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ORIGINAL RESEARCH ARTICLE

Some characteristic wave energy dissipation patterns along the Polish coast

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Summary The paper analyses cross-shore bathymetric profiles between Władysławowo (km 125 of the national coastal chainage) and Lake Sarbsko (km 174) commissioned in 2005 and 2011 by coastal authorities for monitoring purposes. The profiles, spaced every 500 m, cover beach topography from dune/cliff tops through the emerged beach to a seabed depth of about 15 m. They were decomposed by signal processing techniques to extract their monotonic components containing all major modes of the variability of beach topography. They are termed empirical equilibrium profiles and can be used for straightforward assessment of wave energy dissipation rates. Three characteristic patterns of wave energy dissipation were thus identified: one associated with large nearshore bars and several zones of wave breaking; a second, to which the equilibrium beach profile concept can be applied; and a third, characterized by mixed behaviour. Interestingly, most profiles showed significant seabed variations beyond the nearshore depth of closure — this phenomenon requires comprehensive studies in future.

1. Introduction

The first concepts of beach equilibrium profiles were developed empirically by Bruun (1954), who assumed that cross-shore beach topography is basically a function of wave energy E supplied to the shore at a shallow-water group wave velocity c_g. Bruun then concluded that nearshore seabed configurations are best described by monotonic power functions:

$$h(x) = Ax^n. \tag{1}$$

In Eq. (1) h is the seabed depth at the offshore distance x from the shoreline, and the parameters A and n are empirical quantities.

The theoretical background of the equilibrium beach configuration in constant hydrodynamic regimes was developed by Dean (1976), who assumed a constant wave energy dissipation rate E_r across the entire surf zone. Other assumptions included sediment homogeneity along the profile (D_{50} = const), monochromatic waves, linear wave theory

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and a constant wave breaking index $\gamma = H\,h^{-1} = const$. As a result, the wave energy dissipation rate could be calculated by:

$$E_r = \frac{5}{16}\rho g^{3/2}\gamma^2 h^{1/2}\frac{dh}{dx}. \tag{2}$$

Wave energy dissipation disappears at the shoreline for h $(x = 0) = 0$, and the well-known Dean monotonic beach equilibrium power function emerges for E_r = const:

$$h(x) = Ax^{2/3}. \tag{3}$$

The coefficient A has a dimension of $[m^{1/3}]$ and is directly related to E_r:

$$A = \left(\frac{24E_r}{5\rho g^{3/2}\gamma^2}\right)^{2/3}. \tag{4}$$

In Eq. (4), $g = 9.81$ m s^{-2} is the acceleration of gravity, and $\rho = 1000$ kg m^{-3} is the specific gravity of water. The situation of constant wave energy dissipation is known as the saturated wave breaking regime. It reflects the situation in which constant hydrodynamic forcing produces an equilibrium seabed configuration.

The relationships between the coefficient A and physical parameters of beach sediment were first investigated by Moore (1982). Next, Dean (1987) related this coefficient to the sediment fall velocity w_s with the formula $A = 0.067$ $(w_s)^{0.44}$. A similar contribution by Kriebel et al. (1991) produced another fairly straightforward relationship:

$$A \approx 2.25\left(\frac{w_s^2}{g}\right)^{1/3}. \tag{5}$$

A temporal dependence of beach equilibrium profiles was proposed by Pruszak (1993), who introduced a time-varying A in the form of a sum of components oscillating over time:

$$A(t) = \mathring{A} + A_1 + A_2 + A'. \tag{6}$$

In this expression, $\mathring{A}$ is the time-invariant component expressed through e.g. Eq. (5), A_1 represents long-term variations due to the migration of large bed forms or changes in sediment supply driven by long-term variations in the hydrodynamic background, A_2 accounts for seasonal variability, and A' corresponds to short individual events, such as storms. Periodic changes in the parameter describing the equilibrium profile can be presented as:

$$A(t) = \sum_{k=1}^{2} a_k \cos\left(2\pi\frac{t}{T_k} + \theta_k\right) + A'. \tag{7}$$

The periods T_k correspond to long ($k = 1$) and medium (seasonal) time scales ($k = 2$); the period T_1 was found to be approximately 27 years for the Polish coast.

A different refinement of the beach equilibrium theory was proposed by Inman et al. (1993), who assumed a model in which the offshore portion of the profile was treated independently of the inner bar-berm portion, and both portions were matched at the breakpoint bar. Such partitioning was justified by different forcing modes on either side of the breakpoint. Both portions were fitted well by Eq. (1), with $n \approx 0.4$ being nearly the same for the bar-berm portion and the outer portion, irrespectively of seasonal changes. In this way, changes in seasonal equilibriums could be manifested by self-similar displacements of the bar-berm and outer curves, driven by seasonal surf zone variations.

Bodge (1992) addressed two major shortcomings of previous formulations, namely the physically unrealistic offshore-infinite range of beach equilibrium profiles and the infinite slope at the shoreline. He proposed an exponential curve, asymptotically converging to the closure depth to describe the beach equilibrium profiles. This effort was further improved by Komar and McDougal (1994), who replaced the closure depth with a ratio of the shoreline beach slope S_0 to the empirical parameter k [m^{-1}] accounting for profile concavity:

$$h(x) = \frac{S_0}{k}(1 - e^{-kx}). \tag{8}$$

This model predicts asymptotic convergence to a depth of S_0/k metres for the shoreline beach slope of S_0, which can be established as a function of sediment grain size and wave parameters, or evaluated directly from profile measurements, so only the concavity parameter k should be least-square fitted to profile measurements.

Several alternative approaches have been proposed to tackle shoreline singularity. Larson and Kraus (1989) suggested a form that superimposed a planar shallow water component with an offshore Dean form. Özkan-Haller and Brundidge (2007) introduced a further modification to limit the influence of the planar component to shallow water. Perhaps the most advanced model was presented by Holman et al. (2014), who developed an equilibrium beach profile concept capable of accounting for (a) a finite shoreline slope, (b) a concave-up form in wave-dominated shallow waters and (c) an asymptotic planar slope in the far field:

$$h(x) = \alpha(1 - e^{-kx}) + \beta x. \tag{9}$$

This model requires three parameters: (a) the far-field slope β can be obtained directly from available bathymetric charts, (b) the shoreline slope can also be easily established using the expression $d(h = 0)/d(x = 0) = S_o + \alpha k + \beta$, and (c) the depth h should be known at some location x', which can be anywhere in the profile, but should be representative of the background, average profile depth, so it should best be a point seaward of the active bar zone. This last parameter is therefore subjective to some extent, but is necessary to establish the second equation relating α and k: $h(x') = \alpha(1 - e^{-kx'}) + \beta x'$.

The conceptual simplicity and modelling robustness of monotonic beach equilibrium profiles resulted in their wide acceptance. In particular, the equilibrium profiles are used extensively in beach fill design studies and projects, see e.g. CEM (2008) Part III-3, or CEM (2008) Part V-4. The major underlying reason is that the complicated and nonlinear phenomena of wave energy dissipation are often intractable by most physical models, particularly in systems with multiple bars. It can be briefly explained as follows:

1) When waves are mild, the surf zone is narrow, and they break only over the innermost bar.
2) Higher waves begin to break over the 2nd bar; the surf zone now includes two bars, and the breakers can include a spilling or a plunging mode or both.
3) During heavy storms, the outer bars contribute to wave energy dissipation as well — the surf zone now includes