Notes on shoreline erosion due to boat wakes and wind waves

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Abstract
These notes concern the effect of boat wakes and wind waves on shoreline erosion, and are a review of the relevant literature on the topic. The relevance of wave height, period, energy density and transmitted energy, as measures of erosion likelihood, are discussed. Examples are given from measurements made on the Swan River.

1. Introduction

In many coastal, estuarine and river environments, boat-generated waves are seen as a major contributing factor to shoreline erosion. The increasing number of ferries and large recreational vessels in the last couple of decades has brought the issue into sharper focus, as their effects are weighed up against other man-made and natural effects on shoreline stability. In coastal areas subject to significant wave action, or river systems prone to frequent flooding, boat wakes may have a negligible effect on shoreline stability. However in tranquil coastal, estuarine and river environments, boat wakes may be the leading cause of shoreline erosion.

Methods to predict boat wake profiles have been in existence since the slender-ship theory of Michell (1898). However, the application of such theories to typical boat wake cases is complicated by the following factors:

1. Waterways subject to shoreline erosion from boat wash typically have complex bathymetry, making constant-depth analytical methods difficult to apply.
2. Most modern recreational vessels, with a length-beam ratio of only 3 or 4, fall outside the limits of slender-ship theory. Computationally-intensive CFD methods, or dedicated experimental testing, are required to determine the wake pattern of such vessels.
3. Bathymetry, wind waves, currents and shoreline type are site-specific, making it difficult to develop general guidelines for the relative importance of boat wake on shoreline erosion.

Boat wake management principles for high-speed vessels are discussed extensively in PIANC (2003). Desktop methods for assessing boat wake erosion likelihood have been put forward by Glamore (2008) and Stumbo et al. (1999). However, the highly site-specific nature of shoreline erosion means that the most common method of assessment is by dedicated full-scale measurements at each location. Full-scale trials to measure boat-generated wave height as a function of time have been reported by many authors, including Osborne (2007), Velegrakis (2007) and Macfarlane (2009b). Trials measuring sediment concentrations as well as wave profiles have been reported by Bauer (2002), McConchie (2003), Houser (2011) and Rapaglia (2011). In some trials (Nanson et al. 1994, Bauer 2002), erosion pins have been used to measure changes in bank profile over a large number of vessel passes.

The above-mentioned trials provide valuable information on the effects of vessel type, speed and transverse distance on boat-generated wave profiles and hence shoreline erosion. An additional useful quantity is a measure of baseline wave action or erosion rates under standard environmental conditions at a particular location. Soomere (2005) and Kurennoy et al. (2009) performed comparisons of heights and periods between waves produced by high-speed ferries and natural wind waves in Tallinn Bay, Estonia. It was found that ferry wave heights were close to the maximum wind wave height, but ferry wave periods were much longer than maximum wind wave periods. Pattiaratchi & Hegge (1990) compared the estimated annual transmitted energy of boat- and wind waves on the Swan River, Western Australia. It was found that annual transmitted boat wave energy was much smaller than annual transmitted wind wave energy, due to the short duration of boat wakes and limited number of passing boats. However more recent research at the same location (Macfarlane 2009a, Gourlay 2010) found that at this time cumulative boat wake energy was of similar order to cumulative wind wave energy.

2. Erosion due to wind waves

Sediment transport due to wind waves is a well-established field in coastal engineering. According to USACE (2002), sediment transport may be separated into onshore-offshore and longshore components.

2.1 Onshore-offshore transport

Seabed sediment movement has been observed to commence at a certain threshold value of the near-bottom water particle velocity. For constant-velocity flow, such as in a steady stream, the threshold velocity depends on the seabed grain diameter and density (Bagnold 1963). For oscillatory motion due to water waves, the flow acceleration also affects the shear stress, so that the wave period is also important. Komar & Miller (1973,1975) derived an empirical relation for water waves in the case of a laminar seabed boundary layer, corresponding to grain sizes less than 0.5mm (medium sands and finer). Seabed sediment movement was found to occur when the dimensionless relative stress satisfies

$$\frac{\rho u_m^2}{(\rho_s - \rho) g D} \geq 0.30 \sqrt{\frac{d_0}{D}} \qquad (1)$$

Here ρ_s and ρ are the density of the sediment and water respectively, D is the diameter of the sediment grains, and g is the acceleration due to gravity. u_m is the near-bottom maximum water particle velocity and d_0 is the corresponding orbital diameter. For linear waves, d_0 is related to the wave height H, wavelength λ and water depth h through

$$d_0 = \frac{H}{\sinh(2\pi h / \lambda)} \qquad (2)$$

Once water particle velocities are sufficient to produce sediment movement, the movement onshore or offshore is governed by the "dimensionless fall time"

$$F_0 = \frac{H_0}{V_f T} \qquad (3)$$

Here H_0 is the deep water wave height, T is the wave period and V_f is the sediment fall velocity. When the dimensionless fall time is above a threshold value, offshore movement will occur (USACE 2002).

Shoreline erosion during storms is also affected by the changing beach slope. Storm surges raise the mean water level and allow waves to attack the higher, steeper sections of the beach, which are prone to undercutting and collapse (USACE 2002).

2.2 Longshore transport

Longshore sediment transport is typically assessed (USACE 2002) based on wave power, or "energy flux" per metre of wave front

$$\overline{P} = \overline{E} c_g \tag{4}$$

Here $\overline{E}$ is the energy density per square metre of sea surface, while c_g is the wave group velocity. The component of wave power in the longshore direction is calculated from measured or modelled wave data, averaged over a long time period. The method is designed to assess long-term average sediment transport, since no threshold water particle velocity is applied for sediment movement, as is done in the onshore-offshore case.

3. Erosion due to boat waves

Boat waves differ from wind waves in that although they can be of large height and long period, they have short duration. An example wave profile measured on the Swan River for a small vessel is shown in Figure 1.

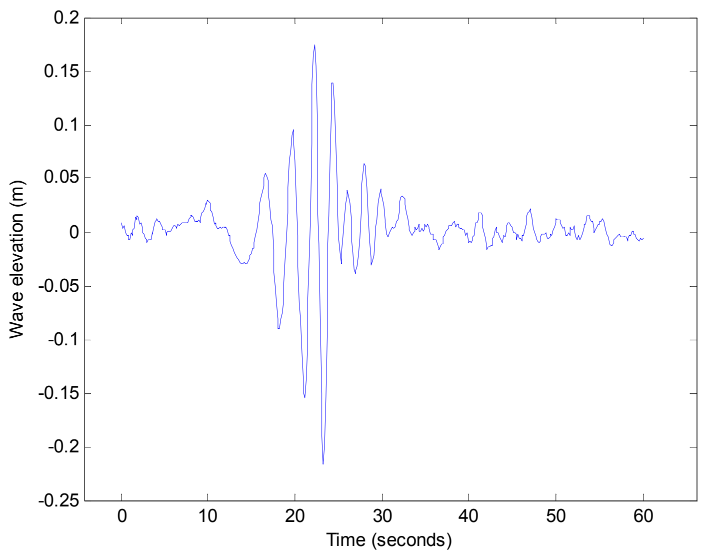

Figure 1: Exampled measured wave profile for a small vessel on the Swan River.

We see that the first few waves tend to be of small height and long period, followed by waves of large height and moderate period, and then a gradually decaying series of smaller waves. The spectrum of wave periods corresponds to a spectrum of wave directions, with each wave direction having a different speed, and hence period, so as to form a total wave field that remains steady relative to the boat (Newman 1977).

Trials to measure sediment concentrations caused by boat wakes have found that there are threshold values of wave height and period above which sediment concentrations are greatly increased (Nanson et al. 1994, Macfarlane et al. 2008, Rapaglia 2011). For example, measured sediment concentrations on the Gordon River (Nanson et al. 1994) were found to increase greatly at wave heights greater than 25cm and wave periods greater than 2.5s. The existence of such a threshold might be expected from the existence of a similar threshold for sediment movement due to wind waves (equation 1).

In river and estuarine environments, a primary difference between boat waves and wind waves is the wave period. For example, in the lower reaches of the Swan River, measured wind wave periods were up to 2 seconds, while measured boat wave periods were up to 8 seconds (Gourlay 2010).

Wave period has the following effects relevant to shoreline erosion:
1. For the same wave height, water particle movement due to long-period waves is felt deeper, and water particle velocities at the seabed are larger.
2. Increasing wave period shifts the type of breaking wave from spilling, to plunging, to surging (USACE 2002), with the transitions depending on wave height and seabed slope. Therefore for gentle seabed slopes, longer wave period may shift the breaker type from spilling to powerful plunging; however for steep slopes, longer period may shift the breaker type from plunging to surging, in which much of the wave energy is reflected.
3. River bank vegetation is naturally adapted to the short period of wind waves, but not to the long periods which may be present in boat wakes. The introduction of long-period waves brings a new erosion mechanism to which riverbank vegetation may be susceptible (Macfarlane & Cox 2004).

The effect of wave period on water particle velocities may be analyzed with reference to the threshold near-bottom water particle velocity for sediment movement (equation 1, Komar & Miller 1973). This threshold also depends on the acceleration (through the particle orbital diameter) and so the effect of wave period is not obvious. We can plot the dimensionless relative stress (left-hand side of equation 1) against the threshold value (right-hand side of equation 1), in order to assess the effect of wave period on sediment movement. We use linear wave theory, and the following example values: wave height $H = 0.3$m, water depth $h = 2.0$m, sand grain diameter $D = 0.5$mm, sand grain to water density ratio $\rho_s / \rho = 2.5$. Results are shown in Figure 2.

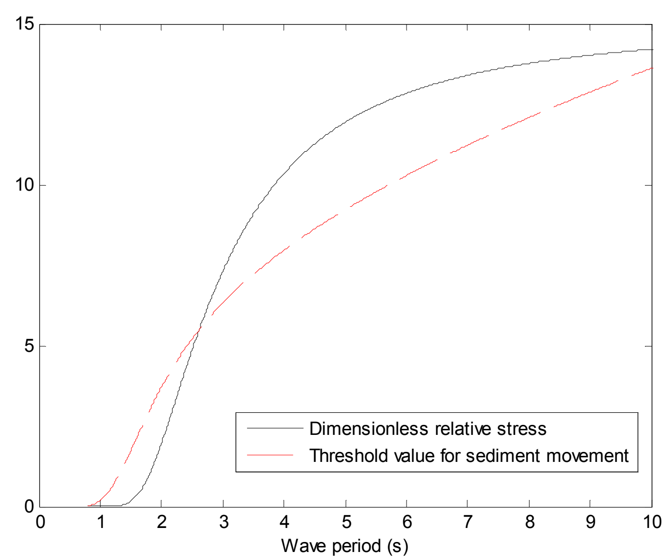

Figure 2: Dimensionless relative stress plotted against threshold value for sediment movement, showing effect of wave period at constant wave height

A large 0.3m wind wave in sheltered waters will typically have a period of around 2 seconds. At this wave period, the dimensionless relative stress at 2.0m depth is very small, and no sediment movement would be expected to occur for this example situation. However, a similar size boat wave with period 3-6 seconds is seen to produce a much higher seabed stress, which exceeds the erosion threshold. Sediment concentration boat wave trials described in Macfarlane et al. (2008) showed a correlation with wave period squared, which agrees with the equation of Komar & Miller (1973) at small wave periods. At very long wave periods, as shown in Figure 2, the shear stress starts to fall back towards the erosion threshold. Therefore it might be expected that the correlation between shoreline erosion and wave period squared may lose applicability at very long wave periods (e.g. greater than 6 seconds).

The effect of wave height on threshold sediment movement is more direct: the dimensionless relative stress is proportional to wave height squared, while the threshold is proportional to wave height. Therefore increasing the wave height monotonically increases the ability of surface waves to exceed the erosion threshold.

4. Comparing boat waves and wind waves

Due to the vastly different nature of boat waves and wind waves, there is at present no widely-accepted method for making fair comparisons between boat- and wind waves with regard to shoreline erosion potential. Typical methods that may be used for comparing boat waves and wind waves are described below.

4.1 Maximum wave height and corresponding wave period

From the preceding discussions, the one conclusive statement regarding wave-induced shoreline erosion is that increases monotonically with both wave height and wave period (except possibly at very long wave periods).

A way of characterizing the "maximum wave" within a measured boat wave profile is to find the largest height between an adjacent crest and trough (Macfarlane 2009b). The corresponding period of this "maximum wave" is found by doubling the time interval between the chosen peak and trough. This is generally not the longest period in the wave profile, and is subject to scatter when there are multiple waves with similar height but different periods. However it does serve to give the appropriate corresponding period (T_{m}) for the maximum wave height (H_{m}), which can be used as a comparison between boat waves and wind waves.

4.2 Transmitted wave energy

The total energy transmitted by a boat wave profile may be compared between different boat wakes, and also serves to determine the annual energy transmission if boat frequency data are available. This annual energy transmission can be compared against corresponding wind wave transmitted energy (Pattiaratchi & Hegge 1990, Glamore 2008, Kurennoy et al. 2009). Such a comparison is similar to the energy flux method described above for longshore sediment transport due to wind waves. Transmitted wave energy is a particularly useful quantity in shoaling water, as it remains approximately constant as waves travel into shallower water, barring friction and reflection (Dean & Dalrymple 1991).

Transmitted wave energy is calculated from the wave power, or energy flux, given in equation (4). The wave energy density $\overline{E}$ per square metre of water surface (USACE 2002) is found from

$$\overline{E} = \frac{\rho g H^2}{8} \qquad (5)$$

The group velocity c_g is given according to finite-depth linear theory by

$$c_g = \frac{\lambda}{2T}\left(1 + \frac{4\pi h/\lambda}{\sinh(4\pi h/\lambda)}\right) \quad (6)$$

Transmitted wave energy E_t is found by integrating the wave power with time t, i.e.

$$E_t = \int \overline{P}\, dt \quad (7)$$

This gives the transmitted energy per metre of *wave front*. If the waves are unidirectional and this direction known, such as in the case of wind waves, the transmitted wave energy per metre of *shoreline* may be calculated based on the angle between the wind and the shore. However, such a quantity cannot be calculated for multi-directional boat waves based on wave measurements at a single location, so the transmitted energy per metre of wave front serves as a better comparison between wind- and boat waves.

The integral in (7) can be calculated over the entire boat wave profile, to determine the total energy transmitted by the boat wake. Because the boat wave profile consists of changing wave height and period, the integral (7) is best evaluated by breaking the wave elevation time trace up into individual half-wavelengths between each neighbouring peak and trough. This process is illustrated in Figure 3.

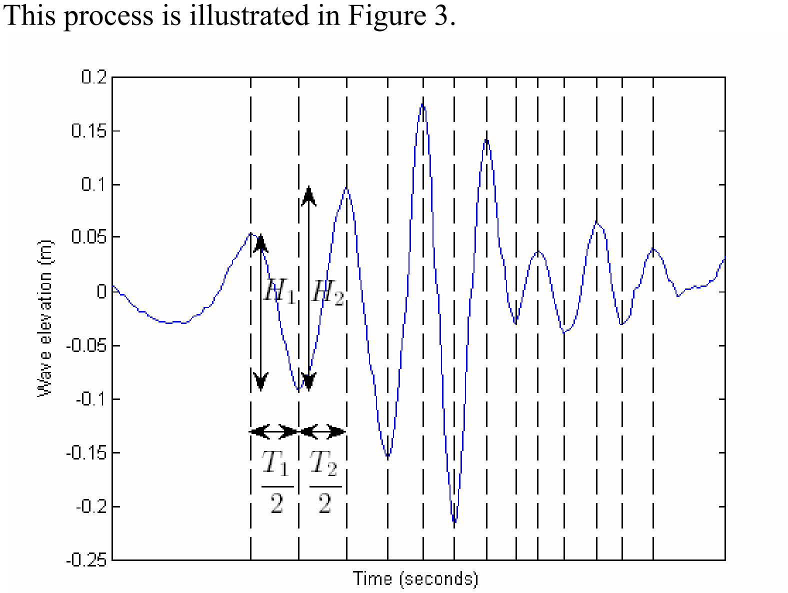

Figure 3: Method for breaking wave elevation time trace into individual half-wave-periods

The total transmitted wave energy is found by summing the contributions due to each half-wave-period, i.e.

$$E_t = \sum_n \overline{P}_n \frac{T_n}{2} \quad (8)$$

Here $\overline{P}_n$ is calculated from H_n, T_n using the standard relations (4,5,6). For example, in deep water the transmitted wave energy becomes

$$E_t = \sum_n \frac{\rho g^2 H_n^2 T_n^2}{64\pi} \quad (9)$$

If wind waves are present at the time of the boat wake measurements, these can be filtered out under certain conditions. Kurennoy et al. (2009) undertook measurements of high-speed vessel wake near the port of Tallinn, Estonia. They found that for small-to-medium wind waves, the wind wave spectrum occupied a higher frequency band than the wake of high-speed vessels, so could be removed by a low-pass filter with cutoff 2.5 seconds.

A problem with the transmitted wave energy calculation is the amount of energy contained in the decaying wave train, which is extremely variable. In some cases, a significant proportion of the transmitted wave energy is contained in the small transverse waves at the end of the measured wave elevation time trace. An example is shown in Figure 4 and Figure 5, which were measured at very similar speed, but travelling in different directions, and with different time available for the wave pattern to develop.

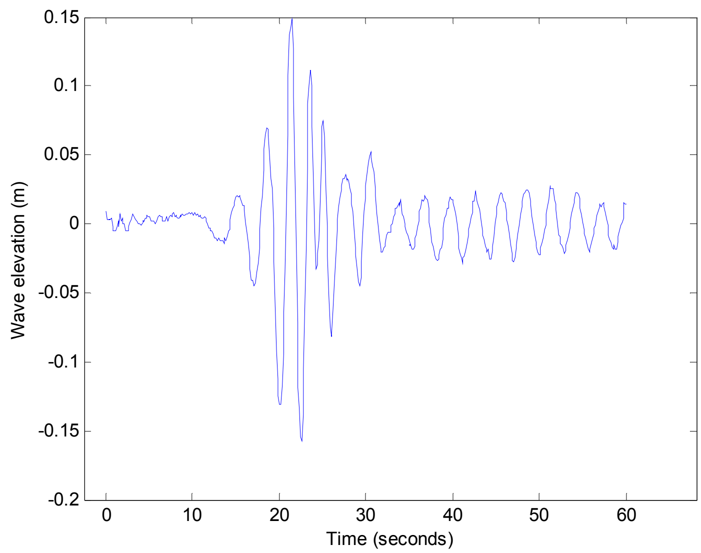

Figure 4: Measured wave profile for Haines Hunter 680 at Ashfield Parade, Swan River. Speed 8.4 knots, transverse distance 23m, travelling upriver. Total transmitted energy 1420 Joules per metre of wave front, over 60 second timeframe shown.

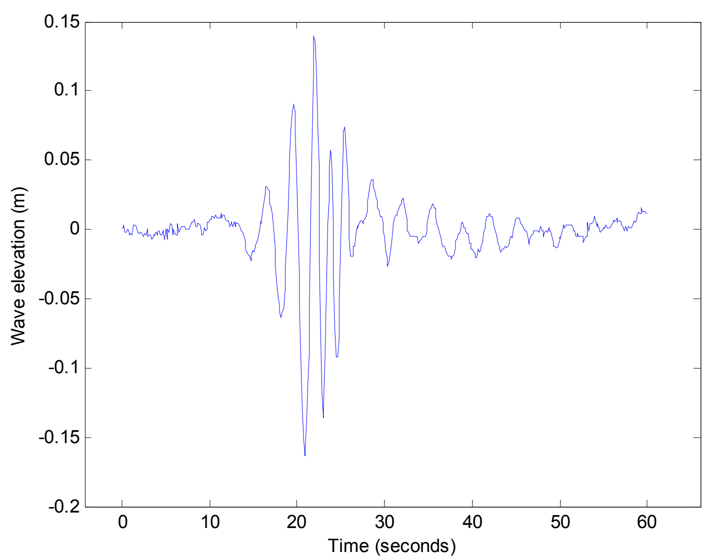

Figure 5: Measured wave profile for Haines Hunter 680 at Ashfield Parade, Swan River. Speed 8.7 knots, transverse distance 20m, travelling downriver. Total transmitted energy 990 Joules per metre of wave front, over 60 second timeframe shown.

We see that although the dominant waves in the wake are very similar between the two cases, the later transverse waves are much smaller in the second case. This may be a consequence of the difference between travelling upriver and downriver (although no current was present), and the corresponding slightly different amount of time for the wave system to develop. In any case, this example serves as a caution on the sensitivity of the transmitted energy to the decaying wave profile. This topic is discussed in Kurennoy et al. (2009), including the extra difficulty in treating the decaying wave train when wind waves are present.

4.3 Spectral energy

The average wave energy, per square metre of sea surface, over a given time interval T_H is proportional to the variance m_0. The variance is calculated (Lloyd 1989) from the wave elevation $\eta(t)$ through

$$m_0 = \frac{1}{T_H}\int_0^{T_H} \eta^2 dt \qquad (10)$$

This method gives a direct energy measure based on the integrated wave elevation time trace, and a similar method can also be employed to determine an energy density spectrum as a function of wave frequency, as done by Velegrakis et al. (2007). The drawbacks to this method are that the energy calculated is per square metre of water surface, rather than transmitted energy; also the solution is sensitive to the time interval T_H chosen.

4.4 Energy per wavelength

The energy per wavelength, per metre of wave front (Dean and Dalrymple 1991) has also been used as a measure of the erosion potential of boat waves (Macfarlane & Cox 2004). Care should be taken when applying this method in shoaling water, as the wavelength of a given wave frequency, and the energy per wavelength, are sensitive to water depth (Dean and Dalrymple 1991).

5. Conclusions

Due to the site-specific nature of boat waves and associated erosion, full-scale measurements remain the method of choice for assessing the erosion potential of boat waves as compared to natural processes. The basic properties of boat wakes and wind waves have been reviewed in terms of erosion potential. It appears that wave period is at least as important as wave height, due to the increased seabed particle velocities and often plunging breakers associated with long wave periods, as well as the fact that riverbanks are not naturally adapted to long wave periods.

Various methods have been reviewed for comparing boat- and wind-waves, including maximum wave height and corresponding wave period, transmitted wave energy, spectral energy density, and energy per wavelength. None of the methods are entirely satisfactory. Maximum wave height and period comparisons do not take into account the difference in duration between boat- and wind-wave events. Transmitted energy comparisons do not take into account the threshold seabed shear stress for sediment movement. Spectral energy density does not reflect the physics of energy transfer to the shore, and is sensitive to wake duration. Energy per wavelength is difficult to apply in shoaling water.

Ideally, cumulative transmitted wave energy above the site-specific erosion threshold would be used to compare boat- and wind-waves, however this is difficult to calculate in practice. Otherwise, maximum wave height and corresponding wave period, and transmitted wave energy, probably form the most useful practical quantities for comparison between boat- and wind-waves in terms of shoreline erosion potential.

6. Acknowledgement

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