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

Harshinie Karunarathna[1], Jose M. Horrillo-Caraballo[4], Roshanka Ranasinghe[2,3], Andrew D Short[5] and Dominic E. Reeve

[1]School of Engineering, University of Glasgow
Glasgow, G12 8LT, UK.
email: Harshinie.Karunarathna@gla.ac.uk

[2] Department of Civil Engineering and Geosciences
Delft University of Technology
P O Box 5048, 2600 GA Delft, The Netherlands.

[3]Department of Water Engineering
UNESCO-IHE
PO Box 3015, 2601 DA Delft, The Netherlands.
email: R.Ranasinghe@unesco-ihe.org

[4]Coastal Engineering Research Group
School of Marine Science and Engineering
University of Plymouth, Plymouth, PL4 8AA, UK.
Email:jose.horrillo-caraballo@plymouth.ac.uk, dreeve@plymouth.ac.uk,

[5] School of Geosciences
University of Sydney
NSW 2006, Australia

email: andrew.short@sydney.edu.au

Corresponding Author
Harshinie Karunarathna
School of Engineering,
University of Glasgow
Glasgow, G12 8LT, UK.
Phone: +44 141 330 5209
Fax: +44 141 330 4557
email: Harshinie.Karunarathna@gla.ac.uk

Abstract

Sand and composite sand-gravel beaches show distinctly different morphodynamic responses to natural forcing as a result, primarily, of differences in sediment properties and wave breaking and dissipation characteristics. As the incident wave conditions fluctuate, so the beaches vary in response, affecting their nature and long-term stability. In this paper, beach profile surveys acquired over more than a decade at a sandy beach (Narrabeen Beach, New South Wales, Australia) and a composite sand-gravel beach (Milford-on-Sea, Christchurch Bay, UK) are analysed to compare and contrast cross-shore morphodynamics of the two beach types. The different behavioural characteristics of the two beach types at decadal, inter-annual and intra-annual time scales are investigated. Comparisons of beach profiles with Dean's equilibrium profile and Vellinga's erosion profile shows that the Dean's profile satisfactorily represents the time mean profiles of both beach types. Statistical and Empirical Orthogonal Function (EOF) analyses confirm the generally accepted model that the inter-tidal zone is the most morphodynamically active region on a sandy beach whereas the swash zone is the most dynamic region on a mixed sand-gravel beach. The results also imply that during storms composite sand-gravel beaches may destabilise due to cutback of the upper beach while sandy beaches are more likely to be unstable as a result of beach lowering due to sediment transport from the inter-tidal zone to the sub tidal zone during storms. EOF results also show that Milford-on-Sea beach is in a state of steady recession while the Narrabeen Beach shows a cyclic erosion-accretion variability. A multivariate technique (Canonical Correlation Analysis, CCA) shows that on the composite beach a strong correlation exists between incident wave steepness and profile response, which could be attributed to the unsaturated surf zone, whereas on the sandy beach any correlation is much less evident.

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

1. Introduction

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

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

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

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

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

Swart (1974) and Sunamura and Horikawa (1974) examined characteristics of beach profiles through laboratory investigations and identified erosive and accretive profiles, relating profile geometry to incident wave conditions and sediment characteristics. Vellinga (1983, 1984) developed a relationship between cross-shore distance and profile depth for erosive beach profiles, which was a function of grain size.

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

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

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

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

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

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

2. Field Sites and Historic Data

2.1 Milford-on-Sea Beach

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

The Milford-on-Sea beach has a steep upper beach face with a gradient between 1:5 and 1:7 and a moderate inter-tidal beach with a gradient between 1:10 and 1:20. The gentler sub-tidal beach is characterised by highly mobile and segmented multiple alongshore bars. Cross-shore gradients on the western part of Milford-on-Sea beach are significantly steeper than those on the eastern part. The sediment grain size at Milford-on-Sea beach varies significantly along the cross shore profile. Coarse shingles and pebbles with a median grain diameter (D_{50}) around 14 mm dominate the upper beach. A sand-gravel mix which has D_{50}-gravel = 10 mm and D_{50}-sand = 1mm with only 12% sand fraction, dominates inter-tidal areas. (Martin Grandes et al., 2009). Sediment grain sizes on the western beach are slightly coarser than those on the eastern end, which contributes to the alongshore variation of the beach slope.

Christchurch Bay receives semi-diurnal tides with a moderate mean spring tidal range of 2.0 m OD, reducing to 0.8 m OD during neap tidal cycle. Mean high water spring (MHWS), mean low water spring (MLWS) and Mean water level (MWL) are 0.87 m, -1.13 m and 0.14 m above OD. Tidal currents as high as 3.0 m/s are observed in close proximity to the Milford-on-Sea beach (SCOPAC, 2003). Waves are incident predominantly from the SSW direction with occasional SSE waves. Waves at the eastern end of Christchurch Bay are more energetic than those incident on the western end due to the sheltering effect of Hengistbury Head. SCOPAC (2003) quote typical (one year return period) and extreme (1 in 100 year) significant wave heights for Milford-on-Sea as 2.5m and 3.4m respectively. **Figure 3** shows near-shore significant wave height measured at a depth of 12 m offshore of the Christchurch Bay beach from 1986 to 1994. The wave climate is seasonal with calmer summer months (March-September) and stormy winter months (October-February).

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

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

2.2 Narrabeen Beach

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

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

As a part of a coastal monitoring programme, beach profiles at five cross-shore locations along the Narrabeen Beach were regularly measured first at bi-weekly intervals and then, at monthly intervals since 1976, by the Coastal Studies Unit, University of Sydney. Surveys were undertaken at low tide and profiles were recorded at 10 m cross-shore intervals from a fixed bench mark at the landward limit of the active beach at 10 m elevation. Hourly non-directional (1976-1992) and directional (1992-2005) wave data were also measured at an offshore wave buoy located at the Long Reef Point, at a depth of 80 m. Cross-shore beach profile surveys carried out at Profile 4 (Figure 2), which is situated in the central part of the Narrabeen Beach, is used for the analysis presented herein. Profile 4 was selected for this analysis as it is the least likely location to be affected by the cyclic beach rotation phenomenon that operates at Narrabeen beach (Short and Trembanis, 2004; Ranasinghe et al., 2004a). Cross-shore profile surveys at Profile 4 from1976 to 1992 are shown in **Figure 5**. Shoreline position is located as MWL.

Narrabeen Beach is exposed to highly variable, moderate- to high-energy wind waves superimposed on long period, moderate- to high-energy south-easterly swell waves (Short and Wright, 1981). Waves are derived from three cyclonic sources: Mid-latitude cyclones pass across the southern Tasman Sea all-year-round, generating south-easterly swell; extra-tropical cyclones off NSW coast generating east and south-easterly waves peaking between May and August; tropical cyclones that generate moderate to high north-easterly and easterly swell during February and March. In addition summer (December to March) sea breeze generating low to moderate north-easterly seas. 20% of the waves are found to exceed 2 m. Mean significant wave height and peak period in the study area are 1.6 m and 10 sec respectively (Short and Wright, 1981; Short and Trenamon, 1992). On average, Narrabeen Beach, is subjected 12 storms per year (based on the local definition that H_s > 3m lasting more than 1 hr represents a storm. **Figure 6** shows typical offshore wave climate measured at the wave buoy at Longreef.

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

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

3. Analysis and Discussion of Cross-shore Beach Variability

3.1 Equilibrium Profile

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

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

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

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

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

3.2 Bulk Statistics

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

3.2.1 *Milford-on-Sea Beach*

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

3.2.2 *Narrabeen Beach*

Figure 9 shows mean cross-shore profile with profile envelope and standard deviation at profile 4. The width of the mean profile at the shoreline (MWL) with respect to the selected bench mark at the top of the dune is 100m. The envelope of the measured profiles shows that the beach width at the shoreline fluctuates by 70 m in the on- off-shore direction, which is 70% of the mean beach width. The standard deviation of beach profile depths drawn against profile depth shows three peaks. The largest peak is around 0.8 m above MWL, which is at the upper region of the inter-tidal zone. A secondary peak with standard deviation is nearly half that of the primary peak, is seen around 6 m above mean water level, which may be attributed to variability of the upper beach as a result of frequent storms. The peak at the end of the profile indicates that the surveys do not extend to the depth of closure.

3.2.3 *Comparison*

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

At Narrabeen Beach on the other hand, cross-shore variability is highest in the inter-tidal region. This can be related to the gradual wave dissipation on the gentle sub-tidal beach which results in more sediment transport in the surf zone than that in the swash zone. The surf similarity parameter determined using the average inter-tidal beach slope with mean wave steepness on the Narrabeen Beach is approximately 0.24, showing mostly spilling breakers. Swash movements on gentle beaches with spilling breakers are significantly lower than that on steep beaches due to partial or full saturation of the surf zone (Baldock and Holmes, 1999; Karunarathna et al., 2005).

3.3 Empirical Orthogonal Function Analysis

Empirical Orthogonal Function (EOF) analysis is widely used to investigate patterns in beach variations (e.g. Winant et al.,1975 and Wijnberg and Terwindt, 1995) and other coastal features (eg. Reeve et al., 2001; Kroon et al., 2008; Reeve et al 2008). The method maps the observed coastal morphological data into a set of shape functions known as eigenfunctions that are determined from the data itself. When applied to cross-shore beach profiles, it can reveal patterns of variation about the mean profile shape, such as bars and toughs (Pruszak, 1993; Larson et al., 2003; Kroon et al., 2008). The cross-shore profile shape is represented as a linear summation of time and space varying functions:

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

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

$$c_n(t) = \sum_{n=1}^{n_t} h_{xt} . e_n(x) \qquad (3)$$

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

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

The first five normalised spatial eigenfunctions for Profile 5f00107 at Milford-on-Sea and Profile 4 at Narrabeen Beach are shown in **Figures 10**. The dark line in the figures gives the first eigenfunction that closely corresponds to the mean cross-shore profile. The primary vertical axis in the figures corresponds to second and subsequent eigenfunctions while secondary vertical axis corresponds to the mean profile. The second eigenfunction reflects the presence of an upper beach ridge at Milford-on-Sea and inter-tidal beach trough and terrace at Narrabeen beach respectively, which distinctly deform the profiles from their mean profile shape. The third eigenfunction reflects the presence of a sub-tidal trough and a bar at both sites. The fourth eigenfunction implies sediment exchange across the profile, which reflects erosion of the upper beach at Milford-on-Sea and inter-tidal zone at Narrabeen Beach. The fifth eigenfunction and subsequent functions (not shown) may be related to other accumulative-erosive features in the profiles which contribute to deform the profile shape in time.

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

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

Beach, sediment moves from the inter-tidal zone to sub-tidal zone that lowers the sub-tidal beach. These characteristics show how each beach will respond to erosive events.

To investigate the temporal variability of different cross-shore morphological features at a range of time scales, temporal eigenfunctions were examined. The first temporal eigenfunction (not shown) is approximately constant at both sites as it corresponds to the time-mean cross-shore beach profile. The second temporal eigenfunction at Milford-on-Sea, shown in **Figure 11**, exhibits a gradual decline over time, indicating long term beach recession due to degradation of the upper beach ridge. No seasonal signature is evident. The second temporal eigenfunction at Narrabeen Beach shows a high frequency signal as well as a longer-term 3-8 years cyclic variability. The high frequency variability can be attributed to frequent storms that govern the NSW wave climate. The lower frequency variability is likely to be due to the ENSO driven cyclic beach rotation signal at Narrabeen Beach as postulated by Ranasinghe et al., (2004). Although Profile 4, being approximately at the centre of the pocket beach, is thought to be least influenced by the rotation signal, the result in Figure 11 indicates that at least a small portion of the rotation signal may still be felt at this location. Subsequent temporal eigenfunctions did not show any significant long term periodicity at either beach.

3.4 Canonical Correlation Analysis

To investigate cross-shore profile response to incident waves canonical correlation analysis (CCA) was performed between cross-shore profiles and corresponding incident waves. CCA, which is a type of multi-variate linear statistical analysis, allows joint patterns of behaviour to be detected in the evolution of the beach profiles and the incident wave conditions.

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

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

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

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

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

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

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

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

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

Table 1 – 'Skill' scores between incident waves and cross-shore profiles.

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

This could be strongly attributed (i) to the saturation of the surf zone when the incident waves break and strongly dissipate in the surf zone of a sand beach where incident wave structure no longer exists. On the other hand individual incident waves dominate the unsaturated surf zone on a steep, coarse-grain beach (Larson and Kraus, 1994) (ii) Dominance of waves at infragravity frequencies, driving surf and swash sediment transport at incident wave group time scale on a sand beach. On a steep, coarse-grain beach, swash sediment transport that dominates beach profile response, is driven primarily by the individual incident waves (Wright et al., 1982; Karunarathna et al., 2005; Masselink et al., 2010). As a result, profile response of a steep beach is strongly correlated to the cumulative effect of incident waves while that of a sand beach shows less correlation to incident waves.

4. Conclusions

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

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

The time mean cross-shore profile at Milford-on-Sea beach indicates a reflective upper beach and a moderately dissipative lower beach. The sub-aqueous mean profile closely resembles Dean's equilibrium profile, with only 11% RMSE, despite the complex spatial variability of sediment characteristics. The observed differences can be attributed to the bimodal sediment distribution across the profile. This observation confirms that Dean's equilibrium profile can still be used as a suitable estimate of long-term profile evolution of a composite sand-gravel beach. The mean beach profile of the Narrabeen Beach is in close agreement with the Dean's equilibrium profile as expected, with only less than 5% RMSE.

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

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

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

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