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Paper:

Karunaratna, H., Pender, D., Ranasinghe, R., Short, A. & Reeve, D. (2013). The effects of storm clustering on beach profile variability. *Marine Geology*, 348, 103-112.

<http://dx.doi.org/10.1016/j.margeo.2013.12.007>

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**An Analysis of the Cross-shore Beach Evolution of a Sandy and
a Composite Gravel Beach**

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38

39 **Abstract**

40 Sand and composite sand-gravel beaches show distinctly different morphodynamic
41 responses to natural forcing as a result, primarily, of differences in sediment
42 properties and wave breaking and dissipation characteristics. As the incident wave
43 conditions fluctuate, so the beaches vary in response, affecting their nature and long-
44 term stability. In this paper, beach profile surveys acquired over more than a decade at
45 a sandy beach (Narrabeen Beach, New South Wales, Australia) and a composite
46 sand-gravel beach (Milford-on-Sea, Christchurch Bay, UK) are analysed to compare
47 and contrast cross-shore morphodynamics of the two beach types. The different
48 behavioural characteristics of the two beach types at decadal, inter-annual and intra-
49 annual time scales are investigated. Comparisons of beach profiles with Dean's
50 equilibrium profile and Vellinga's erosion profile shows that the Dean's profile
51 satisfactorily represents the time mean profiles of both beach types. Statistical and
52 Empirical Orthogonal Function (EOF) analyses confirm the generally accepted model

53 that the inter-tidal zone is the most morphodynamically active region on a sandy
54 beach whereas the swash zone is the most dynamic region on a mixed sand-gravel
55 beach. The results also imply that during storms composite sand-gravel beaches may
56 destabilise due to cutback of the upper beach while sandy beaches are more likely to
57 be unstable as a result of beach lowering due to sediment transport from the inter-tidal
58 zone to the sub tidal zone during storms. EOF results also show that Milford-on-Sea
59 beach is in a state of steady recession while the Narrabeen Beach shows a cyclic
60 erosion-accretion variability. A multivariate technique (Canonical Correlation
61 Analysis, CCA) shows that on the composite beach a strong correlation exists
62 between incident wave steepness and profile response, which could be attributed to
63 the unsaturated surf zone, whereas on the sandy beach any correlation is much less
64 evident.

65

66 **Keywords:** Sand and composite sand-gravel beaches, cross-shore beach profile,
67 beach morphodynamics, Orthogonal Eigenfunction Analysis, Canonical Correlation
68 Analysis

69

70 **1. Introduction**

71 Composite sand-gravel beaches are composed of a gravel inter to supra-tidal swash
72 zone and sand lower to sub-tidal surf zone and are a common feature along many
73 higher latitude coastlines around the world. The importance of such beaches as a part
74 of natural coastal systems and as a form of coastal defence is well recognised in the
75 literature (Carr, 1983; Bradbury and Powell, 1992). There are a growing number of
76 reports and studies of their degradation, and in some instances severe cutback (e.g.
77 Chadwick et al 2005) and breaching (Carter and Orford, 1993).

78 Morphological evolution of a beach is characterised by cross-shore and long-shore
79 morphodynamic changes. Long-shore coastal evolution is mainly characterised by
80 varying coastal forms such as changing shoreline position, beach rotation and
81 development of rhythmic features. Cross-shore beach change is associated with
82 changes to the shape of cross-shore profile in time and space. Our focus here is the
83 morphodynamic changes in the cross-shore direction.

84

85 Changes in beach profile are controlled by many factors including waves, tidal flows
86 and sediment characteristics. The cross-shore variability of composite sand-gravel
87 beaches is distinctly different to that of sand beaches. It is also different to the other
88 forms of coarse-grain beaches (mixed beaches and pure gravel beaches) in terms of
89 profile shape, profile response to hydrodynamic forcing, sediment characteristics and
90 sediment distribution. The composition and cross-shore distribution of beach sediment
91 plays a major role in determining the morphodynamic response of a beach profile to
92 environmental forcing. Sand beaches have gentler cross-shore slopes and wide but
93 shallow surf and swash zones while composite sand-gravel beaches in contrast have
94 coarse steep swash zone that grades abruptly into a low gradient sandy lower inter-
95 tidal to sub-tidal. Gravel has a tendency for net onshore transport due to the more
96 energetic wave uprush followed by less energetic back-wash. (Carter and Orford,
97 1984; Carr, 1983). As a result, sediment sorting takes place across the profile where
98 gravel accumulates at the supra-tidal and upper inter-tidal region of the profile while
99 sand accumulates at the lower inter-tidal and sub-tidal regions thus forming composite
100 beaches (McLean and Kirk, 1969; Ivamy and Kench, 2006). Due to the presence of a
101 steep gravel upper shoreface and a more gentler sand lower beach, composite beaches
102 show characteristics of both reflective and dissipative beaches.

103

104 Morphodynamic evolution of cross-shore beach profiles take place at a range of time
105 scales: millennial scale evolution as a result of Quaternary sea level changes; long
106 term variability in the time scales of several decades to a century associated with
107 climate change impacts; medium-term evolution in the time scales of several years to
108 a decade, associated with engineering intervention and prevailing sedimentary
109 processes; and short term variability in the time scales of days to a year as a result of
110 weather conditions (storms) and seasonal changes.

111

112 Cross-shore variability of beach systems has been studied by various researchers in
113 the past. Early studies on beach profiles date back to the 1950's when Bruun (1954)
114 developed the concept of an equilibrium beach profile shape on sandy beaches and
115 found a simple empirical relationship between cross-shore profile depth and distance
116 measured offshore from the shoreline. Dean (1977) provided the physical argument
117 for the shape of Bruun's profile. Larson et al. (1999) provided physical reasoning for
118 a linearly sloping upper beach but this result was independent of grain size. Later
119 Dean (1991) included gravity effects to the Bruun's profile to get the linear upper
120 beach and also retain the dependence on grain size.

121

122

123 Swart (1974) and Sunamura and Horikawa (1974) examined characteristics of beach
124 profiles through laboratory investigations and identified erosive and accretive profiles,
125 relating profile geometry to incident wave conditions and sediment characteristics.

126 Vellinga (1983, 1984) developed a relationship between cross-shore distance and
127 profile depth for erosive beach profiles, which was a function of grain size.

128

129 There were several of attempts to understand cross-shore morphodynamic variability
130 through statistical analysis of waves and beach profiles. Larson and Kraus (1994)
131 used Empirical Orthogonal Eigenfunction Analysis (EOF) to examine spatial and
132 temporal variability of alongshore bars at Duck, North Carolina. They observed that
133 average profile elevation change is symmetric around the mean sea level and that
134 typical storms transported sand to nearshore. Larson et al. (2000) used a large number
135 of beach profiles at Duck and related their evolution to incident waves using
136 Canonical Correlation Analysis (CCA). They found a strong correlation between
137 profile shape variability and the mean ratio of breaking waves. Horrillo-Caraballo and
138 Reeve (2010) extended this correlation to predict future beach profiles and their effort
139 was reasonably successful.

140

141 Research on coarse grain beaches is scarce, with existing studies either limited to
142 geological time scales (Kirk, 1980; Carter and Orford, 1984; Carter, 1986) or short-
143 term scales (Pontee et al., 2004; Austin and Masselink, 2006); Masselink et al. 2010;
144 Alagria-Arzaburu et al., 2010). Besides, these studies were done on either pure gravel
145 or mixed sand-gravel beaches. Composite sand-gravel beaches differ significantly
146 from pure gravel or mixed sand-gravel beaches where sand and gravel are spatially
147 separated in their cross-shore profile. Morphodynamic variability of composite sand-
148 gravel beaches at a full range of time scales is not well understood.

149

150

151 Understanding the response of a composite sand-gravel beach to morphodynamic
152 drivers at various time scales is extremely important for developing methodologies to
153 predict their behaviour, which is essential to inform effective management decisions.

154 In the absence of systematic investigations and with limited available morphodynamic
155 process knowledge, the appropriate methodologies do not yet exist.

156

157 This study focuses on comparing and contrasting cross-shore morphodynamic
158 variability of a composite sand-gravel beach with a characteristic sandy beach, at a
159 range of time scales, using historic measurements of beach profiles and wave data.
160 The aim here is to systematically investigate the similarities and differences of the
161 two beaches in detail and establish their morphodynamic response characteristics. The
162 outcome of the research will contribute to better understanding of morphodynamic
163 behaviour of composite beaches.

164

165 The beaches considered here are the sandy Narrabeen Beach, located in New South
166 Wales (NSW), Australia (**Figure 1**) and the composite sand-gravel beach, Milford-on-
167 Sea, is located in Christchurch Bay, United Kingdom (Figure 2). Both sites have been
168 extensively monitored over several decades and therefore, rich in cross-shore profile
169 surveys and wave measurements.

170

171 **2. Field Sites and Historic Data**

172 **2.1 Milford-on-Sea Beach**

173 Milford-on-Sea is a composite sand-gravel beach that forms a part of the Christchurch
174 Bay beach system facing the English Channel, UK. The beach extends about 3 km to
175 the west from the Hurst Castle Spit (see **Figure 1**). It is narrow and steep at the
176 western side and has a landward margin of receding cliffs, which becomes wide and
177 less steep at the eastern end.

178

179 The Milford-on-Sea beach has a steep upper beach face with a gradient between 1:5
180 and 1:7 and a moderate inter-tidal beach with a gradient between 1:10 and 1:20. The
181 gentler sub-tidal beach is characterised by highly mobile and segmented multiple
182 alongshore bars. Cross-shore gradients on the western part of Milford-on-Sea beach
183 are significantly steeper than those on the eastern part. The sediment grain size at
184 Milford-on-Sea beach varies significantly along the cross shore profile. Coarse
185 shingles and pebbles with a median grain diameter (D_{50}) around 14 mm dominate the
186 upper beach. A sand-gravel mix which has D_{50} -gravel = 10 mm and D_{50} -sand = 1mm
187 with only 12% sand fraction, dominates inter-tidal areas. (Martin Grandes et al., 2009).
188 Sediment grain sizes on the western beach are slightly coarser than those on the
189 eastern end, which contributes to the alongshore variation of the beach slope.
190
191 Christchurch Bay receives semi-diurnal tides with a moderate mean spring tidal range
192 of 2.0 m OD, reducing to 0.8 m OD during neap tidal cycle. Mean high water spring
193 (MHWS), mean low water spring (MLWS) and Mean water level (MWL) are 0.87 m,
194 -1.13 m and 0.14 m above OD. Tidal currents as high as 3.0 m/s are observed in close
195 proximity to the Milford-on-Sea beach (SCOPAC, 2003). Waves are incident
196 predominantly from the SSW direction with occasional SSE waves. Waves at the
197 eastern end of Christchurch Bay are more energetic than those incident on the western
198 end due to the sheltering effect of Hengistbury Head. SCOPAC (2003) quote typical
199 (one year return period) and extreme (1 in 100 year) significant wave heights for
200 Milford-on-Sea as 2.5m and 3.4m respectively. **Figure 3** shows near-shore significant
201 wave height measured at a depth of 12 m offshore of the Christchurch Bay beach
202 from 1986 to 1994. The wave climate is seasonal with calmer summer months
203 (March-September) and stormy winter months (October-February).

204 Beach profiles have been surveyed at 45 cross-shore beach transects along
205 Christchurch Bay. Inter-tidal beach was measured using RTK-GPS, using the UK
206 South-East Regional Coastal Monitoring Programme's ground control network. This
207 is tied into Ordnance Survey (OS) Active Network in the UK. Measurements along
208 the profile are deemed accurate to +/- 30mm (vertical and horizontal). GPS was used
209 for all profiles from 1994. Prior to that, profiles were measured by line and level from
210 a fixed marker at the back of the beach (the markers were tied into OS by theodolite
211 height transfer). All heights are relative to Ordnance Datum Newlyn (ODN), the
212 standard UK reference level. The zero chainage position is a fixed bench mark some
213 distance from the back of the beach beyond the area which might erode in the next
214 100 years. All surveys use this chainage as zero, so the profiles can be overlain for
215 comparison. Earlier line and level survey data was corrected to this start of line
216 position.

217

218 Surveys at transect 5f00107, located at the central part of the bay, (See Figure 1),
219 where net long-shore transport is minimal, for the period 1987 to 2005 were selected
220 for the analysis here. There are 49 surveys in total, irregularly spaced over the 18 year
221 period. The length of profile measured varied from survey to survey, but always went
222 out at least to MLWS. Thus, all profiles were truncated at MLWS to provide a
223 consistent basis for analysis. The shoreline position is defined as the point of
224 intersection between the cross-shore profile and the Mean Water Level (MWL).

225

226 **2.2 Narrabeen Beach**

227 Narrabeen is a wave-dominated embayed beach located 20 km north of Sydney, in
228 NSW, Australia (Short and Wright, 1981). The beach that faces east into the Tasman

229 Sea, is 3.6 km long and bounded by two headlands, Narrabeen Head to the north and
230 Long Reef Point to the south. It is composed of medium to fine quartz and carbonate
231 sands with $D_{50} = 0.3-0.4$ mm and has a relatively steep upper beach and a gentler
232 lower beach in the sub-tidal region.

233

234 As a part of a coastal monitoring programme, beach profiles at five cross-shore
235 locations along the Narrabeen Beach were regularly measured first at bi-weekly
236 intervals and then, at monthly intervals since 1976, by the Coastal Studies Unit,
237 University of Sydney. Surveys were undertaken at low tide and profiles were recorded
238 at 10 m cross-shore intervals from a fixed bench mark at the landward limit of the
239 active beach at 10 m elevation. Hourly non-directional (1976-1992) and directional
240 (1992-2005) wave data were also measured at an offshore wave buoy located at the
241 Long Reef Point, at a depth of 80 m. Cross-shore beach profile surveys carried out at
242 Profile 4 (Figure 2), which is situated in the central part of the Narrabeen Beach, is
243 used for the analysis presented herein. Profile 4 was selected for this analysis as it is
244 the least likely location to be affected by the cyclic beach rotation phenomenon that
245 operates at Narrabeen beach (Short and Trembanis, 2004; Ranasinghe et al., 2004a).
246 Cross-shore profile surveys at Profile 4 from 1976 to 1992 are shown in **Figure 5**.
247 Shoreline position is located as MWL.

248

249 Narrabeen Beach is exposed to highly variable, moderate- to high-energy wind waves
250 superimposed on long period, moderate- to high-energy south-easterly swell waves
251 (Short and Wright, 1981). Waves are derived from three cyclonic sources: Mid-
252 latitude cyclones pass across the southern Tasman Sea all-year-round, generating
253 south-easterly swell; extra-tropical cyclones off NSW coast generating east and south-

254 easterly waves peaking between May and August; tropical cyclones that generate
255 moderate to high north-easterly and easterly swell during February and March. In
256 addition summer (December to March) sea breeze generating low to moderate north-
257 easterly seas. 20% of the waves are found to exceed 2 m. Mean significant wave
258 height and peak period in the study area are 1.6 m and 10 sec respectively (Short and
259 Wright, 1981; Short and Trenamon, 1992). On average, Narrabeen Beach, is subjected
260 12 storms per year (based on the local definition that $H_s > 3\text{m}$ lasting more than 1 hr
261 represents a storm. **Figure 6** shows typical offshore wave climate measured at the
262 wave buoy at Longreef.

263

264 The beach experiences micro-tidal, semi-diurnal tides with mean spring tidal range of
265 1.6 m and neap tidal range of 1.2 m. MHWS and MLWS are 0.9 m and -0.7 m above
266 Australian Height Datum (AHD) respectively. The effect of tides on the morphology
267 of the Narrabeen Beach is considerably less than waves (Short, 1985; Short and
268 Trembanis, 2004).

269

270 Due to the prevalence of moderate to high wave energy conditions and the exposed
271 nature of the beach, the morphodynamic response of Narrabeen Beach is highly
272 variable and extremely rapid where erosion and accretion can take place any time of
273 the year. Accordingly, cross-shore beach profile shape varies rapidly with time.
274 (Wright and Short, 1984; Ranasinghe et al., 2004b).

275

276 **3. Analysis and Discussion of Cross-shore Beach Variability**

277 **3.1 Equilibrium Profile**

278 In order to assess long-term cross-shore morphodynamic variability of Milford-on-
279 Sea and Narrabeen Beach and compare and contrast long-term beach profile shape
280 and its association with beach sediment properties, the time-mean beach profiles at
281 both sites were first computed using available historic cross-shore profile surveys at
282 Profile 5f00107 (Milford-on-Sea) and Profile 4 (Narrabeen Beach). The mean profiles
283 were then compared with Dean's (1991) equilibrium profile and Vellinga's (1983)
284 erosion profile.

285

286 D_{50} for Milford-on-Sea was taken as 10 mm (Martin Grandes et al., 2009). D_{50} for
287 Narrabeen Beach was taken as 0.35 mm (Short and Trembanis, 2004). The resulting
288 Dean's equilibrium profiles and Vellinga's erosion profile for Milford-on Sea (profile
289 5f00107) and Narrabeen beach (Profile 4) are shown in **Figure 7**. Both profiles
290 commence from the MHWS.

291

292 At Narrabeen Beach, the mean profile is in good agreement with the Dean's
293 equilibrium profile, with less than 5% root mean square error. This could be expected
294 as Narrabeen Beach consists mostly of uniformly distributed sediment and is similar
295 in type to the beaches used to derive Dean's equilibrium profile. Vellinga's profile
296 agrees well with the mean profile in the upper inter-tidal region but overestimates the
297 lower inter-tidal region. This may partly be attributed to the slightly steeper frequent
298 storm waves ($H_s/L_s \sim 0.042$) prevailing at Narrabeen than the wave steepness
299 considered for deriving Vellinga's erosion profile ($H_s/L_s \sim 0.034$).

300

301 At Milford-on-Sea beach, Dean's equilibrium profile slightly overestimates the mean
302 profile in the upper part of the inter-tidal zone and is in better agreement in the lower

303 inter-tidal zone. This could mainly be attributed to the fact that Moore's (1982)
304 relationship is based on a uniform grain size to determine profile scale parameter
305 where as the inter-tidal region of the Milford-on-Sea beach consists of sediment with
306 a bimodal distribution with 88% gravel 12% sand. Pilkey et al. (1993) describes the
307 difficulty in choosing a single shape parameter for beaches with large cross-shore
308 sediment variability as well as the shortcomings of the Moore's expression for A .
309 Overall, despite possible differences between wave energy dissipation on the steep
310 Milford-on-Sea beach and on a gentle slope associated with Dean's profile shape
311 parameter, the mean sub-aqueous profile shape of Milford-on-Sea beach agrees well
312 with the concave shape of the Dean's profile shape with only 11% root mean square
313 error. On the other hand Vellinga's profile significantly overestimates the mean
314 profile throughout the inter-tidal region, which could again be attributed mainly to the
315 bimodal sediment composition at Milford-on-Sea. This shows that the Dean's profile
316 can be taken as a suitable measure to describe long-term averaged profile shape of a
317 composite beach, if time averaging is taken over a sufficiently long period of time.

318

319 However, the overall profile shape of a composite sand-gravel beach cannot simply be
320 determined by wave dissipation and a single sediment size. Profile response to wave
321 action is complicated by the complex mix of sediment and sediment sorting across the
322 profile.

323

324 **3.2 Bulk Statistics**

325 In order to quantify cross-shore variability of beach profiles, bulk statistics were
326 computed at Milford-on-Sea and Narrabeen beaches. All available survey data are
327 used to determine statistical parameters.

328

329 **3.2.1 Milford-on-Sea Beach**

330 **Figure 8** shows mean cross-shore profile, the profile envelopes determined from the
331 cross-shore profile surveys, and the standard deviation of the profile depth. The mean
332 profile is indicative of a high energy upper beach with a gradient of 1:5 and an inter-
333 tidal beach with gradient 1:10. The mean beach width at the shoreline (mean water
334 level), measured from the shoreward limit of the active profile at the benchmark, is 43
335 m. The envelope of the beach profiles shows that the beach width at the shoreline
336 varies by around 13 m during the 18 year study period, with a minimum width of 37
337 m and a maximum of 50 m, i.e. 30% of the mean beach width. The maximum cross-
338 shore beach movement of 17 m occurs around 2-3 m elevation. The envelope shows
339 the upper beach berm development/recession associated with accretion/erosion in the
340 swash region, which is typical of coarse-grain beaches. However, it should be noted
341 that these results may have been slightly affected by the beach filling that had been
342 carried out at Milford-on-Sea between 1996 and 1999 (SCOPAC, 2003). The standard
343 deviation peaks in the supra-tidal zone, around 2 m elevation above mean water level.
344 This is well above the inter-tidal zone and that indicates the swash dominance in
345 cross-shore beach morphodynamics of a composite sand-gravel beach. A secondary
346 peak is seen at 1m water depth, which is the swash region at low tide. Even though
347 the standard deviation sharply drops through the inter-tidal zone, values well above
348 zero at the MLWS indicate that the active beach profile extends further seaward.

349

350 **3.2.2 Narrabeen Beach**

351 **Figure 9** shows mean cross-shore profile with profile envelope and standard deviation
352 at profile 4. The width of the mean profile at the shoreline (MWL) with respect to the
353 selected bench mark at the top of the dune is 100m. The envelope of the measured

354 profiles shows that the beach width at the shoreline fluctuates by 70 m in the on- off-
355 shore direction, which is 70% of the mean beach width. The standard deviation of
356 beach profile depths drawn against profile depth shows three peaks. The largest peak
357 is around 0.8 m above MWL, which is at the upper region of the inter-tidal zone. A
358 secondary peak with standard deviation is nearly half that of the primary peak, is seen
359 around 6 m above mean water level, which may be attributed to variability of the
360 upper beach as a result of frequent storms. The peak at the end of the profile indicates
361 that the surveys do not extend to the depth of closure.

362

363 **3.2.3 Comparison**

364 Investigation of raw data and bulk statistics of cross-shore profiles at Milford-on-Sea
365 and Narrabeen beaches show that composite sand-gravel and sandy beaches have
366 distinctly different cross-shore profile shapes, and spatial and temporal variability. At
367 Milford-on-Sea, the highest beach variability occurred at the supra-tidal level (2-3m
368 MSL). This is attributed to strong swash movements associated with incident wave
369 groupiness and waves breaking on or at close proximity to the shoreline
370 (Karunaratna et al., 2005; Masselink et al., 2010). The surf similarity parameter at
371 Milford-on-Sea calculated on the mean inter-tidal profile gradient with mean wave
372 steepness is 1.4, showing plunging to surging waves near the waterline. Highly
373 dynamic swash motions enabled by plunging/surging waves then initiate the strongest
374 sediment transport at the upper beach face.

375

376 At Narrabeen Beach on the other hand, cross-shore variability is highest in the inter-
377 tidal region. This can be related to the gradual wave dissipation on the gentle sub-tidal
378 beach which results in more sediment transport in the surf zone than that in the swash

379 zone. The surf similarity parameter determined using the average inter-tidal beach
380 slope with mean wave steepness on the Narrabeen Beach is approximately 0.24,
381 showing mostly spilling breakers. Swash movements on gentle beaches with spilling
382 breakers are significantly lower than that on steep beaches due to partial or full
383 saturation of the surf zone (Baldock and Holmes, 1999; Karunaratna et al., 2005).

384

385 **3.3 Empirical Orthogonal Function Analysis**

386 Empirical Orthogonal Function (EOF) analysis is widely used to investigate patterns
387 in beach variations (e.g. Winant et al., 1975 and Wijnberg and Terwindt, 1995) and
388 other coastal features (eg. Reeve et al., 2001; Kroon et al., 2008; Reeve et al 2008).

389 The method maps the observed coastal morphological data into a set of shape
390 functions known as eigenfunctions that are determined from the data itself. When
391 applied to cross-shore beach profiles, it can reveal patterns of variation about the
392 mean profile shape, such as bars and troughs (Pruszek, 1993; Larson et al., 2003;
393 Kroon et al., 2008). The cross-shore profile shape is represented as a linear
394 summation of time and space varying functions:

395

$$396 \quad h_{xt} = \sum_n c_n(t).e_n(x) \quad (2)$$

397

398 where h = profile depth, x = distance measured offshore. $n = n_x$ = the number of
399 measurement points in the cross-shore profile and $n = n_t$ = number of cross-shore
400 profile surveys. e_n and c_n are spatial orthogonal functions and corresponding time
401 coefficients respectively, where

402

403
$$c_n(t) = \sum_{n=1}^{n_t} h_{xt} \cdot e_n(x) \quad (3)$$

404

405 Each eigenfunction corresponds to a statistical description of the data with respect to
406 how the data variance is concentrated in that function. The functions are usually
407 ranked according to the magnitude of their corresponding eigenvalues which are
408 proportional to the data variance. Typically, a large proportion of the data variance is
409 contained within a small number of eigenvalues and hence, only a limited number of
410 eigenfunctions are needed to explain most of the variation in the measurements
411 (Pruszek, 1993; Reeve et al 2001, Larson et al., 2003).

412

413 EOF analysis was performed on the beach profiles measured at both study sites. The
414 results at both sites show that more than 93% of the data variation is captured by the
415 first five eigenfunctions.

416

417 The first five normalised spatial eigenfunctions for Profile 5f00107 at Milford-on-Sea
418 and Profile 4 at Narrabeen Beach are shown in **Figures 10**. The dark line in the
419 figures gives the first eigenfunction that closely corresponds to the mean cross-shore
420 profile. The primary vertical axis in the figures corresponds to second and subsequent
421 eigenfunctions while secondary vertical axis corresponds to the mean profile. The
422 second eigenfunction reflects the presence of an upper beach ridge at Milford-on-Sea
423 and inter-tidal beach trough and terrace at Narrabeen beach respectively, which
424 distinctly deform the profiles from their mean profile shape. The third eigenfunction
425 reflects the presence of a sub-tidal trough and a bar at both sites. The fourth
426 eigenfunction implies sediment exchange across the profile, which reflects erosion of
427 the upper beach at Milford-on-Sea and inter-tidal zone at Narrabeen Beach. The fifth

428 eigenfunction and subsequent functions (not shown) may be related to other
429 accumulative-erosive features in the profiles which contribute to deform the profile
430 shape in time.

431

432 There are distinct differences between the spatial eigenfunctions at Milford-on-Sea
433 and Narrabeen Beach. At Milford-on-Sea, the spatial variability of all eigenfunctions
434 is strongest between 18 m and 40 m, which covers the entire swash zone and the
435 upper half of the inter-tidal zone. This confirms that the sub-aerial (above MWL)
436 beach undergoes the strongest morphodynamic variability, as indicated by the bulk
437 statistical analysis of raw profile data. Eigenfunctions at the Narrabeen Beach show
438 strongest variability beyond 60 m, which covers the inter-tidal and sub-tidal zone of
439 the profile. Variability of eigenfunctions in the swash region of the Narrabeen Beach
440 is significantly smaller than that of the rest of the profile. On both beaches, spatial
441 eigenfunctions do not reach constant values at the seaward end of the profile,
442 indicating that the depth of closure is located further offshore from the truncation
443 point of the measured profiles.

444

445 As seen in the third eigenfunction, the bar crest at Milford-on-Sea is located in the
446 inter-tidal zone and therefore can be exposed at low tide. On the other hand, the bar
447 crest on the Narrabeen profile is located in the sub-tidal zone and is submerged at all
448 times except during low water spring tide. The fourth eigenfunction which implies
449 sediment exchange cross the profile, shows offshore sediment transport, which
450 typically happens during storms. At Milford-on-Sea, sediment moves from beach
451 foreshore to the inter-tidal zone thus eroding the upper beach while at Narrabeen

452 Beach, sediment moves from the inter-tidal zone to sub-tidal zone that lowers the sub-
453 tidal beach. These characteristics show how each beach will respond to erosive events.
454
455 To investigate the temporal variability of different cross-shore morphological features
456 at a range of time scales, temporal eigenfunctions were examined. The first temporal
457 eigenfunction (not shown) is approximately constant at both sites as it corresponds to
458 the time-mean cross-shore beach profile. The second temporal eigenfunction at
459 Milford-on-Sea, shown in **Figure 11**, exhibits a gradual decline over time, indicating
460 long term beach recession due to degradation of the upper beach ridge. No seasonal
461 signature is evident. The second temporal eigenfunction at Narrabeen Beach shows a
462 high frequency signal as well as a longer-term 3-8 years cyclic variability. The high
463 frequency variability can be attributed to frequent storms that govern the NSW wave
464 climate. The lower frequency variability is likely to be due to the ENSO driven cyclic
465 beach rotation signal at Narrabeen Beach as postulated by Ranasinghe et al., (2004).
466 Although Profile 4, being approximately at the centre of the pocket beach, is thought
467 to be least influenced by the rotation signal, the result in Figure 11 indicates that at
468 least a small portion of the rotation signal may still be felt at this location.
469 Subsequent temporal eigenfunctions did not show any significant long term
470 periodicity at either beach.

471

472 **3.4 Canonical Correlation Analysis**

473 To investigate cross-shore profile response to incident waves canonical correlation
474 analysis (CCA) was performed between cross-shore profiles and corresponding
475 incident waves. CCA, which is a type of multi-variate linear statistical analysis,

476 allows joint patterns of behaviour to be detected in the evolution of the beach profiles
477 and the incident wave conditions.

478

479 In the application of CCA here, a regression matrix (ψ), which relates the beach
480 profiles to incident wave properties is derived based on the dominant patterns of these
481 two variables. A detailed description of the methodology is given in Clark (1975) and
482 Rózyński (2003).

483

484 CCA requires two time series (cross-shore profiles and incident waves) sampled at the
485 same rate. Therefore, the waves between the dates of each consecutive pair of beach
486 profiles were used to compile probability density functions (pdf), before using in
487 CCA. Larson et al (2000) proposed the use of a parameteric distribution for describing
488 the waves. Rihouey (2004) subsequently proposed the use of an empirical distribution.
489 Horrillo-Caraballo and Reeve (2008) tested both suggestions on data from Duck,
490 North Carolina and found superior results when using an empirical distribution. The
491 empirical distribution is a cumulative probability distribution function that
492 concentrates probability $1/n$ at each of the n numbers of a sample. A combined pdf
493 (p_n) may then be derived by superimposing the individual pdfs available for the period
494 between two consecutive profile surveys,

495

$$496 \quad p_n(a) = \frac{1}{n} \sum_{i=1}^n I(a_i \leq a) \quad (4)$$

497

498 where a is the wave height or steepness, n is the number of individual wave
499 measurements between two consecutive source functions and i is an index.

500

501 Offshore waves measured at Long Reef Point off the coast of Narrabeen Beach were
502 first transformed to a nearer location in 20m water depth, using the SWAN wave
503 transformation model. In order to investigate profile response to both wave height and
504 period, CCA was then performed between sequences of beach profiles and, in turn,
505 wave height and wave steepness probability density functions. **Figure 12a & b** show
506 composites of the probability density functions of wave height and wave steepness
507 respectively for Milford-on-Sea and Narrabeen Beach respectively.

508

509 It is evident that the structure of **Figure 12b** significantly differs from the structure of
510 **Figure 12a** at both sites. This indicates that different relationships between cross-
511 shore profiles and incident waves may be expected when wave height alone, and
512 combined wave height and period, are considered.

513

514 The performance of CCA can normally be improved by filtering the input data time
515 series. Here, we have followed Clark (1975) and expanded the data sequence as EOFs.
516 The data sequence is then reconstructed using only a subset of the EOFs in order to
517 filter out noise. The appropriate number of EOFs required for data reconstruction is
518 determined using a ‘rule of thumb’ (North et al., 1982).

519

520 Table 1 shows the “skill scores” of the CCA method for both Milford-on-Sea and
521 Narrabeen Beach. The “skill score” is analogous to the correlation coefficient between
522 cross-shore profiles and wave height or steepness, with a value of 0 corresponding to
523 no correlation and a value of 1 being a perfect correlation. The “skill” is calculated
524 using the regression matrix, and the percentage of total variance in the profiles and the
525 percentage of variance of input predictand EOFs following Różyński (2003).

526

Profile	Skill	
	H_s	H_s/L_s
Milford-on-Sea 5f000107	0.88	0.96
Narrabeen Beach Profile 4	0.37	0.41

527

528 Table 1 – ‘Skill’ scores between incident waves and cross-shore profiles.

529

530 The results given in Table 1 show that the wave steepness is, in general, better
531 correlated to the cross-shore profile shape, than the incident wave height, at both
532 Milford-on-Sea and Narrabeen Beach. However, it should be noted that the
533 correlation coefficient at Milford-on-Sea is substantially larger than that of Narrabeen
534 Beach, for both wave height and steepness, indicating that beach profiles at Milford-
535 on-Sea are strongly correlated to incident waves while only a moderate correlation
536 exists at the Narrabeen Beach.

537

538 This could be strongly attributed (i) to the saturation of the surf zone when the
539 incident waves break and strongly dissipate in the surf zone of a sand beach where
540 incident wave structure no longer exists. On the other hand individual incident waves
541 dominate the unsaturated surf zone on a steep, coarse-grain beach (Larson and Kraus,
542 1994) (ii) Dominance of waves at infragravity frequencies, driving surf and swash
543 sediment transport at incident wave group time scale on a sand beach. On a steep,
544 coarse-grain beach, swash sediment transport that dominates beach profile response,

545 is driven primarily by the individual incident waves (Wright et al., 1982;
546 Karunaratna et al., 2005; Masselink et al., 2010). As a result, profile response of a
547 steep beach is strongly correlated to the cumulative effect of incident waves while that
548 of a sand beach shows less correlation to incident waves.

549

550 **4. Conclusions**

551 Long term historic beach profile surveys at Milford-on-Sea beach, UK and Narrabeen
552 Beach, Australia, were analysed using a variety of techniques to compare and contrast
553 the behavioural characteristics of composite sand-gravel and sandy beaches at various
554 time scales.

555

556 The profile locations at both Milford-on-Sea and Narrabeen Beach have been selected
557 so as to minimise the influence of alongshore transport and to allow focus on cross-
558 shore sediment mobility. Overall, swash dominance on Milford-on-Sea beach and the
559 highly dynamic surf zone at Narrabeen Beach determine their morphodynamic
560 variability and hence long term beach behaviour.

561

562 The time mean cross-shore profile at Milford-on-Sea beach indicates a reflective
563 upper beach and a moderately dissipative lower beach. The sub-aqueous mean profile
564 closely resembles Dean's equilibrium profile, with only 11% RMSE, despite the
565 complex spatial variability of sediment characteristics. The observed differences can
566 be attributed to the bimodal sediment distribution across the profile. This observation
567 confirms that Dean's equilibrium profile can still be used as a suitable estimate of
568 long-term profile evolution of a composite sand-gravel beach. The mean beach profile

569 of the Narrabeen Beach is in close agreement with the Dean's equilibrium profile as
570 expected, with only less than 5% RMSE.

571

572 The standard deviation of profile depth shows that the swash zone is the most
573 morphodynamically active region of the composite sand-gravel beach and the inter-
574 tidal zone on the sandy beach. Both bulk statistical and EOF analyses confirm this
575 observation and identifies cross-shore beach profile variability at different time scales.
576 In the short-term, the composite sand-gravel beach responds to different wave
577 conditions through variability in the upper beach (swash zone) while the sandy beach
578 responds mainly through variability in the inter-tidal zone. This specific profile
579 response characteristic may lead to distinctly different mechanisms of beach
580 instability; a composite sand-gravel beach may become unstable due to sub-aerial
581 profile cutback during storms while sandy beaches destabilise as a result of beach
582 lowering. This same characteristic may make it more difficult for the upper foreshore
583 of a composite sand-gravel beach to recover from an erosive event than for a sandy
584 beach. Also, as Pontee et al (2004) observed, upper beach evolution is governed by
585 the upper foreshore itself, and therefore recession of the foreshore contributes to
586 further recession. This is supported by the form of the second eigenfunction which
587 reflects the observation of steady recession of the beach foreshore at Milford-on-Sea
588 and the mainly cyclical beach erosion at Narrabeen.

589

590 The CCA shows that beach profile change on Milford-on-Sea beach is more strongly
591 correlated to the incident wave steepness than at the Narrabeen Beach, which signifies
592 the impacts of surf zone saturation and the presence of infragravity waves in the surf
593 and swash on cross-shore profile evolution.

594 Finally, the impacts of the above observations on current modelling practises of cross-
595 shore beach profiles should be noted. Most cross-shore evolution models either use
596 sediment transport routines applicable only to sandy beaches (Roelvink et al., 2009),
597 based on single sediment size (Larson and Kraus, 1989; Larson et al., 1989) or use
598 only the sub-aqueous profile (Reniers et al., 1995; Southgate and Nairn, 1993).
599 Therefore, development of new routines, such as described by Jamal et al (2010), to
600 incorporate profile response of gravel beaches will be extremely timely.

601

602 **Acknowledgements**

603 Beach profile surveys and wave data at Milford-on-Sea are from the Channel Coastal
604 Observatory, UK. HK and DER acknowledge support from EPSRC through Grant
605 EP/C005392/1 – RF-PeBLE (“*A Risk-based Framework for Predicting Long-term*
606 *Beach Erosion*”). JMH-C and DER acknowledge the support of the European
607 Commission through FP7, 2009-1, Contract 244104 – THESEUS (“*Innovative*
608 *technologies for safer European coasts in a changing climate*”).

609

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810
811
812

813 **List of Figures**

814

815 **Figure 1** - Milford-on-Sea beach in Christchurch Bay and it's location in the UK

816

817 **Figure 2** – Narrabeen beach and its location in New South Wales, Australia.

818

819 **Figure 3** – Nearshore wave climate at Christchurch Bay. Waves were measured using
820 a wave rider buoy deployed at 12 m water depth.

821

822 **Figure 4** – Measured cross-shore beach profiles at transect 5f00107 at Milford-on-Sea
823 from 1987 to 2005. Profiles extend from the top of the dune to the mean
824 low water level.

825

826 **Figure 5** - Historic cross-shore profile survey data at Profile 4 at Narrabeen Beach,
827 NSW, Australia. Profiles have been measured from 10m elevation above
828 shoreline.

829

830 **Figure 6** – Measured wave height time series at a water depth of 80 m offshore of
831 Narrabeen beach, NSW, Australia. Waves were measured using a non-
832 directional wave rider buoy.

833

834 **Figure 7** – Comparison of Mean beach profile with Dean's equilibrium beach profile
835 (Dean, 1991) and Vellinga's erosion profile (Vellinga, 1983, 1984) Top
836 panel – Milford-on-Sea, Bottom panel – Narrabeen Beach.

837

838 **Figure 8** – Mean profile elevation (dark line) and profile envelop (faint lines) -top
839 panel- and Standard deviation - bottom panel - of cross shore profiles at
840 survey location 5f00107 at Milford-on-Sea beach.

841

842 **Figure 9** - Mean profile elevation (dark line) and profile envelop (faint lines) -top
843 panel- and Standard deviation - bottom panel - of cross shore profiles at
844 Profile 4, Narrabeen beach, NSW, Australia.

845

846 **Figure 10** – Spatial orthogonal eigenfunctions for profile 5f00107 at Milford-on-Sea
847 beach (top panel) and Profile 4 at Narrabeen Beach (bottom panel). Dark
848 line shows the mean profile.

849

850 **Figure 11**– Second Temporal Eigenfunction for Profile 5f00107, Milford-on-Sea (top
851 panel) and Profile 4, Narrabeen Beach (bottom panel).

852

853 **Figure 12** – Probability density functions of (a) incident wave height and (b) wave
854 steepness on Milford-on-Sea (top panel) and Narrabeen beach (bottom
855 panel).

856

857

858