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Ship-driven mini-tsunamis at a depth change: field measurements and theory compared

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Short summary. Wave radar measurements of mini-tsunami generated by large ships passing by great depth change in the 20-70 m deep Oslofjorden, Norway, are compared to model calculation. Wave period is 30 seconds. Wave height grows according to the ship speed to power $n \sim 6$ (small speed) and ~ 4 (great speed).

Background and motivation. A small tsunami may be generated by a ship running across a substantial, shallow depth change. The linear surface wave formulation applies (Grue, 2017, 2020). This kind of precursor waves due to high speed ferries have been measured in San Francisco Bay, suggesting that the small wave slopes of magnitude 0.0004 were nonlinear solitons generated at transcritical speed (Neumann et al., 2001). However, the mechanism discussed here fundamentally differs from and has no connection to nonlinear upstream solitary wave generation at a flat bottom (e.g., Wu, 1987). Neither are the upstream waves connected to effects associated with a steady depression (Bernoulli effect) attached to the driving disturbance (Parnell et al., 2015). The long waves pose a new erosion along the shore (Parnell et al., 2007).

Ship-driven small tsunamis occur at many places in Oslofjorden, Norway, at the depth changes along the northward and southward ship routes. Waves contribute to erosion, hazard to leisure activity, and maneuvering difficulties of commuter ferries. Reports by the Norwegian Broad Casting have raised public awareness of the phenomenon. Eventually, Miros Group (miros-group.com) has installed a wave radar on Søndre Flaskebekk Brygge (pier), where wave heights have been the greatest, for measurement of the waves and information to public. Measurements by this wave radar are discussed here. The wave response due to four different cruise ferries (all with a car deck) are investigated: Pearl Seaways and Crown Seaways of Det Forenede Dampskibs-Selskab (DFDS) and Fantasy and Magic of Color Line. The displacements of Fantasy and Magic are similar, of 36 000 m^3, and approximately twice those of Pearl and Crown, although the details of the ship vessels are not commonly known. Each morning DFDS is arriving from Denmark. Next Color Line is arriving from Germany. Pearl and Fantasy are passing by on one day. Crown and Magic the day after. Pearl, Crown and Fantasy are cruising along the same, old route past the generation site at Ildjernsflu. Since 2016, Magic has developed a new route that avoids the abrupt depth changes, strongly reducing the wave amplitude.

The wave generation mechanism has been described by Grue (2020). A ship moving at constant speed at constant depth induces a flow in steady balance. This is modified at a depth change. A reaction velocity (arrow 2 in figure 1c) of equal magnitude and opposite direction to the ship-induced fluid velocity (arrow 1), orthogonal to the bottom, is induced. The reaction velocity appears as a vertical velocity at the water surface (arrow 3). Generated waves propagate with the shallow water speed, upstream of the ship moving at subcritical speed. Model calculation in wave channel of vertical walls and width twice the distance of 1.2 km between the ship track and shoreline has water depth of 46 m (figure 2a). The model depth change extends from -0.7 km to 0 km in the along track direction (and is uniform laterally). The depth profile is indicated by the thin line in figure 1b.

Wave radar measurements. Position and speed of the ships have been obtained from marinetrafic.com. The ships of DFDS have speed of 13-18 knots (kn). Magic and Fantasy have been moving faster than 22 kn but have volunterly reduced the speed to below 19 kn during the passing of Ildjernsflu. Location of the wave radar and ship routes are indicated in figure 1a. The shallow region has a shallowest depth of approximately 14 m (and even shallower east of the ship route). The depth reduces from approximately 46 m before and after. The bathymetry is rather uneven and varies both along and across the ship route (figure 1b). A slight lateral variation of the track does not matter as regards the wave period but has implications to the wave height. The wave radar continuously records the elevation. The time resolution is twice per second. Elevation series from the wave radar have been collected during autumn 2019, from the end of September to the beginning of December, through a collaboration between Miros and the University of Oslo. The wave radar measurements show that the mini-tsunami appears approximately 6–8 minutes prior to the ship wave wake (figure 2b,c). Wave height (H) of the mini-tsunami of Fantasy is 0.4 m, and of Pearl, Crown and Magic of approximately 0.1 m. For Fantasy at speed $U = 18.8$ kn, wave height of the mini-tsunami compares to that of the wave wake. Note that $H = 0.9$ m (for speed 22 kn) has been documented by photos (figure 4). A record high $H = 1.4$ m has been measured at the shore of Flaskebekk (Grue, 2017, 2020).

Measured elevation and model computation for Pearl at speed 15.6 ± 0.2 kn (model at 15.5 kn) and Fantasy at 18.7 ± 0.9 kn (model at 19.6 kn) show period of the main wave of 30 seconds for both ships (figure 3). Measured, small oscillations of long period prior to the main wave are caused by unevenesses of the bathymetry, not accounted for by the model. A slight variation of the track modifies the measured wave response.

Measured H vs. U for Pearl presented in double logarithmic plot shows a linear fit corresponding to $H = 0.096$ m $\cdot (U/16$ kn$)^{5.3}$. Model calculations show a similar growth, fitting with the extremes of H (figure 4a). Results for Fantasy show an even greater growth with speed where model calculations fit well to extremes (figure 4b). Figure 4b includes previous measurements on the shore of 0.9 m for speed 22 kn and 0.36 m for speed 18.3 kn (Grue, 2020). Extremes of H grow with speed according to U^n with n close to 6 for small speed and n close to 4 for great speed. Wave height due to Magic cruising along a modified track is always smaller than 0.2 m. Wave heights due to Crown are similar to those of Pearl.

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References

Grue, J. (2017) Ship generated mini-tsunamis. J. Fluid Mech., 816, 141-166.

Grue, J. (2020) Mini-tsunami made by ship moving across a depth change. J. Waterway, Port, Coastal and Ocean Engng., 146(5).

Neuman, D.G., Tapio, E., Haggard, D., Laws, K.E., Bland, R.W. (2001) Observation of long waves generated by ferries. Canadian J. of Remote Sensing, 27:4, 361-370.

Parnell, K.E., McDonald, S.C., Burke, A.E. (2007) Shoreline effects of vessel wakes, Marlborough sounds, New Zealand. J. Coastal Res. 50, 502-506.

Parnell, K.E., Soomere, T., Zaggia, L., Rodin, Lorenzetti, G., Rapaglia, J., Scarpa, G.M. (2015) Ship-induced solitary Riemann waves of depression in the Venice Lagoon. Phys. Lett. A 379(6): 555-559.

Wu, T.Y. (1987) Generation of upstream advancing solitons by moving disturbances. J. Fluid Mech., 184, 75-99.

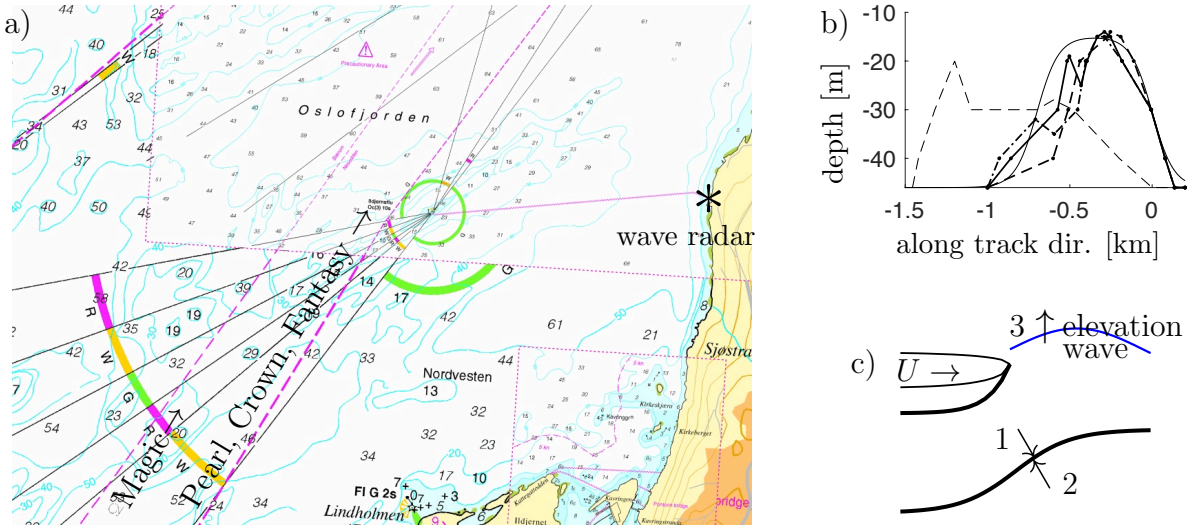

Figure 1: a) Sea chart (section) of Inner Oslofjord. Wave radar at Flaskebekk (∗). Distance (orthogonal) to ship route: 1.2 km. Lighthouse at Ildjernsflu indicated. Pearl, Crown and Fantasy follow old ship route. Magic has developed a new ship route a few hundred meters to the west of the old route. b) Depth profiles along track direction (model depth, thin solid line). c) Wave generation mechanism at depth change.

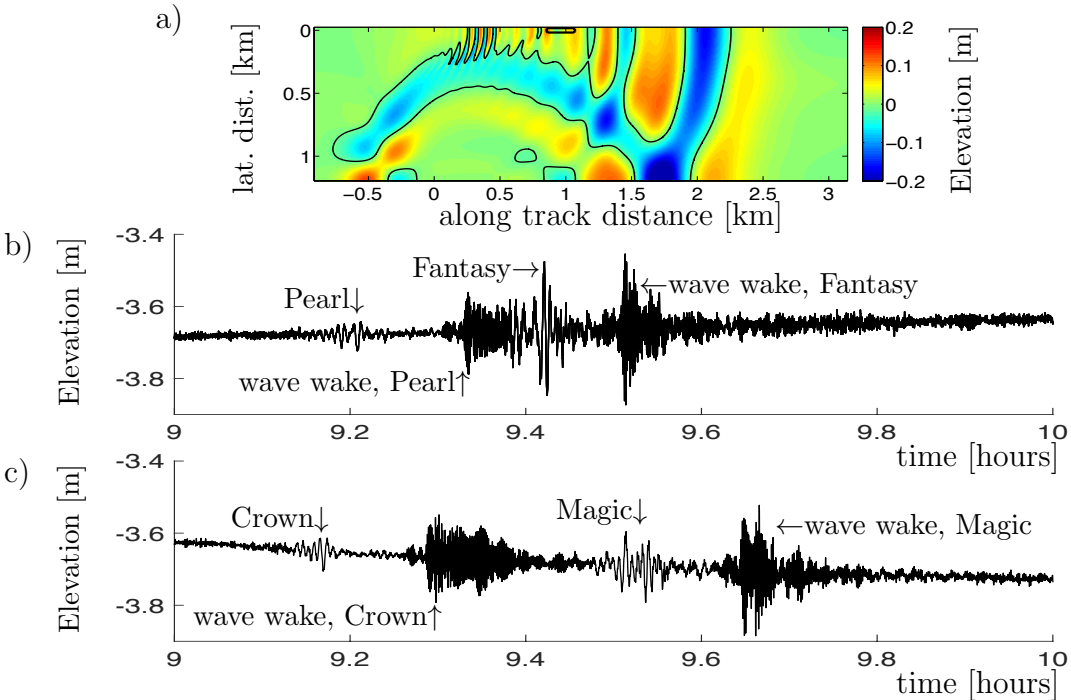

Figure 2: a) Model computation of wave field due to Fantasy/Magic at speed 19 knots. b) Elevation measurement by wave radar (meter) vs. time, from 09:00-10:00 hours on 6 November 2019. Mini-tsunami and wave wake due to Pearl (speed 16 kn) and Fantasy (18.8 kn) indicated. c) Same as b) but for 15 November 2019. Crown (16 kn) and Magic (19 kn).

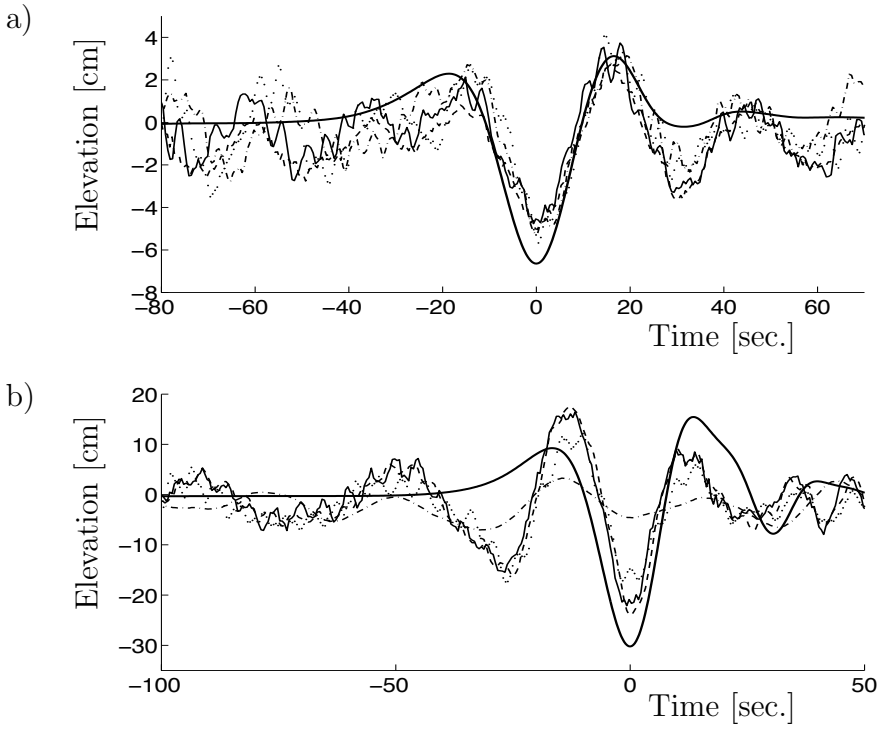

Figure 3: Measured and computed (thick solid line) elevation vs. time. a) Pearl. U=15.6±0.2 kn and 15.5 kn (computation). b) Fantasy. U=18.7± 0.9 kn and 19.6 kn (computation).

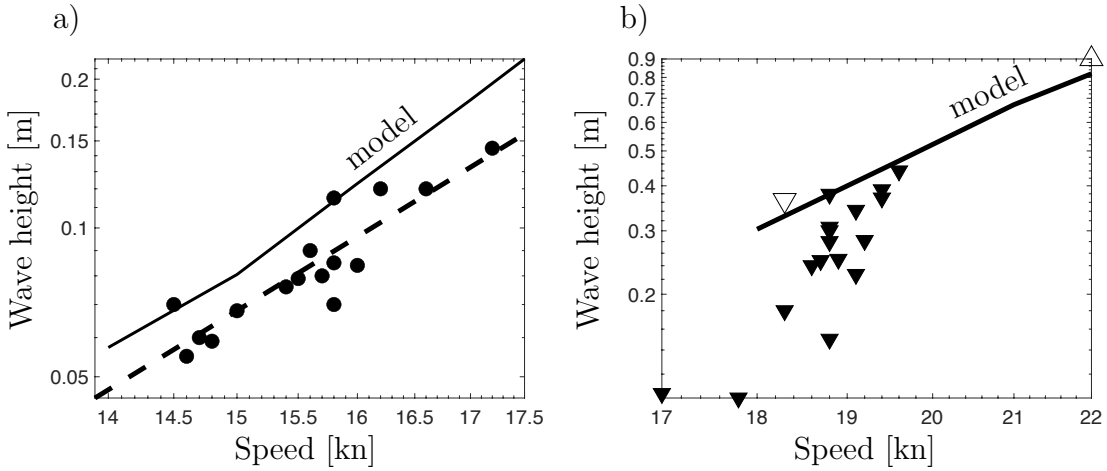

Figure 4: Wave height vs. ship speed. Double logarithmic plots. Measurements (symbols), fit to measurements (- -), model calculation (solid line). a) Pearl. b) Fantasy.