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Short communication

Quantifying the storm erosion hazard for coastal planning

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ABSTRACT

The quantity of coastline retreat resulting from storm erosion is one of the most important phenomena that needs to be accurately quantified to facilitate effective coastal management strategies. Historically, the volume of storm erosion (and coastline retreat) accommodated for coastal planning decisions has been directly linked to the storm (usually defined by considering wave height and duration only) with a certain pre-defined return period, known as a Synthetic Design Storm (SDS) (e.g. 1 in 100 year storm). The SDS method of estimating storm erosion volumes for coastal planning thus assumes that, for example, the 1 in 100 year storm event also results in a 1 in 100 year erosion event. This communication discusses the physical reality of this assumption and demonstrates the improved performance of a new method, based on Joint Probability Distributions (JPD) for estimating storm erosion volumes proposed by Callaghan et al. [Callaghan, D.P., Nielsen, P., Short, A.D. and Ranasinghe, R., 2008. Statistical simulation of wave climate and extreme beach erosion. Coastal Engineering, 55(5): 375–390] using one of the world's longest beach profile surveys from Sydney, Australia.

1. Introduction

Coastline retreat due to both chronic (e.g. sea level rise, gradients in alongshore sediment transport) and ephemeral (e.g. Storm erosion) need to be accurately quantified for effective coastal planning/management. Several approaches are currently applied to estimate these phenomena. For example, aerial photograph analysis is used (decadal timescales) to estimate chronic coastline retreat due to prevalent gradients in alongshore sediment transport along a coastline. To estimate chronic coastline retreat due to sea level rise, the Bruun rule (Bruun, 1962) approach is routinely applied (for more details on Bruun rule applications, see discussion by Cowell, 2006). To quantify ephemeral coastline retreat due to storm erosion the most commonly applied methods are a) adoption of a previous severe storm erosion volume for planning purposes (Gordon, 1987), and b) the Synthetic Design Storm approach (SDS method) (Carley and Cox, 2003). More recently, Callaghan et al. (2008) proposed a statistical approach, referred to as the Joint Probability Method (JPM) in which the dominant forcing mechanisms to estimate storm erosion volumes are simulated within a probabilistic framework. This communication discusses the relative merits of the SDS and the JPM methods and compares the prediction made by both methods when applied to Narrabeen Beach, Sydney, Australia where continuous beach profile surveys are available for over 30 years.

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The synthetic design storm (SDS) method (Carley and Cox, 2003) provides the wave height variation during the storm. The wave direction is not directly included in the approach. To minimise excluding wave direction variability from the SDS method, the wave statistics are estimated in the nearshore region where wave refraction impacts are minimal. The major assumption of the SDS approach is that an x-year return period nearshore wave height results in an x-year erosion event. This is an assumption which simplifies the problem but is a clear departure from physical reality as it removes other processes that effect beach erosion statistics (e.g., wave storms duration and sequencing). Furthermore, the SDS method is not capable of accurately predicting beach erosion when there is insufficient time for beach recovery during closely spaced storm events. As evidenced during the 1974 storms in Eastern Australia, most damage is in fact caused when storms occur in rapid succession (Foster et al., 1975). Notwithstanding these limitations of the SDS approach, Nielsen and Adamantidis (2007) recommend using the SDS approach within a risk framework to select an appropriate return period storm erosion volume, and thus ephemeral coastline retreat, for planning purposes.

While statistical approaches are well established in other geophysical disciplines (for example, floodplain management), the application of rigorous statistical modelling has had limited application to beach erosion. Callaghan et al. (2008) presented a rigorous statistical method for beach erosion that compared satisfactorily with extensive field measurements obtained at Narrabeen Beach, Australia over a period of 30 years. Callaghan et al.'s (2008) JPM builds upon the ideas of Hawkes et al. (2002) in which the storms (extreme wave

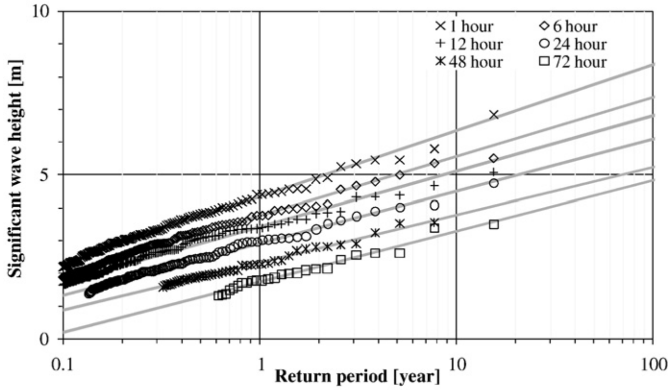

Fig. 1. Significant wave height-frequency-duration empirical estimates using the wave parameters estimated from transferring the Long Reef offshore directional wave buoy measurements to the nearshore, which extend from 1992 to 2007. The grey lines ($H_s = a \ln T_R + c$) have been fitting using least squares.

conditions) are statistically modelled, including the relevant joint probabilities. The significant extension in this approach over Hawkes et al. (2002) is that the storms are simulated temporally to include antecedent beach conditions using a storm occurrence model.

2. Field data

To rigorously evaluate the performance of both the SDS method and JPM require a relative long and continuous data sets of beach surveys, wave characteristics and water level information. The 32-year long data set of monthly beach profile surveys at Narrabeen Beach, Sydney, Australia conducted from 1976 onwards, the availability of offshore wave data (from 1971 from Botany Bay, from 1992 very close to the site) and water level from 1914 in the vicinity of Narrabeen Beach allows such a rigorous evaluation. Five cross-shore profiles were surveyed at approximately monthly intervals at Narrabeen Beach. Of these, Profile 4, located near the centre of the pocket beach was selected for the analysis here as longshore erosion effects are minimal at this location (Short and Trembanis, 2004). The other profile locations monitored in this measurement set will include beach rotation induced erosion and accretion volumes as well as cross-shore erosion. The beach rotation mechanism is excluded from both SDS and JPM approaches. Consequently, comparisons at profiles other than profile 4 would neither clearly demonstrate nor disprove either method as under and over predictions would necessarily occur due to the exclusion of beach rotation from the profile response model.

Two methods were used to estimate extreme storm erosion volume statistics at Profile 4 (see Fig. 1c in Callaghan et al., 2008). The first approach, referred to as block averaging, discretised the data set into 1.5 month long blocks (average time between surveys) and calculated maximum beach volume change between the 1.5 month blocks during each 12 month period. The second approach, referred to as consecutive volumes, uses Botany Bay wave measurements to identify the time that storms occurred. The erosion volume relevant to each individual storm was then obtained from the consecutive profiles bracketing the wave event or events.

The offshore wave measurements available in the vicinity of Narrabeen Beach are the non-directional measurements at Botany Bay and the directional measurements at Long Reef. Both measurements are obtained at approximately 80m depth (see Fig. 1b in Callaghan et al., 2008). Two methods are used to determine the nearshore wave time series from these offshore measurements. The first method transfers the time series of directional wave measurements from the Long Reef directional wave buoy to the nearshore (using the same SWAN model as Callaghan et al. (2008). The second method combines the non-directional Botany Bay wave data and the directional Long reef wave data and simulates the offshore wave climate using the same joint probability distribution functions used in Callaghan et al. (2008). These wave parameters are then transferred to the nearshore using the same SWAN model as above. This second method takes advantage of the longer wave height measurements at Botany Bay.

3. Results and discussion

The nearshore wave time series thus obtained were analysed as follows to generate the synthetic design storm as per Carley and Cox (2003);

1. identify independent wave storms using the offshore measurements where the significant wave height (H_s) exceeded 3 m (Kulmar et al., 2005; Lord and Kulmar, 2000);
2. estimate the wave height exceedance curves (see Fig. 1) using;
   a. for each storm, determine the wave height that was exceeded for 1 h, 6 h, 12 h, 24 h, 48 h and 72 h;
   b. sort the wave heights into ascending order for each duration and assign empirical return periods (the largest wave height for each duration is assigned the empirical return period of N where N is the record length in years, with the second and subsequent events assigned $N/2$, $N/3$ and so on);
   c. use exponential functions (straight lines on a log-linear plot) to extrapolate storm information to extreme event level;
3. establish the synthetic design storm wave height time series at particular return periods by;
   a. use the extrapolated wave height-frequency-duration curves to estimate the wave height-duration estimates at 10-year, 20-year, 50-year, 100-year and 1000-year return periods (Fig. 2);
   b. use exponential functions (straight lines on a linear-log plot) to extrapolate storm information to longer exceedance durations; and
   c. for each return period, estimate the time series of the synthetic design storm using the fitted functions and assuming that the wave storm events are temporally symmetrical (Fig. 3).

For brevity, the corresponding figures (Figs. 1–3) for the combined wave measurements from Botany Bay and Long Reef are not shown. Fig. 4 compares the peak significant wave height for each synthetic design storm shown in Fig. 3 (using only the directional Long Reef data) with those obtained by using the combined Botany Bay and Long Reef wave measurements via the JPM. The longer Botany Bay wave measurements captured several large storms that occurred before the Long Reef measurements commenced, and thus the higher JPM simulated nearshore wave height extreme values are not surprising.

Kriebel and Dean's (1993) beach erosion model, which was also used by Callaghan et al. (2008), is used here to calculate erosion volumes resulting from the storm conditions determined above. The Kriebel and Dean (1993) model used parameter values from the literature and when simulating the 1974 historical storm (Hoffman and Hibbert, 1987), the predicted peak erosion compared well with

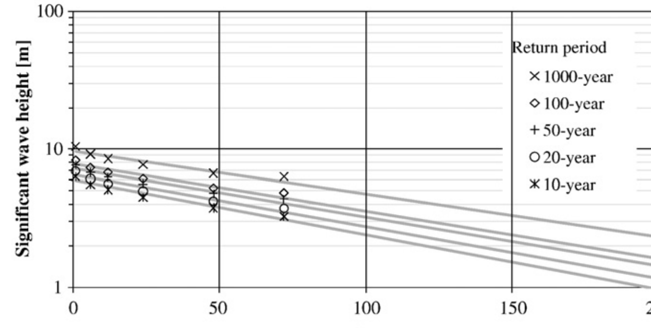

Fig. 2. Empirical estimates of the significant wave height exceeded for various storm durations. The grey lines ($\ln H_s = aD + c$) have been fitting using least squares. The empirical estimates were obtained from Fig. 1.

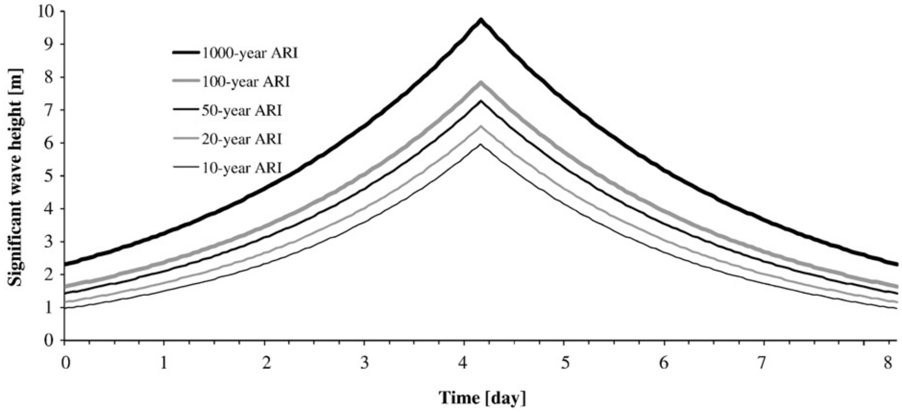

Fig. 3. Storm temporal shape suggested by Carley and Cox (2003) and using the duration curves shown in Fig. 2.

that observed. The tidal anomaly and wave height is modelled within the JPM using a logistics joint probability model. In contrast, the SDS method applies the relevant return period tidal anomaly for the erosion volume being estimated which tends to overestimate beach erosion (Carley and Cox (2003) do point out a more rigorous approach is possible). Fig. 5 compares the beach erosion volumes predicted by the SDS and JPM approaches with measured beach erosion volumes. Statistics of measured beach volumes are presented in Fig. 5 using both the block averaging and consecutive volumes methods as the estimates obtained from these two methods encompass all beach erosion volumes computed using a variety of methods in Callaghan et al. (2008).

Fig. 5 indicates that both the SDS and JPM approaches provide similar estimates for erosion volume return periods up to about 3 years, while they both underestimate the measured erosion volumes. For return periods between 3 and 20 years, the JPM compares well with the measured volumes. The SDS method, on the other hand tends to underpredict the measured volumes for return periods up to 10 years, and appears to compare reasonably well with measured erosion volumes of return periods between 20 and 30 years. However, it should be noted that due to the ~30-year length of the record, it is likely that errors in the empirical beach erosion estimates are considerable due to sampling error for return periods greater than 10 years. Thus, little confidence can be placed on measured erosion volumes with return periods greater than 10 years and consequently not much significance can be attributed to the better comparisons between the SDS predictions and measurements or discrepancies between the JPM predictions and measurements for return periods greater than 10 years.

The clear result is that the JPM provides better predictions than the SDS approach for return periods less than 10 years at this location (the upper limit of 10 years may increase if data were available for a longer period). One main reason for the better performance of the JPM is its allowance of the occurrence of several closely spaced storm events. The JPM includes an exponential beach recovery mechanism using a fixed time scale estimated from the time it takes Narrabeen Beach to transform from longshore bar-trough to transverse bar and rip morphological states (Wright and Short, 1984). This phenomenon is not taken into account in the current SDS approach. Interestingly there have been at least two known instances that severe beach erosion occurred at the study location due this phenomenon of storm sequencing (1974 – worst ever storm erosion, 2007 – 1 in 10 years erosion event and 1978 – 1 in 10 years erosion event). The SDS approach could be modified to incorporate storm sequencing effects, by including different temporal shapes with increasing return period that include multiple and independent wave storm peaks. Alternatively, the SDS could be adjusted to allow for the missing beach erosion due to storm sequencing. The ad hoc approach of augmentation of the design storm intensity is the simplest, albeit most physically unrealistic, option. For the case investigated here, the storm wave heights need to be increased by 15% to "calibrate" the SDS erosions to the measurements (not shown). Such an increase in wave height is analogous to halving the return period originally estimated by the SDS method (e.g., the 20-year ARI erosion becomes the 10-year ARI erosion). Another option is superimposing the estimated erosion from the SDS method on antecedent beach conditions which are specified *a-priori* for different return periods. This approach is fairly

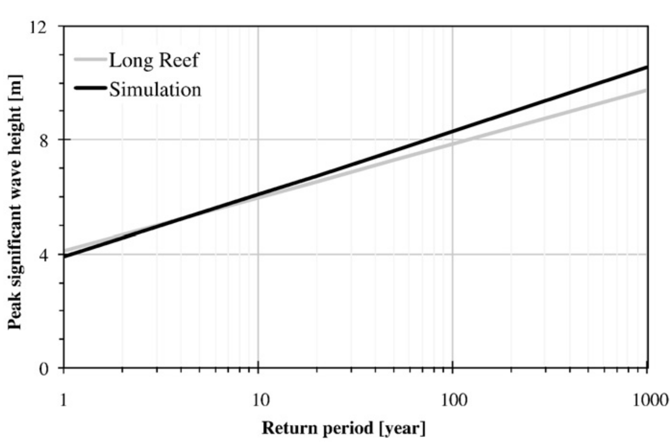

Fig. 4. Peak storm significant wave height from Long Reef (▬, peak from Fig. 3) and using the JPM simulation approach that combines the longer wave height measurements from Botany Bay with the directional wave measurements at Long Reef (▬).

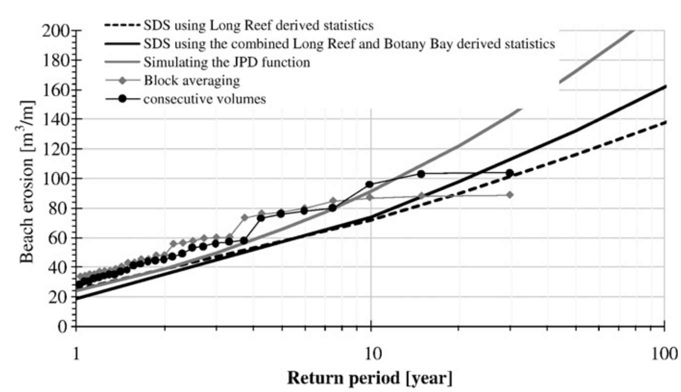

Fig. 5. Comparison of storm erosion volumes predicted by the synthetic design storm approach, the joint probability distribution approach and measured erosion volumes at Narrabeen beach, Sydney, Australia. The empirical (—◆— and —●—, see Fig. 16 of Callaghan et al. 2008) and joint probability distribution function (▬) derived beach erosion statistics are from Callaghan et al. (2008).

subjective as it would require a great deal of engineering judgment and detailed knowledge of the beach system being considered.

4. Conclusion

Coastline management practices are shifting towards using a risk based approach for managing coastal inundation and beach erosion hazards. In this short communication, we focused on short-term beach erosion due to storms which is one of the most important phenomena that needs to be accurately quantified to facilitate effective coastal management strategies. The storm erosion volume predictions given for the data rich Narrabeen Beach, Sydney, Australia (over 30 years of continuous monthly beach surveys) by the commonly used synthetic design storm (SDS) method were compared with those given by the more recently proposed joint probability method (JPM) (Callaghan et al., 2008). The results indicate that the JPM provides better predictions than the SDS approach for return periods less than 10 years at this location. The SDS method generally tends to underestimate beach erosion compared to the JPM, particularly for return periods greater than 3 years. The main reason for this underestimation by the SDS approach is likely to be the non-consideration of antecedent beach conditions, particularly when closely spaced storms occur (storm sequencing). The accuracy of either method cannot be fully evaluated for return periods greater than 10 years due to the ~30-year length of the beach survey data set that was available for this study. At higher return periods where wave parameters are being significantly extrapolated, the SDS predictions maybe as feasible as JPM predictions given the uncertainty of such extrapolations.

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