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Field observations of waves generated by passing ships: A note

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Abstract

This short contribution reports the results of a field study on the nearshore characteristics of waves generated by both conventional and high speed passenger ferries. The field observations took place in the late summer of 2005, at a beach close to the port of Mytilene (Island of Lesbos, Greece), and involved the visual observation of ship waves, using digital video recordings and image processing techniques. The results showed that passage of the fast ferry was associated with a longer, more complex and energetic nearshore event; this event not only did include higher nearshore waves (up to 0.74 m) and was organised in different wave packets, but it was also an order of magnitude longer (~680 s) than the conventional ferry event. Regarding the effects on beach sediment dynamics, the fast ferry waves were estimated to be very efficient in mobilising the nearshore sediments in contrast to those of the conventional ferry. The fast ferry service appears to generate daily prolonged nearshore events, which contain waves with higher energy than those expected from the normal summer wind wave regime of the area; these events also include some high and very steep waves, which can be particularly erosive. Therefore, fast ferry wakes may have considerable impacts on the seasonal beach sediment dynamics/morphodynamics and the nearshore benthic ecology, as well as they may pose significant risks to bathers, affecting the recreational use of the beaches exposed to fast ferry traffic. Finally, the study has shown that satisfactory field observations of the nearshore characteristics of ship-generated (and wind) waves can be obtained using inshore deployments of calibrated poles, digital video cameras and appropriate image processing algorithms.

Keywords: Ship waves; Nearshore waves; Image processing of waves; Beach sediment mobility

1. Introduction

A fundamental concept of coastal morphodynamics is that cross-shore beach morphological changes follow seasonal cycles: beaches tend to erode under the harsh winter wave regime and accrete under the mild summer wind waves (e.g. Aubrey and Ross, 1985; Komar, 1998). These cycles, however, could be influenced by waves generated by the nearshore traffic of modern, high speed ferry boats: not only ship-generated waves have different characteristics than those of normal wind waves (e.g. Wood, 2000; Gourlay, 2001; Chen and Huang, 2004; Soomere, 2005), but also their occurrence does not follow cycles similar to those of wind waves. In addition to their possible effects on coastal sediment dynamics and morphodynamics (e.g. Schoellhamer, 1996), ship waves may also disturb benthic ecosystems (e.g. *Posidonia* meadows), affect recreational activities and pose risks to bathers and property (SNAME, 2000; Soomere, 2006). On the other hand, speed regulation imposed on ships sailing in coastal waters (e.g. Parnell and Kofoed-Hansen, 2001; PIANC, 2003) can hamper maritime transport operations, create logistical problems and affect economic development. Thus, a considerable amount of research has been carried out in recent years in order to understand ship wave generation and improve vessel designs (e.g. Kirkegaard et al., 1998; Leer-Anderson et al., 2000; Wyatt, 2000; Chen and Huang, 2002).

In recent years, ship wave research has been focused on two broad fields: (a) the design of vessel hulls which can minimise the generation/amplitude of ship waves (e.g. Yang et al., 2002); and (b) the diagnosis/prediction of the characteristics of ship waves propagating/shoaling in coastal waters (e.g. Belibassakis, 2003). Such studies have been largely based on simulations using ship computational fluid dynamics (CFD) codes (e.g. Chen and Huang, 2004) and/or relevant experimental measurements (e.g. Gourlay, 2001), and improved algorithms of wave

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propagation/transformation over shoaling seabeds (e.g. Athanassoulis and Belibassakis, 1999). However, there are only limited field observations of ship waves in shallow waters (e.g. Croad and Parnell, 2002) to validate such models; most of our experience is based on experiments in controlled (lab) conditions (Erikson et al., 2005). Thus, there is an urgent need for suitable field observations in order to validate numerical simulations and complement the physical modelling results.

The present short contribution reports the results of a field experiment regarding the nearshore characteristics of ship-generated waves. The experiment took place at a micro-tidal beach close to the port of Mytilene (Lesbos Island, NE Mediterranean) and concerned visual observations of shoaling waves generated by (a) a conventional passenger ferry sailing with a moderate speed and (b) a modern, fast passenger ferry of the type that recently has become increasingly common in the Greek Archipelago.

2. The study area

The observations took place at a narrow beach (Cape Lena), approx. 10 km to the south of the port of Mytilene, the principal town of the Greek island of Lesbos (Fig. 1). The Cape Lena beach is located at the western coast of Lesbos Strait, the relatively shallow channel (water depths less than 70 m) separating Lesbos from the Asia Minor (Turkish) coastline. The beach forms part of a coastal strip that was reclaimed 20 years ago, using aggregates from the ground levelling works of the airstrip expansion of the nearby Mytilene airport.

The port of Mytilene is busy, as it is the hub of all maritime operations between Lesbos (with a population of ~90,000) and the other Aegean islands and mainland Greece. Nearshore maritime traffic is heavier during the summer, since the island is a popular tourist destination and there are several (3–5) passenger ferry services per day. In recent years, these services are provided by both conventional medium speed (2–3 services per day) and high speed ferries (1–2 services per day), with the trend being the complete replacement of the former by the latter.

The eastern coast of Lesbos is a micro-tidal environment (Tsimplis, 1994; Tsimplis et al., 1995). Its east facing beaches are subjected to wind waves of limited fetch, generated by winds from the northerly, easterly and southerly sectors. During the summer months, the wind regime is mild, with the dominant winds having directions mainly from the SE and NE and maximum speeds not exceeding 8 ms^{-1} (Fig. 1).

3. Data acquisition and analysis

The experiment took place in late September 2005 in calm wave conditions, in order to obtain 'uncontaminated' records of ship-generated waves. The beach was levelled using standard levelling techniques for its sub-aerial section and a diver equipped with a pressure sensor (accuracy ± 0.02 m) for its offshore sub-marine section.

The wave observations were carried out using a video technique. Three scaled poles on heavy concrete bases were placed and secured in position in the shallow nearshore waters, with a deployment pattern chosen to provide information on the direction of impinging waves (Fig. 2). The water depths at each of the poles were measured accurately before each set of observations (i.e. before each ship-generated event, see below):

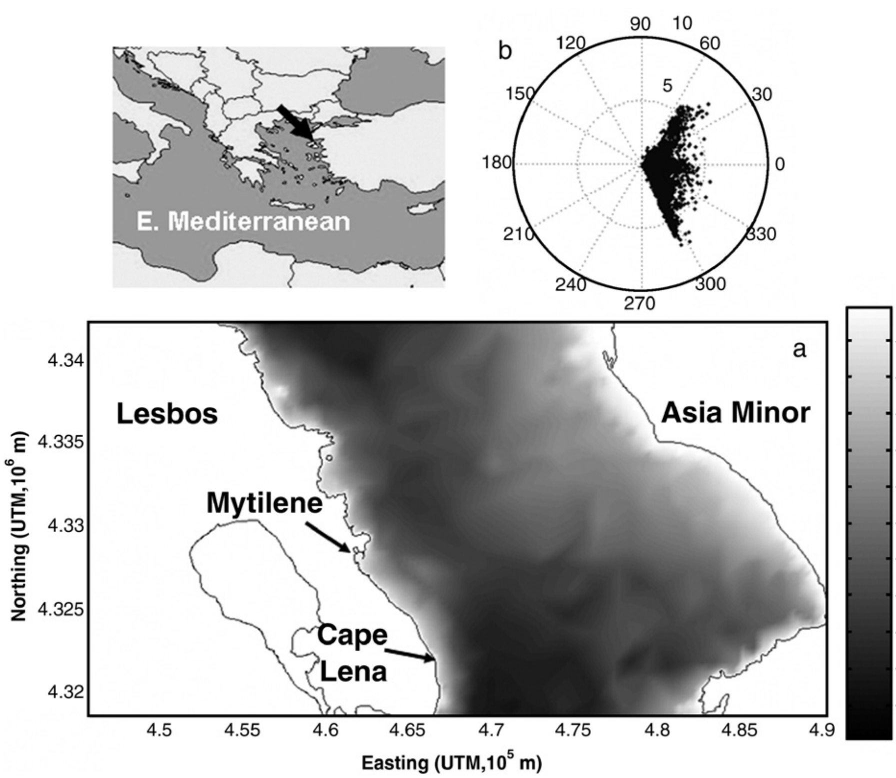

Fig. 1. (a) Location map and hourly summer winds of the study area, which affect the beach (wind data courtesy Dr Kalambokidis). Bathymetry in metres.

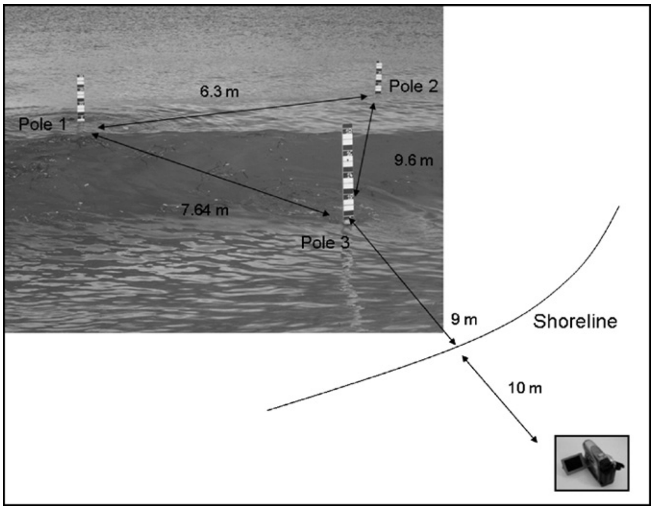

Fig. 2. Experimental layout at the beach of Cape Lena.

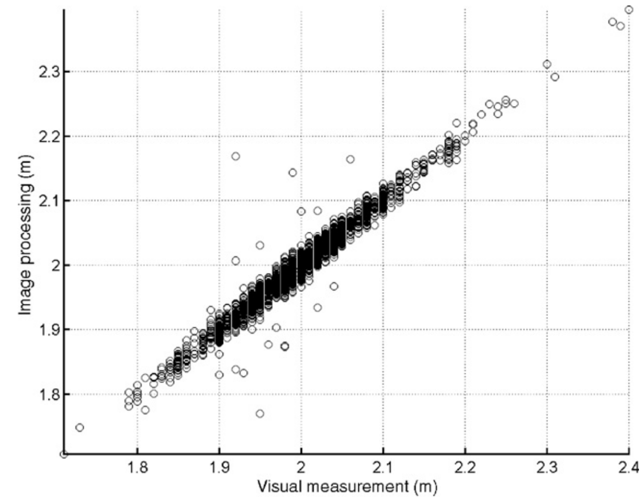

Fig. 3. Comparison between the sea level results (in m) from the image processing technique and those estimated visually (manually) for Pole 1 (water depth of 1.99 m). The results are very similar to those of Poles 2 and 3.

before the first event, the water depths were found to be 1.98 (Pole 1), 2.00 (Pole 2) and 1.18 m (Pole 3), whereas before the second event the water depths were found to be 1.99 m (at Pole 1), 2.00 m (at Pole 2) and 1.20 m (at Pole 3). Ship wave heights at each of the poles were recorded using a commercially-available colour digital video camera with a × 25 zoom lens. The ship waves were generated by the passage of two large passenger ferry boats: *M/V Mytilene* and *M/V Nissos Myconos*. The former is a conventional ferry boat with a length of 138 m, overall tonnage of 9120 tons and operational speed of 17 knots, whereas the latter is a fast ferry boat of the new generation, having a length of 141 m, overall tonnage of 8410 tons and operational speed of 26.5 knots. Offshore of the experimental site (~ 10 km from the port), both boats sail with speeds close to their operational speed.

The obtained videos were split into frames (25 frames for each second of recording), which were then sampled at 5 Hz using a MatLab function. The sea level (and, thus, the wave height) at each of the poles was then estimated at each of the frames, through both a specially developed automated image processing technique and visual (manual) observation. The image processing technique was based upon: (a) the 'calibration' of the frame of the secured in position camera, with the objective to correlate each pixel of the exposed poles to a particular water level; (b) the input of each frame as a matrix of the 3 basic colours (blue (B), green (G) and red (R)) into a specially designed software that identifies the exposed part of the poles and thus the water level (according to the three colour components pixel values); and (c) the establishment, after a series of tests, of criteria and thresholds to control the acceptance of a pixel as the water level pixel (e.g. to take account of uncertainties associated with changes in the natural light and the presence of foam). After a final data control (designed to filter out isolated 'rogue' values), the time series of water level changes along the frame sequence (i.e. every 1/5 of the second) is established for each of the poles.

In addition to the image processing technique, sea levels (at each pole and each frame) were estimated visually (manually), in order to qualify the image processing technique (for the present and future use). Comparison between the image processing and visual (manual) techniques (the latter having an accuracy of 0.01 m) (Fig. 3) showed good correlation, with only few 'suspect' measurements. These outliers were probably due to (a) the occasional presence of wave foam and (b) the pole scales (red and white), which sometimes created problems in the recognition of the water level pixel during the image processing technique. Subsequent experiments showed that the accuracy/resolution of the technique can be further improved, through the use of monochromatic (e.g. red) poles instead of the red–white poles used in the present work.

4. Results

The beach levelling showed the sub-aerial section of the beach to be less than 20 m wide; the water depth ~45 m from the coastline was found to exceed 4 m (Fig. 4). Coarse-grained, poorly sorted sediments formed the sub-aerial part of the beach, whereas the nearshore marine sediments were found to be mostly sand-sized (with a mean size of about 0.4 mm). Two bedrock bars (outcrops) were located close to the coastline (Fig. 4), being sparsely colonised by various types of fauna and flora. A *Posidonia oceanica* meadow was found in the

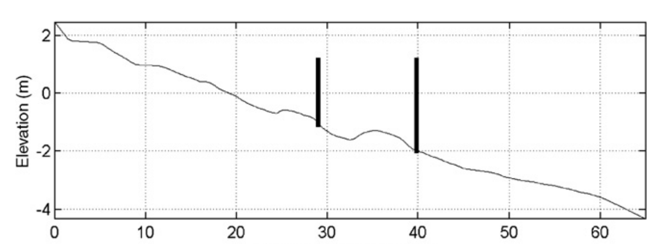

Fig. 4. Beach profile at the experimental site. The two seabed rises (located at water depths of about 0.7 and 1.3 m) are due to the presence of bedrock outcrops and are not sedimentary structures. The positions of the Poles 2 (offshore) and 3 (inshore Pole) are also shown.

nearshore waters, occurring on a 'matte' i.e. a terrace formed by *Posidonia* roots and rhizomes and entrapped sediment (see Buia and Mazzella, 1991), with its inshore margin at about 2.5–3 m water depth. The beach was littered with fragments of *Posidonia* leaves/flowers, which had presumably originated at the offshore meadow. During the experiment, the sea was very calm, particularly in the case of the *M/V Nissos Mykonos* experiment (Fig. 5).

In Figs. 6 and 7, the heights of waves generated by the passage of the passenger ferries *M/V Mytilene* and *M/V Nissos Myconos* are shown for two of the poles, the offshore Pole 2 and the inshore Pole 3 (Fig. 4); the other offshore pole (Pole 1) gave similar results to Pole 2. The geometry of the deployment and the small time lag (approx. 0.2 s) found in the cross correlation of the wave height time series of Poles 2 and 1 suggest that the shoaling wave crests were, in both cases, almost parallel to the coastline.

With regard to the passage of *M/V Mytilene*, the overall time of the nearshore wave event was approximately 65 s, with the waves constituting a single packet (Fig. 6). The wave heights increased to a maximum and then decreased, following a well known pattern of ship-generated waves (e.g. Erikson et al., 2005). Analysis of the records showed that the ship waves reached nearshore heights (Hrms) of 0.19 m at Poles 1 and 2 and 0.17 m at the most inshore Pole 3 (Table 1); the highest wave had a height of ~0.24 m (at Pole 2). Cross correlation between the time series of Poles 2 and 3 showed a time lag of ~2.5 s, suggesting a nearshore wave velocity of ~3.8 ms^{-1}. The wave spectra showed two peaks, centred at the frequencies of about 0.22 and 0.46 s^{-1} (corresponding to periods of 4.7 and 2.2 s, respectively) (Fig. 8b). The latter appeared to be the most dominant frequency, but its dominance was weakened at the inshore Pole 3, as there was greater energy dissipation during shoaling of the shorter waves compared to the longer waves.

The waves of *M/V Nissos Myconos* had very different characteristics than those of *M/V Mytilene*. Not only the nearshore wave event was an order of magnitude longer (about 680 s), but was also characterised by the presence of distinct wave packets (Fig. 7). Moreover, the waves were generally higher than those associated with the conventional vessel (Table 1) and included some waves with heights exceeding 0.7 m (Fig. 7); these 'freak' waves had a beach run-up length of ~3 m. The waves of *M/V Nissos Myconos* were also more energetic than those of the *M/V Mytilene* waves (Fig. 8). There were four significant spectral peaks, centred at the frequencies of 0.16, 0.25, 0.32 and 0.39 s^{-1} (corresponding to periods of approx. 6.3, 4, 3.1 and 2.6 s, respectively); the 0.25 s^{-1} frequency waves were the most energetic. Offshore, the low frequency waves appeared to be also quite energetic, but their energy decreased at the inshore

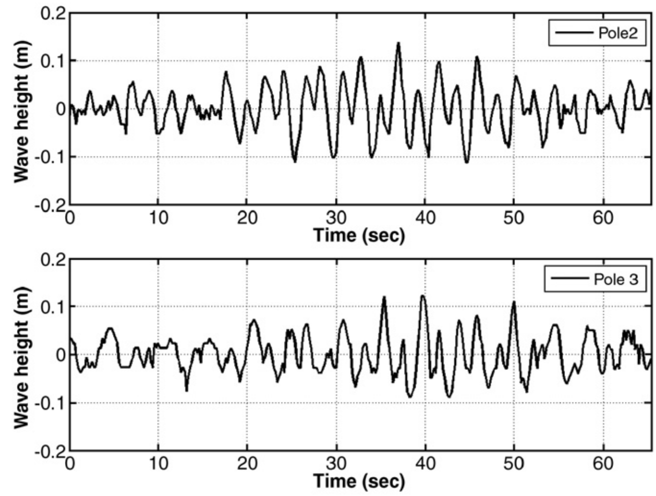

Fig. 6. Wave heights at Pole 2 (water depth of 1.98 m) and Pole 3 (water depth 1.18 m) of the waves generated by the conventional passenger ferry *M/V Mytilene*. The nearshore wave event had a duration of approx. 65 s and greatest wave height (at Pole 2) of ~ 0.24 m.

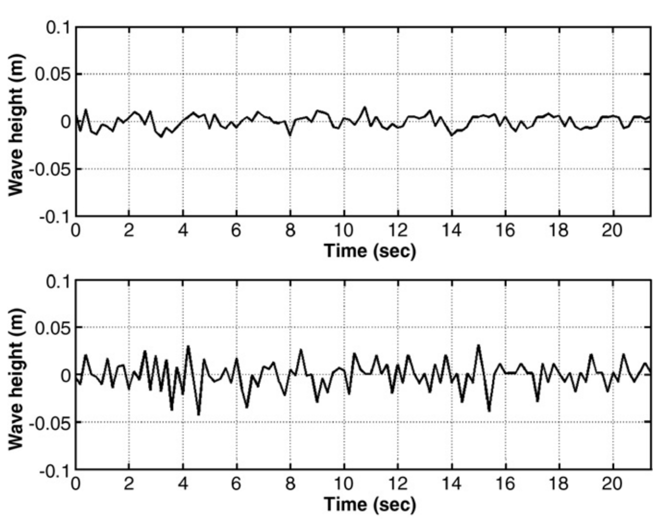

Fig. 5. Wind waves on the day of the experiment at Pole 3: (a) wind waves before the passage of *M/V Nissos Mykonos* and (b) wind waves before the passage of *M/V Mytilene*.

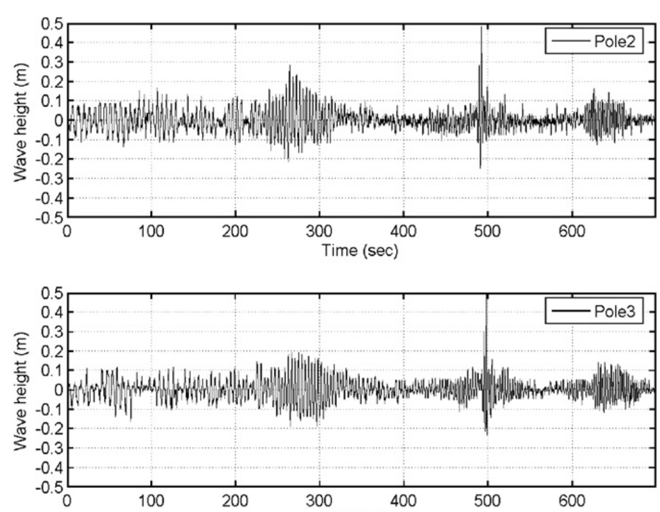

Fig. 7. Wave heights at Pole 2 (water depth of 2.00 m) and Pole 3 (water depth 1.20 m) of the waves generated by *M/V Nissos Mykonos*. There are 4 wave packets in the event: the first packet had a duration of ~185 s and its greatest wave height was 0.37 m (at Pole 2), the second had a duration of about 145 s and greatest wave height of 0.45 m, the third a duration of about130 s and greatest height of 0.74 m and the fourth a duration of about 75 s and greatest height of 0.27 m.

Table 1
Wave characteristics at the 3 poles

Pole boat experiment	Water depth (m)	Hmax (m)	Hs (m)	Hrms (m)	Uw_{rms} (m/s)	Uw_{peak} (m/s)	Uwcr (m/s)
Pole 1 *M/V Mytilene*	1.98	0.23	0.22	0.19	0.10	0.13	0.15
Pole 2 *M/V Mytilene*	2.00	0.24	0.23	0.19	0.10	0.13	0.15
Pole 3 *M/V Mytilene*	1.18	0.21	0.19	0.17	0.17	0.24	0.15
Pole 1 *M/V Nissos Mykonos*	1.99	0.73	0.38	0.27	0.25	0.35	0.18
Pole 2 *M/V Nissos Mykonos*	2.00	0.74	0.36	0.24	0.23	0.33	0.18
Pole 3 *M/V Nissos Mykonos*	1.20	0.69	0.31	0.22	0.29	0.40	0.18

Key: Hmax, maximum wave height; Hs, significant wave height; Hrms, wave height root mean square; Uwrms, bed wave orbital velocity amplitude root mean square; Uwpeak, peak bed wave orbital velocity amplitude; and Uwcr, critical bed orbital velocity for the initiation of bed sediment movement. Bed orbital velocities were estimated using linear wave theory. Sediment threshold velocities (Uwcr) were estimated for medium sand (grain diameter of 0.4 mm), using the Komar and Miller (1973, 1974, 1975) relationships.

pole (Fig. 8(a)). Cross correlations between the time series of the offshore and inshore poles (Poles 2 and 3, respectively), performed with regard to the individual wave packets, showed time lags varying from of 2.6 s to 7.6 s; thus, the speeds of the packets generated by *M/V Nissos Myconos* varied considerably. This variability, together with the distant passage of the ferry may explain the prolonged duration of the nearshore event.

In order to assess the effect of the ship-generated waves on the nearshore sediments, the wave height time series were used to estimate bed wave orbital velocities. In addition, the threshold of movement of the seabed sediments was estimated using the Komar and Miller (1973, 1974 and 1975) relationships (Table 1). The above estimations showed that the bed wave orbital velocities (Uwrms and Uwpeak) of the *M/V Mytilene* waves were lower at all poles than those of the *M/V Nissos Mykonos* (Table 1). Comparison of the Uwrms and Uwpeak bed orbital velocities of the waves generated by *M/V Mytilene* with the

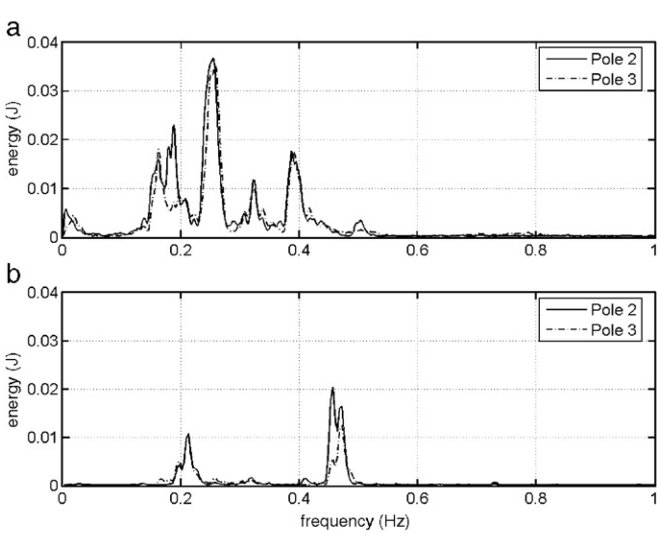

Fig. 8. (a) Spectra for the offshore Pole 2 and the inshore Pole 3 of the waves generated by the fast ferry *M/V Nissos Mykonos*; (b) Spectra for the offshore Pole 2 and inshore Pole of the waves generated by the conventional ferry *M/V Mytilene*.

Table 2
Maximum monthly summer 2005 winds, associated offshore wind waves (hindcasted through the use of the CEM (2002) algorithm) and inshore wave heights (at about 2 m water depth), estimated through the Ebersole et al. (1986) algorithm

Month	Wind direction (°N)	Wind speed (m/s)	Fetch (Km)	Offshore wave height (m)	Offshore wave period (s)	Inshore wave height (m)
June	155	6.5	50	0.55	3.0	0.46
July	120	7.2	55	0.60	3.1	0.46
August	140	6.3	50	0.53	3.0	0.49
September	50	7.1	23	0.41	2.4	0.36

Wind data, courtesy Dr K. Kalampokidis, University of the Aegean.

threshold velocity (Uwcr) of sediments with a grain size of 0.4 mm (a common grain size of the nearshore sediments at the experimental site) showed that bed sediments of such grain size could only be mobilised at the inshore Pole 3 (Table 1). In contrast, the *M/V Nissos Mykonos* waves were able to mobilise quite effectively the bed sediments at the experimental site; both the Uwpeak and the Uwrms were much higher than the threshold orbital velocity Uwcr at all poles (Table 1).

Wind wave hindcasting (CEM, 2002), based on maximum hourly wind speeds and directions for the summer period, showed that the highest summer wind waves come mainly from the SE and NE (depending on the month); the maximum wave heights and periods hindcasted were 0.6 m and 3.1 s, respectively (Table 2). Based on monthly values, maximum nearshore wave heights were estimated for the experimental site, using the regional bathymetry (Fig. 1) and a simple (linear) wave shoaling/refraction software (Ebersole et al., 1986). This exercise showed maximum heights of summer wind waves at water depths similar to those of the offshore poles of ~0.5 m (Table 2). Although such wave heights are higher than the maximum heights associated with *M/V Mytilene*, they are lower than those associated with *M/V Nissos Mykonos* (Table 1 and Fig. 7). It appears that ferry traffic introduces (daily) wave energy fluxes which, although in the case of *M/V Mytilene* are smaller, in the case of *M/V Nissos Mykonos* could be greater than those associated with the highest wind waves expected during the summer period.

5. Discussion

The experiment showed that both passenger ferries generated significant nearshore wave events. However, these events had completely different characteristics, with the fast ferry (*M/V Nissos Mykonos*) generating a much more energetic event, which not only did include much higher waves, but it was also an order of magnitude longer (~680 s) and contained energetic long period waves.

It has been suggested elsewhere (Wood, 2000) that high speed ferries can generate two main groups of wash waves: a group having periods of 3–5 s and a group with periods of 8–10 s. It has been also suggested that, although these long period waves are not always visible from the ship due to their low amplitude, they can be hazardous to other boats and damage benthic ecosystems and the coast. The present field experiment confirmed the presence of different wave packets (with diverse periods) within the event, as it contained an initial packet of relatively long period waves (with a period of 6.3 s), followed by subsequent packets of shorter period waves (Figs. 7 and 8a). It may be suggested that the initial packet is related to the divergent waves generated from the vessel's bow, whereas the subsequent packets are associated with waves generated by stern of the vessel and waves created by frequency dispersion and interactions between the bow and stern waves (see also Croad and Parnell, 2002).

Regarding the effects of ship waves on beach sediment dynamics, the *M/V Mytilene* waves were able to mobilise sediments only at the inshore pole (water depth of ~1.2 m). In contrast, the *M/V Nissos Mykonos* waves were found to be able to mobilise seabed sediments at all poles and for a significant part of the event (Table 1). Moreover, the *M/V Nissos Mykonos* event included some quite high and steep (soliton-like) waves (Fig. 7), which were accompanied with beach run-ups with lengths of about 3 m (see also Erikson et al., 2005); such waves can be quite erosive (Sleath, 1984). As the fast ferry event is long (~680 s) and fast ferries sail offshore of the experimental at least twice per day, it appears that the beach sediment dynamics (and, thus, its morphodynamics) may be significantly affected (Kirkegaard et al., 1998; Croad and Parnell, 2002; Soomere, 2006). This may be particularly true as there were waves within the event which had heights exceeding the maximum heights expected for the summer period.

In addition to their influence on beach sediment dynamics/ morphodynamics, high speed ferry waves may have undesirable effects on the *P. oceanica* meadows found offshore of the experimental site. Apart from the fact that such meadows are protected habitats according to the European *Habitats* Directive (Directive 92/43 EC) and, therefore, should be protected by anthropogenic stresses, they also form effective coastal defences against excessive wave energy fluxes (e.g. Van Keulen and Borowitzka, 2003). Thus, it is interesting to discuss possible effects of ship waves on the nearshore meadow.

Increased hydrodynamic forcing may lead to *Posidonia* leaf fragmentation, which combined with herbivore green/senescent leaf consumption may reduce leaf mechanical strength and increase leaf loss. The shed leaves may then be hydrodynamically exported off the meadow and its potential as a carbon sink, i.e. its potential to store stocks of detritus, may decrease (Cebrian and Duarte, 2001). In addition, ship wave-induced mobility/resuspension of seabed sediments may alter sediment distribution and porosity (e.g. Van Keulen and Borowitzka, 2003) and, thus, affect detritus burial and retention and, ultimately, nutrient resorption, which is an essential mechanism for the development/balance of the *P. oceanica* meadows in the oligotrophic Eastern Mediterranean (Hemminga et al., 1999). Moreover, *Posidonia* flowering in shallow meadows takes place mostly at the end of summer, about a month later than the hottest temperatures of the year (Buia and Mazzella, 1991). To what extent ship waves might affect *Posidonia* flowering cannot be concluded on the basis of the present information. Nevertheless, it may be suggested that increased wave energy/ turbidity during the flowering season does not, probably, contribute to the meadow welfare. It must be also noted that field observations along the Lesbos coastline have shown that the beaches exposed to the passage of fast ferries are characterised by much greater accumulations/ littering of dead *Posidonia* leaves and flowers than those which are not associated with nearshore maritime traffic.

It appears that the waves generated by high speed ferries may affect both beach sediment dynamics/morphodynamics and nearshore benthic ecosystems. This may have significant implications for beaches associated with high speed ferry traffic (Soomere, 2006). Regarding the Greek Archipelago, beach erosion is already severe as 25% of its 7000 km coastline and almost all of its beaches are currently under erosion (Eurosion, 2003; Velegrakis et al., 2005). As nearshore maritime traffic has substantially intensified in recent years, increasingly involving fast ferries of the new generation, further research is required in order to improve our understanding on the nearshore ship wave effects. Such research should focus on obtaining field observations of ship wave breakers and run-ups, the validation of the algorithms used to predict ship wave propagation/shoaling and the detailed monitoring of ship wave effects on beach sediment dynamics/morphodynamics and the nearshore ecosystems.

6. Conclusions

The study showed that nearshore ferry traffic can generate substantial nearshore wave events at the experimental site, the character, duration, energy, wave periods and heights of which appear to depend on the vessel's speed (and design). The longer and more energetic event has been associated with the fast ferry, the passage of which generated a nearshore event, which not only did include higher waves (organised in different wave packets), but it was also an order of magnitude longer (~680 s) than the conventional ferry event. Another difference between the two ship wave events was that the wave energy was concentrated at two frequencies (0.22 and 0.46 s^{-1}) in the case of the conventional ferry and in four (from 0.16 to 0.4 s^{-1}) in the case of the fast ferry.

Regarding the effects of ship waves on beach sediment dynamics, the conventional ferry waves were much less efficient in mobilising the nearshore sediments than those of the fast ferry; the latter were estimated to be able to mobilise the beach sediments down to (at least) 2 m water depth for a considerable period of the event and included some particularly erosive high and steep 'freak' waves. The fast ferry service appears to generate daily prolonged nearshore events, which contain waves with heights and energy greater than those expected from the summer wind wave regime of the study area. Therefore, they may have considerable impacts on the seasonal beach sediment dynamics/morphodynamics and the nearshore benthic ecology, as well as they may pose significant risks to bathers, affecting the recreational use of the beach.

Finally, the study has shown that satisfactory field observations of the nearshore characteristics of ship-generated waves (and wind waves) can be obtained using inshore deployments of calibrated poles, commercially-available digital video cameras and appropriate image processing algorithms.

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