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The shape of wake waves from high-speed ferries and their influence in the coastal area

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Introduction

Recent studies have demonstrated the importance of the contribution of waves from fast ferries to the local hydrodynamic activity in certain areas of semi-enclosed seas [1,2]. The central concern is the possible impact of direct mechanical disturbances of bottom sediments that may lead to a potential intensification of sediment transport and beach destruction processes [3] and to an overall decrease of water quality in areas affected by ship waves [4].

The excessive influence of wakes of high-speed ships occurs when wake waves are much longer than wind waves [1,2]. This happens frequently in some parts of semi-enclosed seas. For example, typical wave periods in Tallinn Bay are 2–4 s and rarely reach 6–7 s [5]. The leading wake waves frequently have a height of about 1 m and a period of 10–15 s [6]. Such waves extremely seldom occur in natural conditions in certain regions of semi-enclosed seas. They are qualitatively similar to long-period ocean swell. Together with wind waves, they may form bi-modal wave systems, impact of which on various coastal processes may be much higher compared with that of wave systems with a single spectral peak and a comparable total energy [7].

Long waves in shallow areas

The properties and influence of ship waves usually have been calculated with the use of the assumption that they can be described by the classical linear wave theory. The length of leading waves of wakes from high-speed ships exceeds 100 m in areas with a depth of $\leq$10 m [6]. At these depths, such waves with a height of about 1 m cannot be considered as linear ones and even higher-order classical theories, for instance the Stokes wave theory, are not always applicable. An appropriate model for long finite-amplitude surface waves in shallow water is the Korteweg-de Vries (KdV) equation. Its periodic solutions are called cnoidal waves. They have more narrow crests, and more broad troughs than sine waves.

The long-wave limit of a cnoidal wave is the KdV soliton. A moving disturbance in open sea areas seldom forms solitary waves of considerable height. Yet long ship waves that approach shallow regions may excite sequences of highly nonlinear or even soliton-like structures.

Long ship waves in coastal area of Tallinn Bay

The shape of long ship-generated waves approaching shallow coastal areas of Tallinn Bay is studied based on recordings of water surface time series [8]. The recorded shape of water surface in a large part of ship-generated waves reaching the coastal area of Tallinn Bay is well described by the cnoidal wave theory whereas the linear theory frequently fails to match the wave profile. For typical leading wake waves nonlinear effects become significant at depths of 10-15 m. A large part of ship waves of already relatively small height (about 0.4 m) considerably differ from sine waves and have the shape of cnoidal waves in shallow areas with depth of 4-5 m. For wind waves of comparable height the linear theory mostly is applicable at this depth, because they are much shorter than ship waves.

The shape of the largest wake waves is close to the solitary wave solutions of the KdV equation. Since cnoidal waves of relatively large amplitude preserve their identity and shape fairly well in time, and partially also during interactions, it is likely that dynamics of a certain part of ship wakes in the shallow areas is very close to that of ensembles of KdV solitons.

Excessive hydrodynamic loads in nonlinear waves

Water motion in long surface waves mainly follows their shape. Therefore, the classical wave theory frequently fails to correctly foretell the temporal behaviour and the maximum values of the wave-induced velocity field. Cnoidal waves excite considerably larger velocities of water particles than sinusoidal waves of the equal height and length. A large difference occur in areas where the cnoidal wave theory is preferable, i.e., for depths less than 10–15 m, depending on the wave period and height.

The influence of long ship waves on seabed, offshore structures, and local ecosystem in certain parts of the coastal slope apparently is much larger than expected from the linear wave theory. Since ship waves are a new component of the water dynamics in the area in question, an extensive reaction of the benthic layer and fine bottom sediments to their frequent occurrence is likely. Indeed, optical measurements combined with analysis of water samples show that wake waves from fast ferries create significant changes in the optical parameters of sea water in a near-bottom layer with a thickness of about 1 m in coastal areas of Tallinn Bay with the depths of about 2–5 m [4]. The suspended matter remains in the water column for about 5 min. Rough quantitative estimates, based on the wave-induced increase of the suspended matter in the water column (about 1 g/m^2) suggest that the bulk influence of fast ferry traffic in Tallinn Bay may result in an annual loss of the order of 100 litres of fine sediments from each meter of the coastal line.

Although species that prefer rocky or sandy bottom may benefit from the increased hydrodynamic activity, the concern is that abrupt changes in forcing conditions usually have an adverse effect on the local ecosystem.

The results of the study are applicable in all non-tidal and micro-tidal basins that are sheltered from long ocean swell and that have extensive shallow coastal areas, for instance, lakes hosting fast ferry traffic, the Azov Sea, the northwestern part of the Black Sea, and certain parts of the Mediterranean and the Baltic Sea.

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