are similar between $t = 0$ h and $t = 14$ h ($z_{wl} = 4.6$ m and $z_{wl} = 4.7$ m). Overtopping of the designed crest was infrequent during this time period (Fig. 6) and the increased horizontal runup excursion between $t = 7$ h and $t = 14$ h ($z_{wl} = 4.7$ m) for DynaRev2 is explained by the crest being constructed slightly landward of that for DynaRev1 (see Section 2.3 for details of the construction). As the water level increased further, the crest of both revetments began to be regularly overtopped (0%–8% DynaRev1, 11%–13% DynaRev2) (Fig. 6) and this led to substantial crest growth for the poorly-sorted revetment (DynaRev2). Despite the large crest growth in DynaRev2, the revetment experienced higher overtopping rates than for DynaRev1 at $z_w l = 4.8$ m. This may be due to the fact that the crest of the revetment in DynaRev2 is 0.3 m seaward of the DynaRev1 crest and it was demonstrated by Blenkinsopp et al. (2022) that overtopping rates decay rapidly with cross-shore distance. Alternatively, the water depth seaward of the revetment is consistently larger for DynaRev2, allowing more wave energy to reach the shoreline and drive runup (Blenkinsopp et al., 2022). After increasing the water level to $z_w l = 4.9$ m, the overtopping rates increased again. This led to rapid crest growth during the first hour at the new water level for DynaRev2 which acted to limit overtopping to 23%, compared to 31% in DynaRev1 where crest growth was minimal. It is noted that there is substantial variability in the overtopping rates during both experiments and this is thought to be due to the fact that the geometry of the structures is constantly evolving, meaning that the instantaneous crest elevation is varying and provides variable rates of overtopping protection.

The overtopping rate in both experiments increased further during the erosive tests (38–43 h; Table 2). For the poorly-sorted revetment in DynaRev2, the overtopping rate increased by less than 10% compared to the final hour of wave testing under standard wave conditions (28%, 37–38 h in Fig. 6) and at no point was the structure's crest overtopped by more than 38% of the waves in any given hour. Conversely, overtopping of the well-sorted DynaRev1 revetment was very variable and reached as high as 59% (38–39 h in Fig. 6), this is 26% larger than the final value under standard wave conditions (33%, 37–38 h in Fig. 6). Overall, the ability of a revetment constructed from poorly-sorted, angular material to form an elevated crest is beneficial as it reduces overtopping of the structure and provides increased resilience under energetic wave conditions. The poorly-sorted revetment's ability to rapidly develop a significant crest feature suggests that it is highly adaptable to a rising water level.

3.3. Gravel transport and surface sorting

For both experiments gravel particles tagged with passive RFID transmitters were placed along the cross shore centreline of the revetment in three layers; On the surface (top), at half the revetment depth (middle) and along the gravel-sand interface (bottom). Fig. 9 details the movement of the gravel for both the poorly-sorted (DynaRev2) and well-sorted revetment (DynaRev1) by placement layer, Table 3 provides further details on the quantity of tagged gravel particles transported and direction of travel. This was supported by an analysis of the surface gravel size distribution (intermediate axis length) along the central axis of the poorly-sorted revetment using a digital gravel count method (Fig. 8, see section 3.4.4 for methodological details). Photos of the toe and crest of the poorly-sorted revetment at the end of the standard wave conditions are provided in Fig. 10, these give a visual reference for the

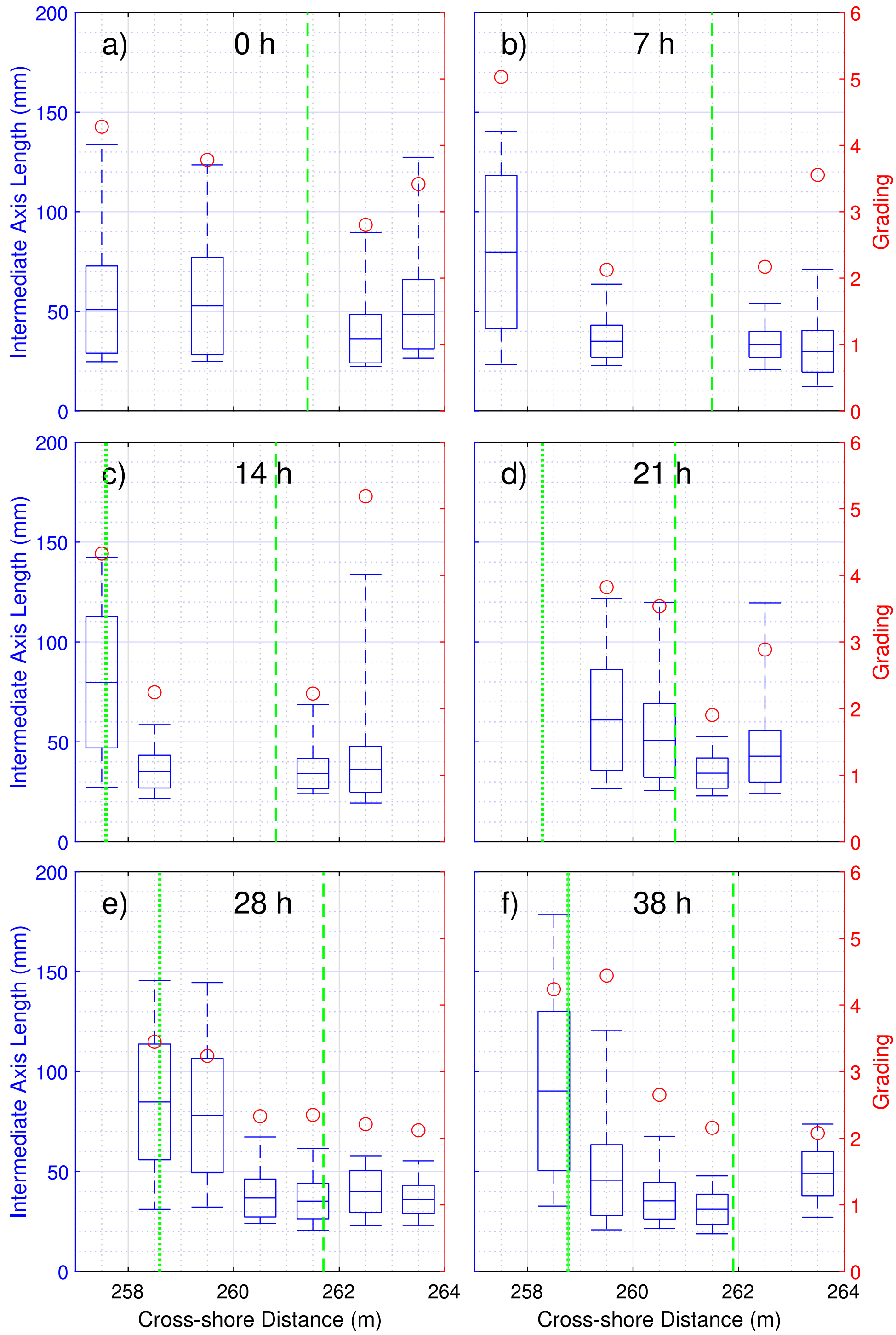

Fig. 8. Surface grain size distribution across the poorly-sorted revetment at the end of each test (t = 0,7,14,21,28,38). The left hand y-axis corresponds to a box plot centred over the median intermediate axis length with inner bounds provided by the median absolute deviation and branches reaching D_{90} 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.

results presented. The well-sorted revetment had a consistent grading and a small range of gravel sizes and so no size sorting was observed.

The distribution of gravel on the surface of the poorly-sorted revetment was initially very consistent at all cross-shore positions (Fig. 8a). Subsequently, the surface gravel underwent a sorting process throughout the experiment as they were mobilised by wave forcing. This sorting process led to the median gravel size decreasing landward of the toe, combined with a smaller grading value (Fig. 8), indicative of better sorted gravel moving landwards as expected. This sorting was limited to the seaward limit of the revetment during test 2DR1 (0–7 h, z_{wl} = 4.6 m) when no overtopping occurred (see Fig. 8b). Overtopping appears to accelerate this process by transporting smaller, more easily mobilised gravel onto and landward of the crest during uprush where they become stranded and bury existing larger gravel. This sorting is most evident during the final water level test 2DR4 (21–38 h, z_{wl} = 4.9 m; see Fig. 8e,f) and is visible in the images shown in Fig. 10 for both the toe and crest of the revetment. Throughout the experiment both the smallest range of gravel sizes and smallest median gravel

Table 3
Percentage of gravel 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 gravel and several size categories.

Gravel 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

sizes were detected at the crest of the structure (see Fig. 8). Note, the RFID-tagged gravel particles had a minimum size of 40 mm and therefore this trend is not evident in Fig. 9 because the majority of gravel particles forming the crest are smaller than 40 mm. Conversely, the toe of the revetment and the sparse gravel layer became less sorted with a higher median gravel size than was initially present (see Fig. 8). The median gravel size at the toe increased from 51 mm at 0 h to 90 mm at 38 h. This is caused by a high proportion of smaller gravel being transported landward from the toe, leaving the larger, less easily mobilised gravel to form a stable toe for the revetment. Notably, no tagged gravel of weight greater than 2 kg was detected more than 40 cm landward of its initial position by the end of standard wave testing (38 h, see Fig. 9b). Some gravel larger than 2 kg were detected seaward 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 transport of tagged gravel particles by layer for both the poorly and well-sorted revetments is shown in Table 3. At the end of standard wave testing (t = 38 h) only 54% were moved form their initial position for the poorly-sorted revetment (DynaRev2), predominantly in the seaward direction (see Table 3 and Fig. 9b). The gravel forming the well-sorted revetment was more mobile, with 87% displaced from initial position, primarily in the landward direction (see Table 3 and Fig. 9a). It is important to note however that the largest tagged gravel particles for the well-sorted revetment had an intermediate axis size (D_{50}) less than 100 mm, meaning that the whole tagged gravel population was more susceptible to mobilisation by wave action. The movement of the tracked RFID gravel particles was markedly different between the two experiments. For the well-sorted revetment (DynaRev1) the gravel showed a cyclic pattern of being dragged down to the toe when exposed, these were then transported up and over the crest by overtopping events where they were swiftly reburied by gravel. For the poorly-sorted revetment (DynaRev2), the gravel were either dragged down into the toe of the revetment (D_{50} > 100) or transported over the crest upon being exposed (D_{50} < 75). At the end of the poorly-sorted revetment testing (t = 45 h), the quantity of tagged gravel displaced from their initial position increased and the primary direction of travel became landward with an average displacement of 0.69 m (see Table 3 and Fig. 9d). The erosive testing (t = 38 to 43 h) was characterised by increased wave energy resulting in a greater ability to transport heavier gravel landward, combined with the exposure of tagged gravel particles that were initially deeper within the revetment. This led to an increase in the proportion of tagged gravels being displaced (Table 3).

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

3.4. Renourishment

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

4. Discussion

This section discusses the results presented above, particularly focussing on the performance and behaviour of the revetment structure. It further comments on the application of dynamic cobble berm revetments for coastal defence".

The majority of revetment response in DynaRev2 happened within the first seven hours of test 2DR4 (21–28 h), after this the retreat slowed (Fig. 5) and the degree of morphological change greatly reduced during the final 10 h of standard wave condition testing as expected (28–38 h, Fig. 3). This suggests that the revetment moves towards an equilibrium state within approximately 7 h after each rise in water level. The ability of the revetment to rapidly reshape towards a new equilibrium condition is also seen in Fig. 7 which shows that the revetment responds quickly to erosive conditions but is already re-establishing the peaked revetment crest after only 2 h of low energy recovery conditions. As the bulk of material remains part of the main gravel body and the geometry remains approximately constant, the revetment can be considered dynamically stable even though individual gravel particles are moving with every wave. Further investigation

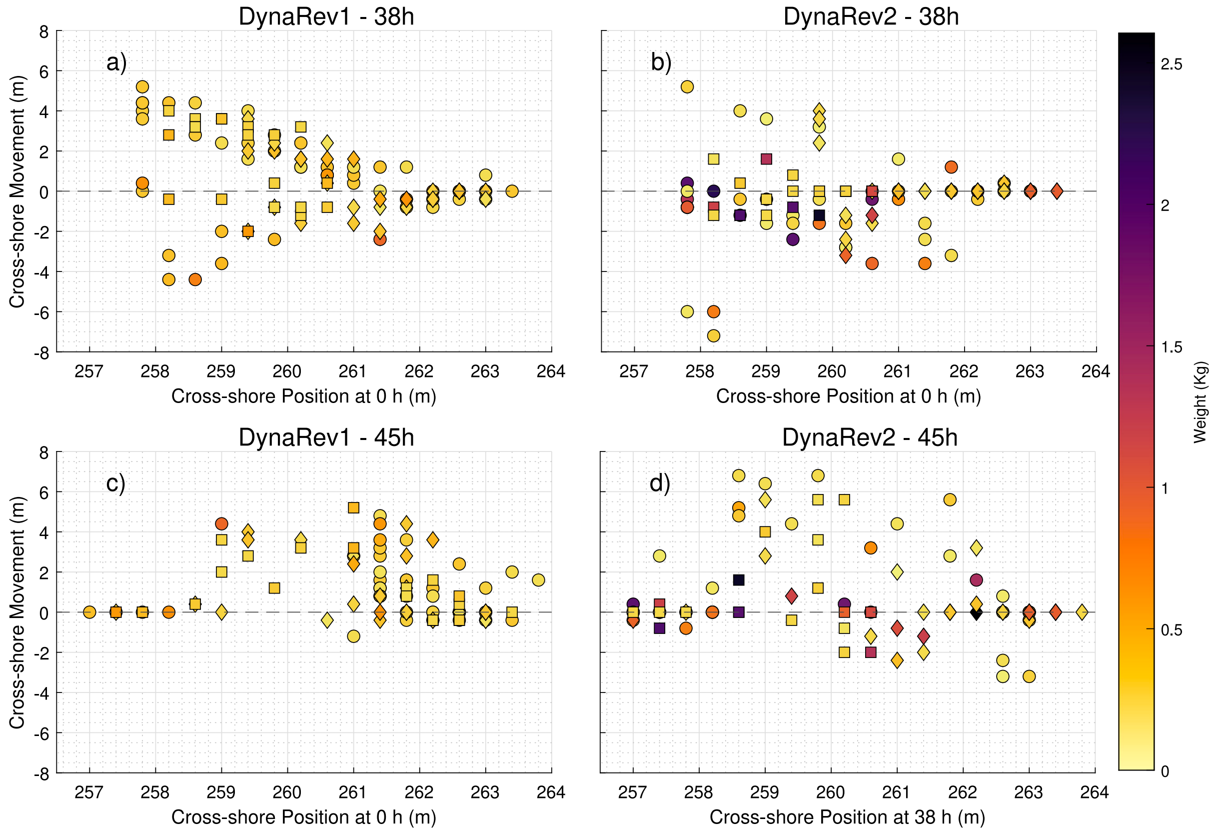

Fig. 9. Absolute cross-shore distance travelled by tagged gravel from their initial position, where positive is landward and negative is seaward for the (a) well-sorted revetment (DynaRev1) and (b) poorly-sorted revetment (DynaRev2) after 38 h of standard wave conditions. Absolute distance travelled by tagged gravel particles from their detected position at 38 h 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 gravel particles weight as shown by the colour bar (left). The gravel particles were distributed in three layers; revetment surface (circles), middle layer (diamonds) and sand-gravel interface (squares).

Fig. 10. Photo of surface gravel 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.

involving longer testing at each water level, as well as larger water level increases is suggested to give additional insight into the time for a stable geometry to be reached and the level of coastal protection provided. However, the rapid nature of this reshaping should be considered a positive for revetment design as it suggests the initial shape of placed material is not indicative of the revetment's shape under a particular wave climate and water level. Further, it should be noted that dynamic cobble berm revetments are expected to offer protection during storm events which exhibit varying wave conditions, therefore the structure will be constantly changing morphology during these events.

The behaviour of the gravel body for the poorly-sorted revetment in DynaRev2 under wave attack is that of a coherent structure, see Fig. 4. The location of the toe, crest and centre of gravity retreat in unison under standard wave conditions (Fig. 5), which can be viewed as a retreat of the whole body. Further, the gravel body of the revetment is estimated to contain at least 97% of the original material at the end of the testing (t = 45 h). The rapid development of a peaked crest constructed from smaller angular gravel acted to limit overtopping to a greater degree than that observed in DynaRev1. Overtopping was highest after the revetment crest was pushed over landward by a series of energetic overtopping events, reducing the effective crest height (see 41–43 h in Fig. 5b). The crest height is clearly important for protecting the upper beach and hinterland from wave inundation. Therefore, any design should seek to maximise this crest growth.

The lack of variation in gravel size and the rounded nature of the gravel for the well-sorted revetment are the primary reasons for the different morphological responses observed and are thought to be responsible for the greater loss of sand and sinking of the structure. Loss of sand beneath the revetment and associated sinking was much reduced for the poorly-sorted revetment and this is thought to be due to the development of a layer of small gravel at the sand-gravel interface which acts as a filter layer and prevents sand from entering into the revetment structure due to its reduced porosity at this location. The material for existing dynamic cobble berm revetments is often poorly-sorted local material (Komar and Allan, 2010; Weiner et al., 2019) and sinking has not been reported at these sites. Bayle et al. (2021), reported a similar "natural filter layer" of small gravel at the sand-gravel interface of a poorly-sorted revetment at North Cove and they reported short term sand accumulation and loss within the gravel matrix driven by both wave and aeolian processes, but no evidence of sinking. It is suggested therefore that a wide size grading of gravel material should be used when constructing dynamic cobble berm revetments. The results presented here also suggest that angular gravel increase interlocking and hence the stability of the revetment crest, which provides overtopping protection to the back of the revetment and hinterland. Additionally, the paper identified that dynamic cobble berm revetments exhibit sorting across the revetment surface. It is therefore

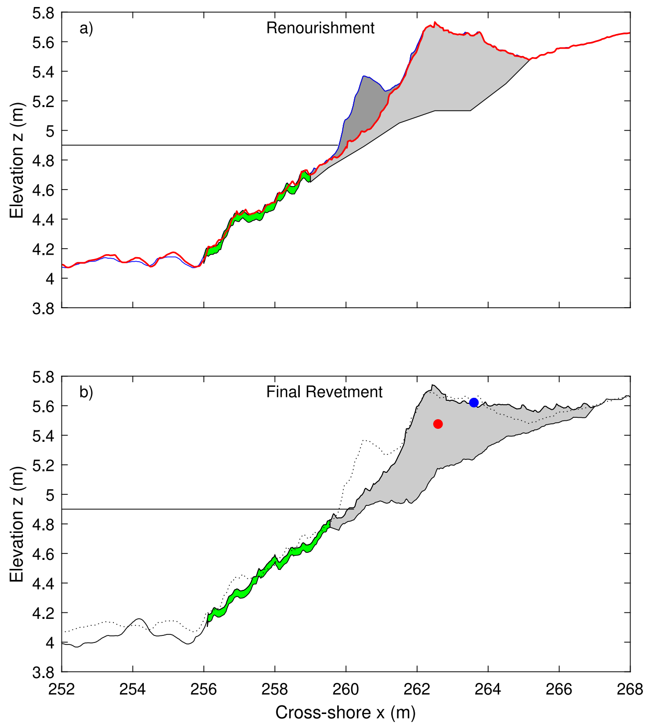

Fig. 11. (a) Renourished revetment where the light grey area outlined in red shows revetment cross-shore profile at the end of recovery wave conditions (2DRR1, 45 h, Table 2) and the dark grey area outlined in blue indicates the added material. (b) The final shape of the revetment after 2 h 40 m of additional tests, the blue dot indicates the runup location under standard wave conditions and red dot gives the centre of mass for the cross-shore profile of the revetment. The dotted line indicates the revetment profile immediately following renourishment.

highly probable that the internal sorting of gravels with the structure is greater than just the formation of the filter layer which was observed. At present however the authors are not aware of a reliable way to obtain accurate measurements of the sediment size distribution within the internal cobble matrix.

Similarly the wide size distribution and lower mobility of the interlocking angular gravel in the poorly-sorted revetment (DynaRev2) meant that the average landward movement of gravel during the erosive wave conditions was substantially smaller than for the well-sorted case (DynaRev1): 0.69 m and 2.08 m respectively. Also, the tagged gravel population was far less mobile during DynaRev2 despite the degree of morphological change presented. This is a key factor in the selection of gravel material for the structure as the reduced retreat from erosive wave conditions results in a longer lasting structure that is more resistant to extreme conditions and its resultant erosion of the beach face. In the analysis, a gravel was only categorised as displaced if it was detected at the end of the given test, while tagged gravel particles that were not detected at all were categorised as ‘not detected’. The decrease in the total number of displaced gravel for the well-sorted revetment during the erosion and accretion testing (87% to 80%) is therefore explained by the greater number of non-detected tagged gravel and not an indication of a reduced quantity of transported gravel. As a result, it is probable that the displacement of tagged gravel during both experiments is under represented.

Overall, given the differing morphological response of the two revetments, it is arguable that the new design for DynaRev2 performed better. The development of the filter layer prevented the structure from sinking. When combined with the crest growth it maintained the majority of the main gravel body above the water level till the end of the experiment (96.2%, 2DDR1, 45 h). Additionally, the structure maintained a significant difference in height between the crest peak and still water level. This reduced overtopping providing better protection to the upper beach. van der Meer (1988) presented a similar finding where it was shown that a larger grading led to an increased crest height for gravel slopes constructed using smaller sized gravels than utilised in the present design. Therefore the degree of sorting for a gravel material is related to potential crest height for many gravel materials. The presented results suggest that a key consideration for dynamic cobble berm revetment design is the characteristics of the gravel used for construction. As a result it may be desirable to use poorly-sorted angular, or at least sub-angular material when constructing dynamic cobble berm revetments. Indeed many field sites have utilised poorly-sorted material angular material and performed well for their designed purpose (Weiner et al., 2019; Allan and Gabel, 2016; Allan et al., 2005), though this has implications for the recreational function of the beach and is not in keeping with the natural character of typical composite beaches.

Maintenance of dynamic cobble berm revetments is vital to their long-term efficacy. The renourishment of the structure suggests that there is no need to carefully place the renourishment material. It appears sufficient to simply dump the material on the revetment front face where it will be rapidly reshaped by wave action. It is likely in fact that a revetment could be initially constructed by simply dumping material around the high tide line and allowing wave action to shape the berm, however this has not been tested. At present best practise for the size and frequency of renourishments has not been established and is expected to be site specific. Allan and Gabel (2016) suggest a frequency of 10–20 years and the North Cove revetment is being monitored to establish a schedule (Weiner et al., 2019). During the erosive tests (see Table 2) the revetment was pushed over by wave action reducing its active crest height (Figs. 5 and 7), therefore reducing its efficacy at reducing overtopping of the structure. The renourishment increased the active crest height of the structure but it is anticipated that a larger renourishment would have a greater effect. It may be sensible to take an opportunistic approach to renourishment after periods of erosive wave conditions, the rapid inclusion of gravel material suggests that this could also be targeted to areas where the revetment shows greatest reduction in crest height.

Previous research has investigated artificial gravel beaches and their response to wave forcing, in particular the work of van der Meer (1988). In these tests gravel slopes of differing characteristics including gravel size and grading were subjected to a range of wave forcing conditions. Comparison of the berm region that formed during van der Meer’s experiments and dynamic cobble berm revetments may give insight into the expected resultant morphology when constructing revetments. It was found that the distance between the shoreline and the crest of the revetment in both DynaRev experiments compared well with the relationship presented by van der Meer. Similarly, the observed horizontal excursion of waves (or runup length) seen in both experiments matched the relationship for horizontal excursion as a function of wave steepness presented by van der Meer. Van der Meer observed that less well-sorted gravel, resulted in greater crest height which matches the observations from the DynaRev experiments. However, the equation to predict crest height provided by van der Meer cannot be used to accurately estimate the crest height for the DynaRev experiments, probably due to the differently sorted gravel used.

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

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

5. Conclusions

The purpose of a dynamic revetment is to provide protection to the hinterland as well as reducing erosion of the upper beach face. It is clear that both the well and poorly-sorted revetments are appropriate for this purpose based on the experimental results, with the caveat that the observed sinking process needs to be better understood. Both revetments reduced the horizontal runup excursion compared to a sand beach only case (see Bayle et al., 2020) and the erosion of the beach face is significantly less than during the sand-only case measured during the DynaRev experiment. Further, both revetments remained dynamically stable and maintained the majority of their gravel mass during testing.

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

Based on the presented discussion in this paper and the previous work by Bayle et al. (2020) updated design guidance for dynamic cobble berm revetments can be surmised as follows;

1. Dynamic revetments are suitable for deployment in energetic open coastal environments and represent one of the few nature based solutions for these areas.
2. Using highly graded angular or sub angular material will lead to the highest potential crest height based on placed volume. It will also preserve more sand beneath the structure reducing the comparative shoreline retreat.
3. There is still insufficient testing to suggest that dynamic cobble berm revetments can 'self construct' from dumped gravel material and the authors suggest that manual reshaping should be incorporated into construction practises. However, the angle of the front slope will rapidly change under wave attack and is therefore not an important design consideration.

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

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

CRediT authorship contribution statement

Ollie Foss: Conceptualization, Methodology, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing, Visualization. **Chris E. Blenkinsopp:** Conceptualization, Methodology, Investigation, Resources, Writing – review & editing, Supervision, Project administration, Funding acquisition. **Paul M. Bayle:** Conceptualization, Methodology, Formal analysis, Investigation, Data curation, Writing – review & editing. **Kévin Martins:** Investigation, Writing – review & editing. **Stefan Schimmels:** Investigation, Writing – review & editing. **Luis Pedro Almeida:** Investigation, Writing – review & editing.

Declaration of competing interest

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

Data availability

Data will be made available on request.

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