FIELD MEASUREMENTS OF BEACH-DUNE DYNAMIC PROFILES TO ASSESS EROSION HAZARD ON THE COAST OF NSW, AUSTRALIA

Zai-Jin YOU[1,2,3], Ray Laine[2], David J. Hanslow[2], Tom Baldock[3] and Daniel Wiecek[2]

The coast of New South Wales (NSW), Australia is about 2000 km long and consists of 721 sandy beaches (68%), rock coastline (32%), and more than 185 estuaries. It is most populated in Australia and one of the NSW greatest assets with significant economic, social and environmental values. The NSW coast has epsodically been ravaged by severe storms together with large ocean waves and high water levels, resulting in severe dune-beach erosion/recession, damaging coastal infrastructure and properties and degrading coastal ecosystems. With potential changes to storm-wave climate and rising sea level, coastal erosion hazards on the NSW coast are likely to worsen in the future. This study was undertaken to collect essential field data on beach-dune profiles and sediment grain-size distributions over more than 200 sandy beaches to assess NSW coastal erosion hazard. For each of the selected beaches, three beach-dune profiles of shore-normal transects at 50m apart were surveyed by RTK-GPS, and three sediment samples only on the first transect line were also colleced from the dune, dry beach/berm and swash zone by using a simple hand grabbing method. A sediment grain size analyzer, Malvern Mastersizer 2000E, was used to obtain sediment grain size distributions. It is found that the 618 sediment samples analysed consist of fine sand (10%), medium sand (82%) and coarse sand (8%), and that the dune sand d_{50} correlates well with the dry-beach sand d_{50} and is about 8% smaller, but less well correlates with the swash sand d_{50} and is about 15% smaller. The beach orientation was estimated from the direction of the shore-normal transect lines and generally ranges from 90° to 150°. The beaches surveyed are found to have erosion problems when they were directly exposed to predominant waves in the south-east direction and also when the dune toe elevations were lower than 3~3.5m (AHD). A conceptual model is also developed to assess likelihood storm erosion of a beach-dune system.

Keywords: beach profile, transect line, predominant waves, erosion hazard, swash zone, dune toe, sediment, swash, berm.

1. INTRODUCTION

The coast of New South Wales, Australia spans the northern Coral Sea to the southern Tasman Sea and is located in the southern hemisphere between latitudes 28° S and 38° S and longitudes 143° E and 154° E (see Figure 1A). The coast is about 2000 km long, stretches from the Queensland border in the north to the Victorian border in the south, and most populated in Australia, The coastline consists of 721 sandy beaches (62%) and rocky coastline (38%) (Short, 2007) and more than 185 estuaries, and is one of the NSW greatest assets with significant economic and environmental values.

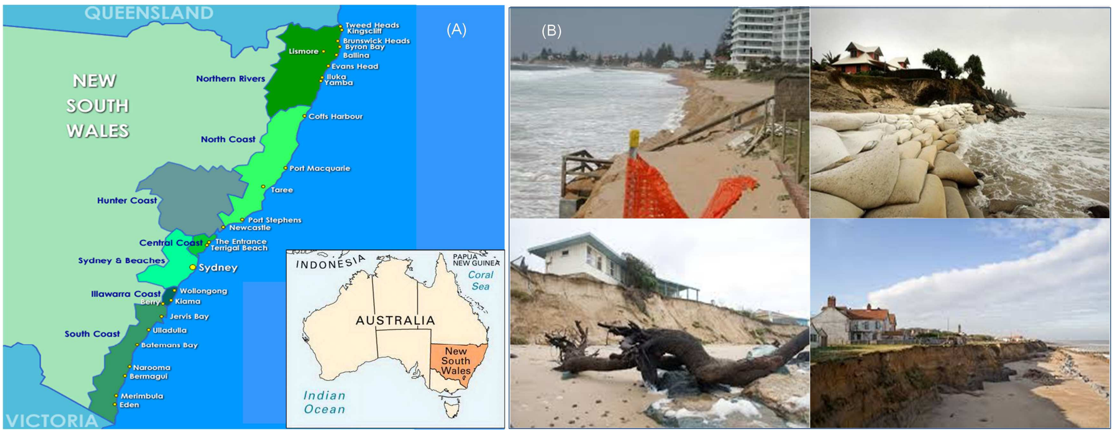

Figure 1 (A) Coastline of New South Wales (NSW), Australia and (B) Beach erosion hazard on NSW coast.

The coast of NSW is subject to episodic attack from coastal storms, large waves and high water levels. The open ocean tides along the coast are relatively uniform with a mean range of 1.93m, although there is a slight increase of 0.22m in the tidal range and 0.11m in the high tidal levels off the north coast than the south coast (You et al, 2012). The wave climate is generally moderate with the predominant direction from the south to south-east. The average offshore significant wave height is about 1.55m and the average peak period 9.5s (Lord and Kulmar, 2000; You, 2011). This generally moderate wave climate is often periodically affected by large coastal storm events, such as the 1974 *Sygna* storm, the 1997 *Mothers-Day* storm and the 2007 *Pasha Bulker* storm.

[1] Ports and Coastal Engineering Research Centre, Ludong University, Yantai, China. Email: b.you@ldu.edu.cn
[2] Coastal and Marine Science, NSW Office of Environment and Heritage, Newcastle 2300, Australia
[3] School of Civil Engineering, University of Queensland, St Lucia QL 47, Australia

These large storms, which were investigated and classified by PWD (1985, 1986), vary in their genesis, intensity and track both spatially and temporally. When they episodically attack the NSW coastline, they result in widespread coastal inundation, beach erosion, damage to property and marine structures, and risks to public safety particularly when they are coincident with high water levels (Figure 1B). In the 1974 storm event, for example, the severe coastal storms caused six deaths and the loss of about beachfront 20 resident houses and other assets worth many millions of dollars at that time.

Beach-dune erosion/recession is a major coastal hazard on the NSW coast. Fifteen coastal erosion “hot spots” were identified in eleven Local Government Areas along the NSW coast, where five or more houses or a public road under threat. The NSW coastal erosion has resulted in significant impacts to private properties and public infrastructure, and also caused permanent loss of valuable coastal land as partly illustrated Figure 1B.

The NSW coastal dune systems are vitally important in providing a source of sediment to nourish eroding beaches and protect the coastline from coastal inundation due to high tides, major storm surge, storm wave runup and rising sea level. Large wave runup, exacerbated by coinciding high tides, is a main driver for erosion of a beach-dune system due to wave notching, undercutting or scouring at the base/toe of the dune. When the wave notching reaches a critical depth into the dune, the frontal dune will become unstable and collapse into the sea. The volume of sand eroded from the dune front is a function of wave runup limit, dune height and slop, sediment property, beach width and slope, and storm duration.

This study is undertaken to comprehensively collect and analyze field data on shore-normal beach profiles and sediment grain size distributions over 200 sandy beaches along the NSW coast to assess the coastal erosion. A simple conceptual model for erosion of a beach-dune system is also presented.

2. FIELD DATA COLLECTION AND ANALYSIS

2.1 Study Sites

More than 200 representative sandy beaches along the NSW coast were purposely selected to collect a large quantity of field data on: i) profiles of beach-dune transects, ii) sediment grain size distributions, iii) dune baseline elevations, iv) maximum wave runup levels of debris, and v) visual observations of beach erosion and dune vegetation.

2.2 Sediment Grain Size Data

There were 618 sediment samples collected along the NSW coast. Three sediment samples for each of the selected beaches were collected in the swash zone, dry-beach/berm, and dune face/toe on the first transect line only by applying a simple hand grabbing method (see Figure 2). The swash sediment sample was taken between the upper and lower limits of swash zone, while the dry-beach or berm sediment sample was taken at which sand was dry on the transect line. The dune sediment sample was taken from dune face or sometime from dune baseline/toe when the dune face did not exist. Each sediment sample weighed about 200~300g and stored in a small plastic bag with sealable top and clearly marked with its name and unique ID. Site photos were also taken with a GPS digital camera to collect additional field data such as beach-dune erosion and maximum wave runup elevation of debris.

For each of the 618 sediment samples collected, a grain size analysis was performed to obtain grain size distribution and characteristic particle size parameters d_p (d_5, d_{10}, d_{16}, d_{25}, d_{50}, d_{75}, d_{84}, d_{90}, d_{95}), where d_p is the diameter at which p% of the sediment sample is finer than d_p. Additional statistical parameters were also calculated, including the mean, sorting, skewness, and kurtosis. The calculation of these parameters is performed in terms of $\varphi = -\log_2 d$, where d is measured in millimeters.

The majority of the collected samples were analyzed with a Malvern Mastersizer 2000, a laser diffraction method. The grain-size analyzer includes the wet sample dispersion unit Hydro 2000MU to mix a sand sample with water in a beaker of 1000 ml, including a stirrer to provide a well-mixed sand-water sample in the beaker. All measurements were conducted with a stirring rate of 3000 rpm. The Mastersizer is capable of analyzing sediment particle sizes in the range 0.02μm to 1 mm. For each sand sample, particle sizes were measured five times for duration of 5 seconds with a laser sampling frequency of 1 kHz. Ensemble averaging was conducted to further enhance the accuracy of the particle size distribution and the characteristic grain size parameters. The laser diffraction method is well accepted due to its precision (Syvitski, 2007).

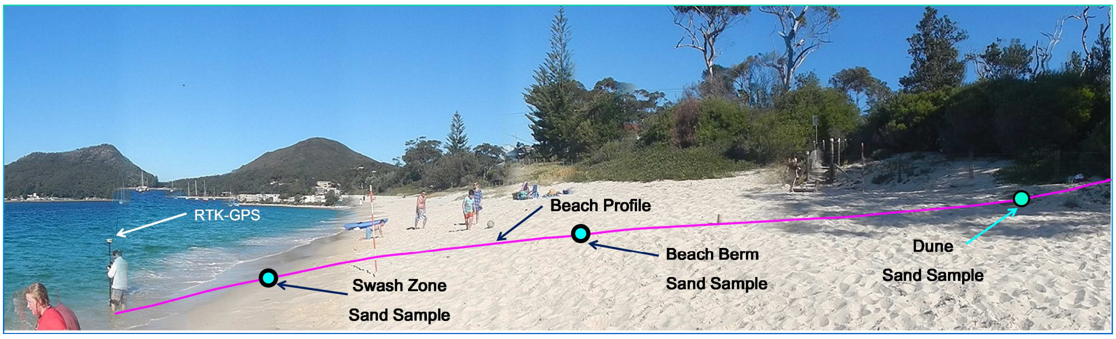

Figure 2 Field data collected on a NSW beach of Shoal Bay: i) profiles of beach-dune transect liness at 50m intervals, (2) three sediment samples at the swash zone, dry beach and dune face on the first transit, (3) dune toe elevations between the transects, (4) maximum wave runup levels of debris, and (5) site photos.

Fifteen of the 618 collected sediment samples, which contained a significant proportion of coarse sediments and shells, were not suitable for analysis by the Mastersizer. For these samples, the sediment sample was oven-dried and then pre-sieved through a sieve with size of 1.18 mm to exclude sediment fractions that are unsuitable for the Mastersizer. The percentage of these coarse sediments was documented, and the sieved sand sample was then analyzed with the Mastersizer. For the samples analysed with this method, the characteristic particle parameters d_{10} and d_{50} are generally accurate, but d_{90} may not be correct if more than 10% of the sample was excluded during the pre-sieving stage.

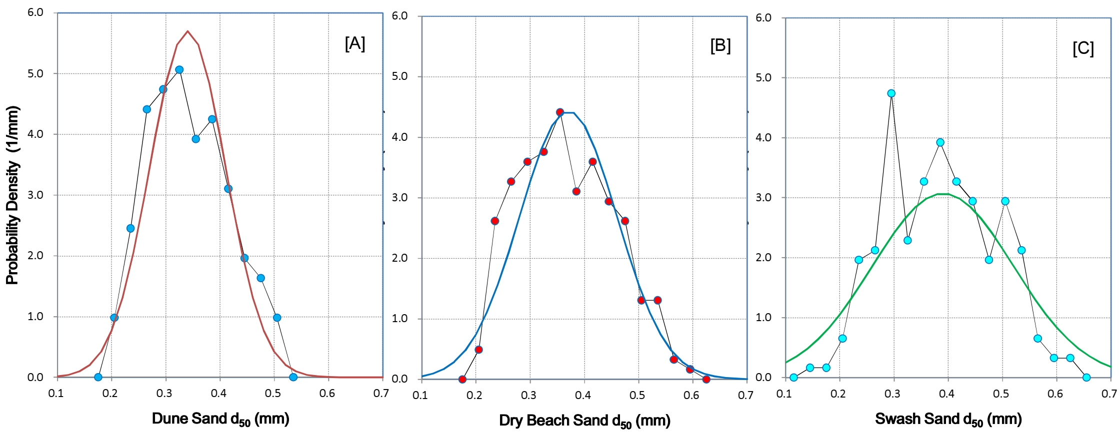

Figure 3. Probability density distributions of sediment grain sizes d_{50} measured at the swash zone, dry beach and dune for more than 200 beaches along the NSW coast, and also fitted to the normal distribution.

Figure 3 shows the probability density distributions of sediment grain sizes d_{50} measured at the dune, dry beach and swash zone over more than 200 beaches on the NSW coast. It can be seen that the distribution of d_{50} at the dune is more narrowly distributed than at the dry beach or berm, and much more than at the swash zone. The distributions of d_{50} in Figure 3 are also fitted to the normal distribution, where the mean and standard deviation of d_{50} are calculated from the analysed sediment data to be 0.34mm and 0.07mm at the dune, 0.37mm and 0.09mm at the dry beach, and 0.39mm and 0.13mm at the swash.

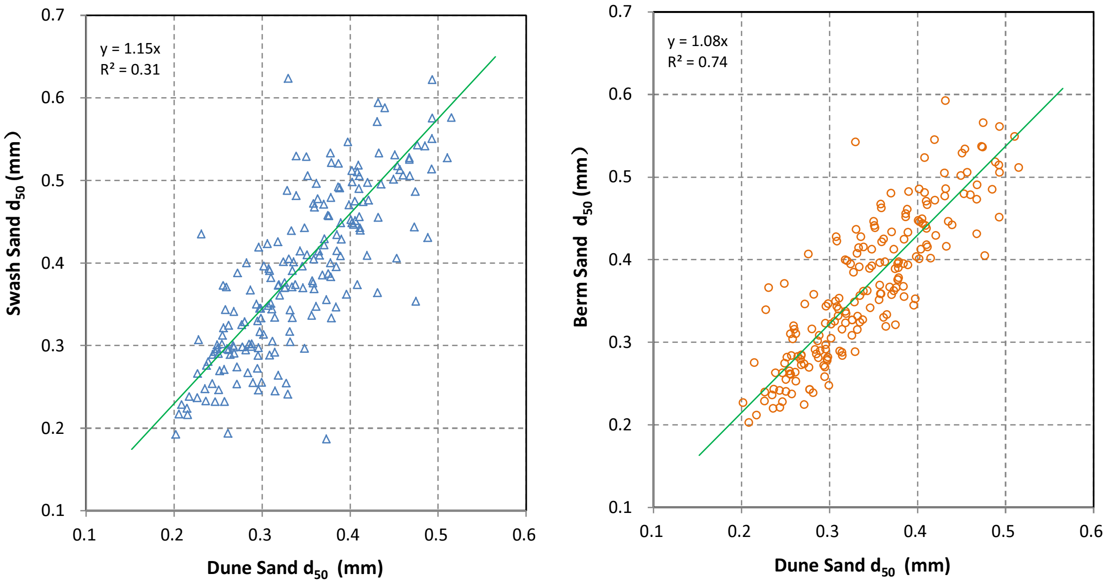

Figure 4 Sediment grain sizes d_{50} measured at the swash zone and dune are compared with those at the dry beach or berm over about 200 beaches of NSW, Australia.

Figure 4 also shows that the analyzed sand sizes d_{50} at the dune face/toe are compared with those at the swash and dry beach, respectively. It can be seen that the sand sizes at the dune correlate well with and is about 8% smaller than those at the dry beach, but correlate less well with and is about 15% smaller than those at the swash zone.

The 618 sediment samples collected are analyzed and found to consist of fine sand (10%), medium sand (82%) and coarse sand (8%), where very fine sand is classified as d_m=0.05~ 0.1mm, fine sand d_m=0.1~ 0.25mm, medium sand d_m=0.25~ 0.5mm, and coarse sand d_m>0.5mm. The coarse sand samples (8%) are found mostly in the swash zone (5%), rarely from the dry beach or berm (3%) and ever from the dune face, while the fine sand samples (10%) are approximately equal from the sand dune (4%), dry beach (3%) and swash (3%). The medium sand samples (82%) are from the dune (29%), dry beach (27%) and swash zone (25%).

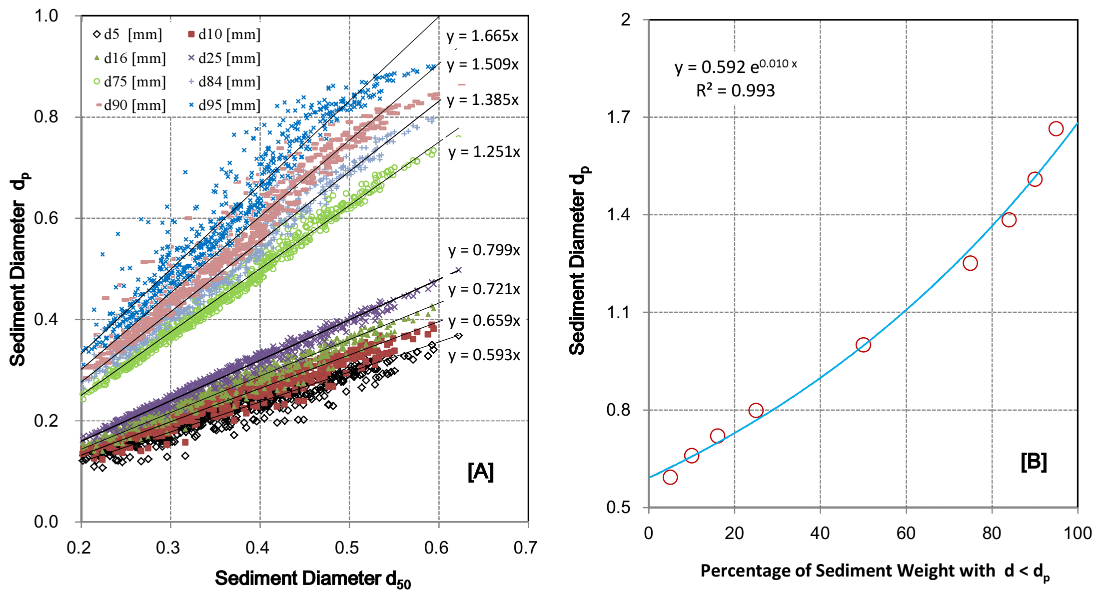

Figure 5. [A] Ratio of d_p to d_{50} measured at the dune toe, beach berm and swash zone for more than 200 beaches of NSW, Australia and [B] a derived relationship for d_p/d_{50} from the data.

Sand uniformity can be assessed by using a gradation index or uniformity coefficient. The gradation index is calculated from the characteristic sand diameters d_p, e.g d_{90}/d_{10}. The average d_{90}/d_{10} gradation index, which is obtained by plotting the d_{10} data versus the d_{90} data from this study, is about 2.35 in Figure 5A. In general, larger values ($\gg 1$) of the gradation index indicate less uniform sand, while smaller values (~ 1) imply more uniform or well sorted sand. The sand uniformity, which is analysed from the 618 samples collected along the NSW coast, is found to be well sorted.

Table-1 Measured values of d_p/d_{50} at the swash zone, berm and dune along the NSW coast

d_p	d_5	d_{10}	d_{16}	d_{25}	d_{50}	d_{75}	d_{84}	d_{90}	d_{95}
d_p/d_{50}	0.593	0.659	0.721	0.799	1.0	1.251	1.385	1.509	1.665
R^2	0.91	0.94	0.96	0.98	1.0	0.98	0.97	0.95	0.93

Several useful ratios of d_{50} to d_p are also obtained by plotting d_{50} versus d_p and shown in Figure 5A and in Table-1, where the d_{50} and d_p values are from all samples of the dune, dry beach and swash, and R^2 is the linear regression coefficient. An empirical formula, which is fitted to the data in Figure 5B, is proposed to estimate the ratio d_p/d_{50} as

$$\frac{d_p}{d_{50}} = 0.60\exp(0.01p) \qquad (1)$$

where p is the cumulative percentage passing. Eq.(1) can be then used to derive different values of d_p/d_{50} including some special values, e.g. $d_0 \approx 0.60d_{50}$ and $d_{100} \approx 1.63d_{50}$.

Figure 6 also shows the spatial distribution of berm sand diameter d_{50} from the south to the north along the NSW coast, where there are 203 sand size data points plotted. The sand grain sizes d_{50} on the north of the coast, which is experiencing serious coastal erosion/recession, are shown to be generally smaller than those in the south and middle.

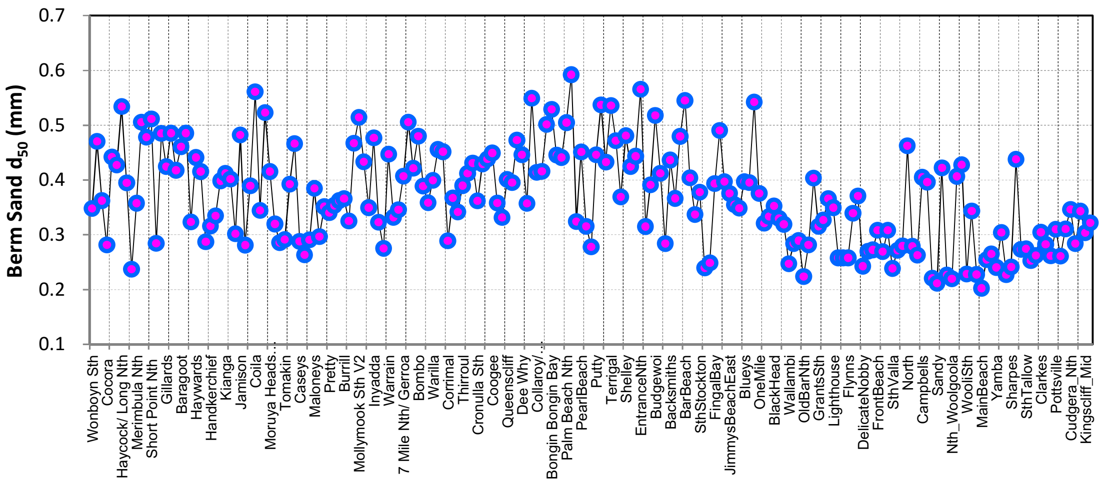

Figure 6 Spatial distribution of beach berm sand diameter d_{50} measured along the coast of NSW, Australia.

It is well documented that the measured particle sizes are different between laser diffraction and sieve analysis techniques (e.g. Xu and Di Guida, 2003; Blott and Pye, 2006). Particle sizes measured with the laser diffraction method are generally larger compared to those from the sieve analysis. In this study, the differences between the laser diffraction and the sieve analysis methods were also determined specifically for six typical sediment samples. It has been reconfirmed that the laser diffraction method overestimated d_{10} by 3~8%, d_{50} by 11~18% and d_{90} by 19~25% compared to the classic sieving method. These differences between the results of the laser diffraction and the sieve analyses methods agree well with the range of differences given in the literature (Cheetham et al, 2008). Rodríguez and Uriarte (2009) also derived empirical formulas to convert the particles diameters d_{10}, d_{50} and d_{90} analyzed with the laser diffraction method to those with the sieving method.

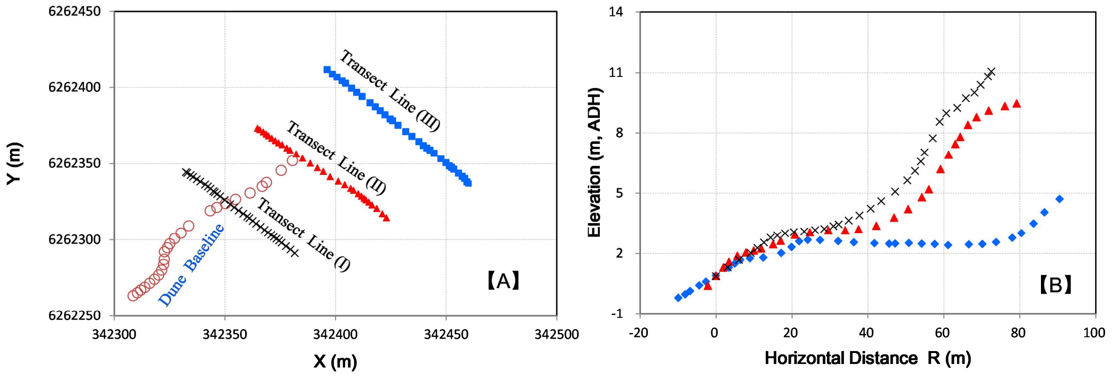

Figure 7 [A] Global horizontal positions (x, y) of shore-normal transects and dune baseline, and [B] beach-dune profiles of shore-normal transects measured with RTK-GPS on Curl Curl Beach of NSW.

2.3 Beach Profile Data

Beach-dune profiles of more than 200 sandy beaches were surveyed along the coast of NSW with a RTK-GPS that employed the CORSnet-NSW NRTK to ensure that the fundamental positioning network is available across all of NSW including its coastline (Janssen and Haasdyk, 2011).

For many of the surveyed beaches, only three profiles of shore-normal transects, which often located at the center of the beaches, were surveyed at 50m intervals approximately, but for some important and long beaches, up to nine profiles at two ends and middle of the beaches were surveyed. The field data on dune-toe elevation were also collected along dune baseline between the transect lines, but sometimes outside of the transect lines to collect more suitable field data. Figure 8 shows a typical dataset collected on North Curl Curl Beach with RTK-GPS.

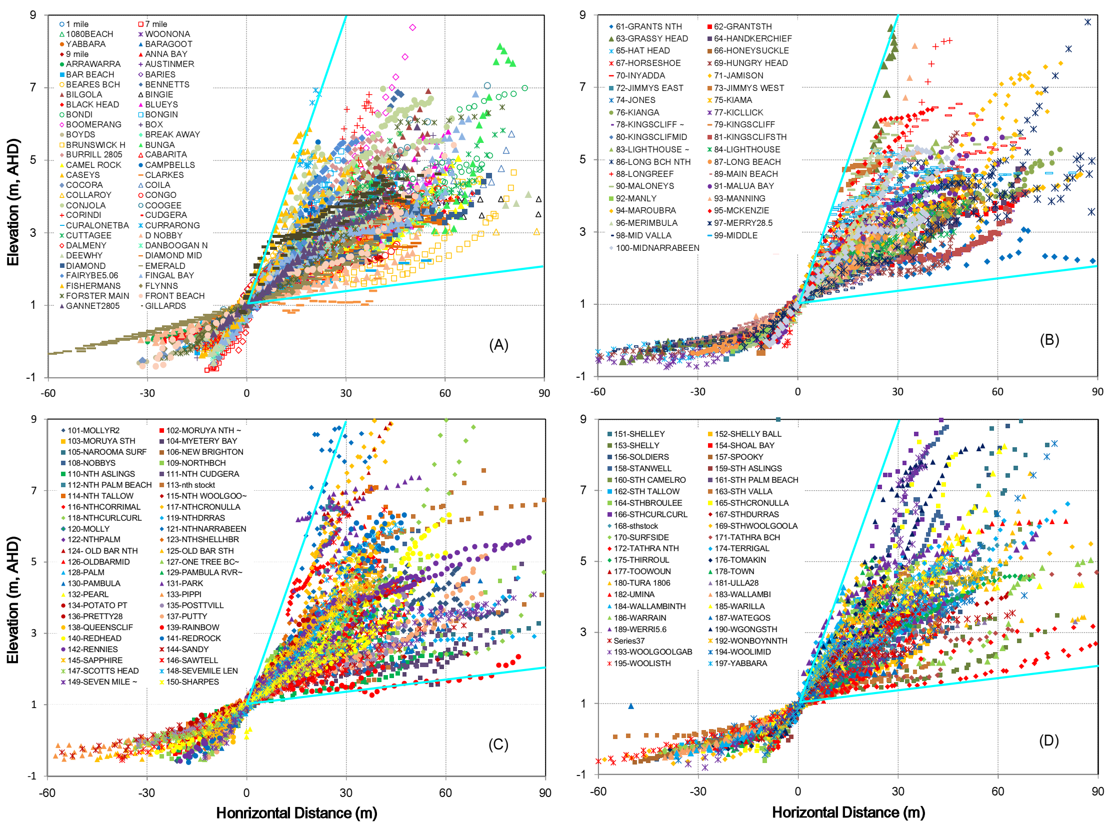

Figure 8 Beach-dune profiles of shore-normal transects surveyed along NSW coast with RTK-GPS.

In Figure 7, the horizontal distance is measured relative to the origin of the z axis locate at (x_o, y_o,1m), where (x_o, y_o) are the global horizontal positions of the beach profile at z=1m. The elevation of z=1m was purposely chosen to be approximately equal to the maximum tidal amplitude on the NSW coast. For a given beach profile (x, y, z), the horizontal distance is then calculated simply as

$$R = \begin{cases} [(x - x_o)^2 + (y - y_o)^2]^{0.5} & z \geq 1m \\ -[(x - x_o)^2 + (y - y_o)^2]^{0.5} & z < 1m \end{cases} . \quad (2)$$

Naturally, the z axis may be preferred to locate at (x_o, y_o, 0), but during high tides, many beach profiles close to z=0m could not be surveyed to establish the z axis at z=0m for those beach profiles.

Figure 9 shows how well beach berm sand size d_{50} correlates with shore-normal direction ∅. The value of ∅ is directly estimated from the beach profile (x,y,z) of shore-normal transect line by fitting a linear regression line thorough the data points (x,y), of which ∅ is equal to the slope of the regression line. It can be seen from Figure 9A that the berm sand size d_{50} is almost independent of ∅ and a majority of the ∅ values range from 90^0 to 130^0. The probability density distribution of ∅ is also given in Figure 9B. The value ∅, at which the highest probability density occurs, is shown to be approximately equal to the predominant wave direction (SE) on the NSW coast. In other words, a majority of the beaches surveyed on the NSW coast face into the direction of predominant waves

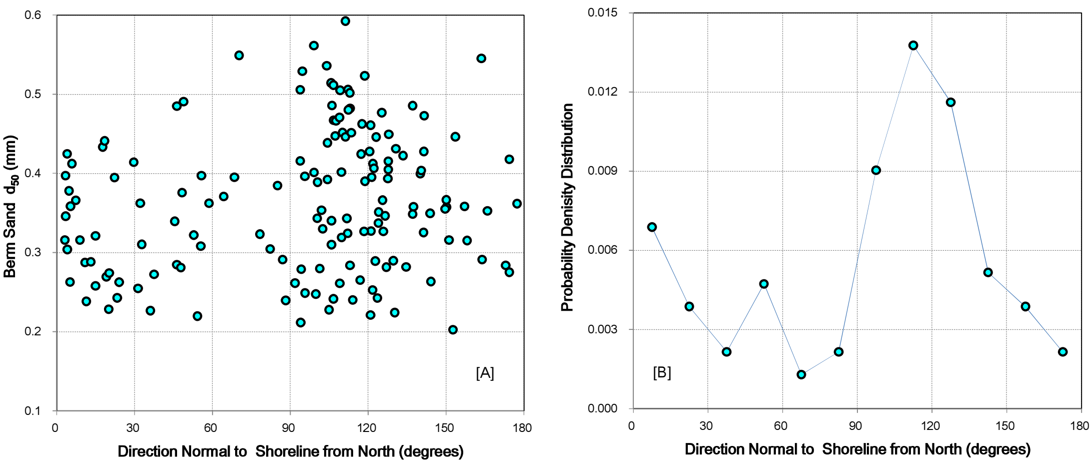

Figure 9 [A] Correlation between berm sand size d_{50} and the beach orientation (shore-normal direction), and [B] the probability density distribution of beach orientation measured on the NSW coast.

2.4 Beach-Dune System and Classification

Coastal beaches may be classified into three classes: dissipative, intermediate and reflective beaches in terms of beach slope tanα in swash zone (Wright and Short, 1984). A dissipative beach is classified when tanα ≤0.03 in the swash zone, and a reflective beach when tanα = 0.1~0.2, and an intermediate beach when 0.03< tanα≤0.1. Nielsen and Hanslow (1991) suggested that the distinction between the dissipative and reflective beaches should be tanα=0.10. As the location of the wash zone oscillates with changes of tides and waves and beach profiles, the beach types will change with coastal hydrodynamics. As discussed by Holman and Sallenger (1985), for example, a beach can be considered as reflective during high tides, but becomes as intermediate during low tides due to bar influence on wave breaking. A simple but reliable parameter, sediment grain size d_{50} in beach berm or dry beach may be proposed to replace the beach slope tanα for the classification of coastal beaches.

The NSW beach-dune systems in Figure 8 may also be defined into three types in terms of how waves act with a dune: collision, overwash and inundation. The collision type is defined when waves run up on the beach and attack the baseline of the dune resulting in dune-front erosion, but can't overtop the dune. The dunes of this type are generally higher than 6-7m (AHD), which is approximately equal to the upper limit of the sum of storm tide, wave setup, and wave runup (NSW Gov, 1990). The overwash type occurs when waves can overtop the dune and transport sediment landward, but the storm tide levels are still below the crest of the dune. The inundation type, the most extreme of the three, happens when waves completely overtop the dunes and storm tide levels also are higher than the crest of the dune resulting in inundation. The beach-dune systems of this type are generally lower than 3m (AHD) in Figure 8 and often located at the coastal river entrances of NSW. The beach-dune systems of the three types need to be treated differently in modelling of storm erosion or accretion on the NSW coast.

3. ASSESSMENT OF DUNE-BEACH EROSION

3.1 Conceptual Model

An important finding of this field study is that the dunes of the surveyed beaches were found to be eroded generally when their toe elevations were less than 3.0~3.5m (AHD) above mean sea level. The dune erosion is defined in this study when the dune vegetation, trees or fences were observed to fall onto the beach, the dune front/toe was found wet and attached by waves, or the dune toe was freshly scoured. Even though the field data were collected over a short period of a few months, the dune erosion events recorded in this study could occur a few years ago before this study was undertaken. The criterion of R=3~3.5m (AHD) was established after the elevations of numerous dune toes, which were observed to be eroded or stable, were surveyed by the RTK.

This criterion was further verified by the convincing data collected in a 500m test section of a long and straight beach, Lighthouse Beach in this study. The dune sat on the rock platform at both the north end and the middle of the test section, but on the sandy bottom at the south end. It was observed that the dune toe at 3.16m (AHD) in the north end was well protected by dune vegetation and no erosive evidence was found, but obviously eroded at 2.32m (AHD) in the middle and also at 2.64m (AHD) in the south end of the test section.

Based on the field experimental evidence obtained in this study, a conceptual model is proposed here for assessment of beach-dune storm erosion only

$$W = R_2 - (R_t + R_s + R_w + R_r + R_h) = R_2 - R_1, \quad (3)$$

where R_2 is the current dune-toe elevation, R_t tidal elevation, R_s storm surge height, R_w wave setup height, R_r wave runup height, and R_h sea level rise height, and $R_1 = (R_t+R_s+R_w+R_r+R_h)$. All terms in Eq.(3) are defined in Figure 10. Actually the term R_1 physically represents wave runup elevation (m, AHD) and can be directly observed and measured (see Figure 11).

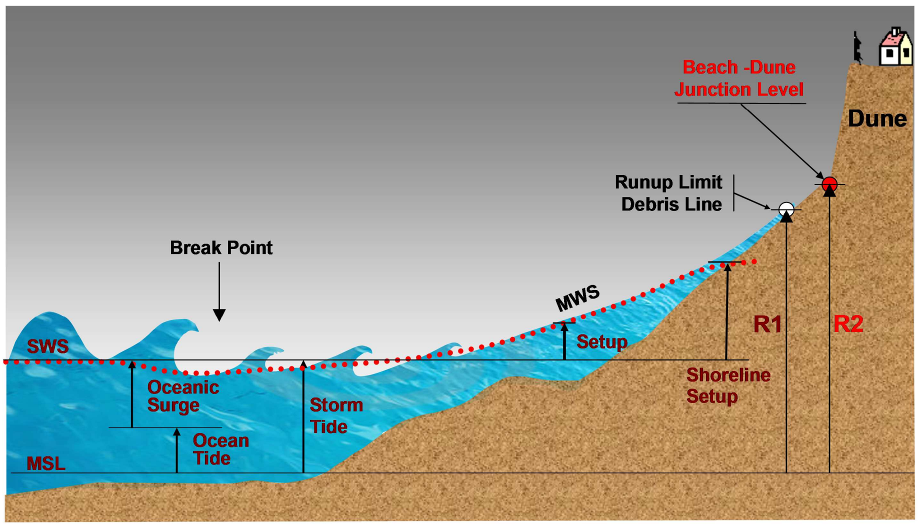

Figure.10 Coastal physical processes and mechanism for storm erosion of a beach-dune system, where MSL is mean sea level, SWS is still water surface, MWS is mean water surface, and i) Storm Tide = Ocean Tide + Oceanic Surge; ii) Oceanic Surge = SWS - Ocean Tide, iii) Wave Setup = MWS – SWS, and iv) Wave Runup = MWS – Shoreline Setup (You and Nielsen, 2013).

The conceptual model in Eq.(3) proposes that a beach-dune system with $R_2 < R_1$ is expected to keep moving landward until such a time when the condition of $R_2 > R_1$ is achieved, as partially illustrated in Figure 11. The model assumes that the erosion of dune occurs only when $R_2 < R_1$ and the beach profile, which is averaged over a long time period, does not or slowly change with time. At high storm tides, storm breaking waves arrive at the beach, resulting in large volumes of high kinematic water that runs up on the beach high enough to attack the dune face and especially the due toe and take away sand from the dune toe by the downrush mechanism in the swash zone, subsequently causing the collapse of the dune front into the sea when the eroding dune slope is larger than the equilibrium dune slope and lumps of the dune sand are carried into the sea by the high speed downrush water. The physical processes will be continued until the storm waves become smaller and the storm tides become lower.

Figure 11. The conceptual model for assessment of beach-dune erosion: It states that a beach-dune system with $R_2 < R_1$ is expected to keep moving landward until such a time when the condition of $R_2 > R_1$ is reached.

3.2 Model Application

The conceptual model in Eq.(3) is applied to assess whether or not the Narrabeen and Old Bar beaches, of which the surveyed beach-dune profiles are shown in Figure 12, are currently vulnerable to beach-dune erosion problems. Based on Eq.(3) and as shown in Figure 12, Narrabeen Beach could lose the shaded area of sand if the current dune toe elevation of about R_2=3m (AHD) was extended to dune toe elevation of R_1=R_n=3.5m (AHD), while Old Bar Beach could lose the shaded large area of sand from the dune if the current dune toe elevation was extended from the current dune toe elevation of R_2=2m (ADH) to a dune toe elevation of R_1=R_n=3m (AHD), where R_n is the n-year return value for the dune toe elevation. A straight line of many other forms is proposed to connect the current dune toe elevation R_2 to the dune toe elevation R_n even though the true distribution to connect R_2 and R_n is unknown. The current dune face slope is also assumed to be the same as the future one in Figure 12.

The extent of the future dune toe elevation R_1=R_n is likely to be a product of several parameters such as dune sand property (sand size, porosity and permeability), storm type, local wave climate, and astronomical tide. Since coastal sediment grain sizes may also correlate with local wave climate partially at least, R_n is expected to increase with increasing sediment grain size. For example, when sediment of a coastline is fine, the local wave climate is mild and waves should be small and the beach slope should be also very flat.

When R_1 is unknown, it may be estimated from the joint distribution of R_{rsw} and R_t based on both water level and wave data collected, where R_{rsw}=(R_s+R_w+R_r) represents the superelevation of storm-elevated water column height above tide level R_t. This approach may not be accurate because all terms in Eq.(3) can't be directly measured (see Figure 10) and the accuracy of the terms depends on the other parameter to be also determined. Another new approach is to directly collect the long-term field data on wave runup elevation R_1 (see Figure 11) especially during storm events, from which the n-year return dune toe elevation R_n can be estimated.

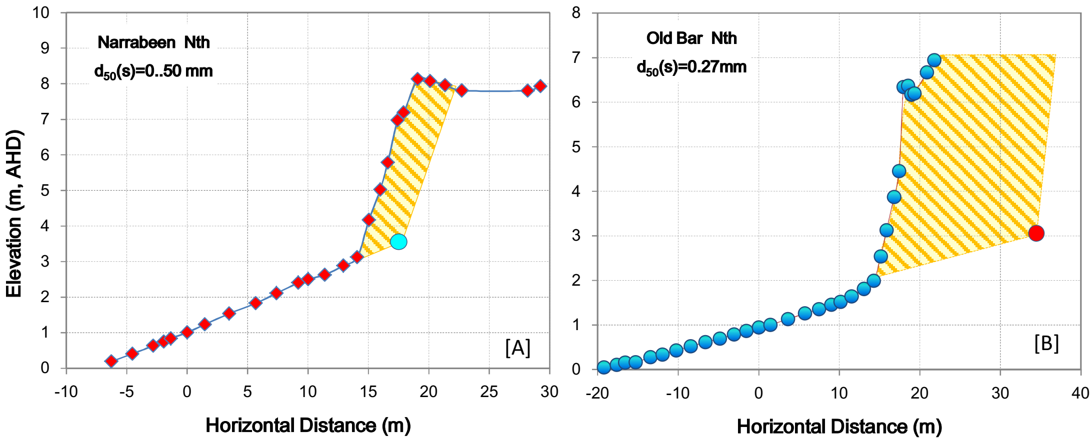

Figure 12 The conceptual model in Eq.(3) used to assess erosion problems of: [A] Narrabeen Beach with a future toe elevation of 3.5m (AHD), and the shaded area of sand is expected to be eroded from the current dune and [B] Old Bar Beach with a future dune toe elevation of 3m (ADH), and the shaded area is predicted to be eroded from the current sand dune.

4. CONCLUSION

An extensive field study was undertaken to collect the field data on beach-dune profiles of shore-normal intrasects and sediment grain-size distributions over more than 200 sand beaches to assess coastal erosion hazard along the NSW coast, Australia. There are about 600 beach-dune profiles of shore-normal transects were surveyed by RTK-GPS, and 618 sediment samples collecgted from the dune, dry beach/berm and swash zone by using a simple hand grabbing method. A sediment grains size analyzer, Malvern Mastersizer 2000E, was used to obtain sediment grain size distributions. It is found that the collected 618 sediment samples consist of fine sand (10%), medium sand (82%) and coarse sand (8%), and that the dune sand d_{50} correlates well with and is about 8% smaller than the dry-beach, but less well correlates with and is about 15% smaller than the swash sand d_{50}. The beach orientation was estimated from the direction of the shore-normal transect lines and generally ranges from 90^o to 150^o. The beaches surveyed are found to have some erosion problems when they were exposed to open coastal predominant waves from the south-east direction and also when their current dune toe elevations were lower than 3~3.5m (AHD). A conceptual model is also developed to assess likelihood storm erosion of a beach-dune system by introducing the concept of the n-year return dune toe elevation R_n.

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