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Numerical Investigation on Ship Generated Mini-tsunamis

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1 Introduction

A new type of long upstream waves was recently observed in the Oslofjord in Norway (Grue, 2017). The waves will emerge when conventional ships, like cruise ferries, travel across certain depth changes at relatively fast, however, subcritical speed, where the depth change is comparable to the average water depth. The typical wave height is about 1 m at specific locations along the shore and a wave height up to 1.4 m has also been observed. Such kind of waves can lead to a new kind of erosion due to the wave induced fluid velocity being up to approximately 1 m/s.

The generation of upstream waves can be related with two mechanisms. One is nonlinear generation solitons at transcritical speed. Li & Sclavounos (2002) investigated the nonlinear solitary waves generated by a disturbance moving at subcritical, critical and supercritical speed in unbounded shallow water in the lengthwise direction. The other is correlated with depth changes. Although mini-tsunami was first observed and discussed recently, there are few studies about it. Following Grue (2017) this kind of waves were denoted as mini-tsunamis since they share strong similarities with tsunamis but appear on a lesser depth scale. He also provided mathematical and numerical analysis.

In the present study, we perform extensive numerical simulations using a CFD code, STAR-CCM+, to examine the effects of different parameters, such as draught, ship speed and ship width, on the generation of mini-tsunamis in different cases. Another motivation is to maximize the elevation of mini-tsunami for improving measurement accuracy for future experiments. Some new phenomena found in the simulations will also be discussed. It may be used as a reference for the future experimental investigation.

2 Numerical model and setup

The computational model is illustrated in Fig. 1. The horizontal dimension of the numerical wave tank is $L_1 \times L_2$. The generation of mini-tsunami requires that the depth change, namely $\Delta h = h_1 - h_2$, is comparable to the average water depth $h = (h_1 + h_2)/2$, where h_1 and h_2 are the depth of the deep and shallow regions, respectively. U is the ship speed, l is the ship length, w is the ship width and d is the draught.

The mini-tsunami in observation emerges when the depth change is comparable to the average water depth, i.e. $\Delta h/h \simeq 1$. Depth Froude number $Fr = U/\sqrt{gh}$ is in the range of $0.4 - 0.7$, while the Froude number based on the ship length $Fr_l = U/\sqrt{gl}$ is in the range of $0.17 - 0.24$.

The cross section of depth change is shown in Fig. 2. A smooth function is adopted as follows

$$z = (\tanh[2(x - x_0)] + 1) \times h/2$$

where x_0 is the position of the depth change and x_0/L_1 is in the range of $0.2 - 0.4$.

The time step Δt is determined by $\Delta t\sqrt{g/h} = 0.025$. To minimize the disturbance due to start-up, a slow variation in ship speed should be ensured. Here we choose the same type of ramp function as that in Grue (2017), with $U = U_0 \sin(t/T_0)$ when $t \leq T_0$ and $T_0\sqrt{g/h} = 150$. The initial position of the ship is $6h$ away from the backside as show in Fig. 1.

The boundary conditions for the computational are set as velocity inlet, pressure outlet, symmetry plane and wall, which are denoted in Fig. 1. Since the maximum elevation of mini-tsunami occurs at the middle section of the ship in longitudinal direction, all the results presented in the next section are collected on $y = L_2/2$. We choose the $k - \omega$ turbulence model and the free surfaces are resolved by the Volume-of-Fluid (VOF) technique.

3 Results and Discussion

We reproduced most of the conditions of Grue (2017) except lesser scale, due to the limitation of the CFD code. We first verified the relationship between depth Froude number $Fr = U/\sqrt{gh}$ and maximum upstream elevation η_{max} for a ship moving from deep to shallow waters. The average depth is $h = 2.5$ m, the background region 500 m×32.5 m and the depth change ratio $\Delta h/h = 0.909$. The scale of the ship is $l = 10.18$ m, $w = 1.59$ m,

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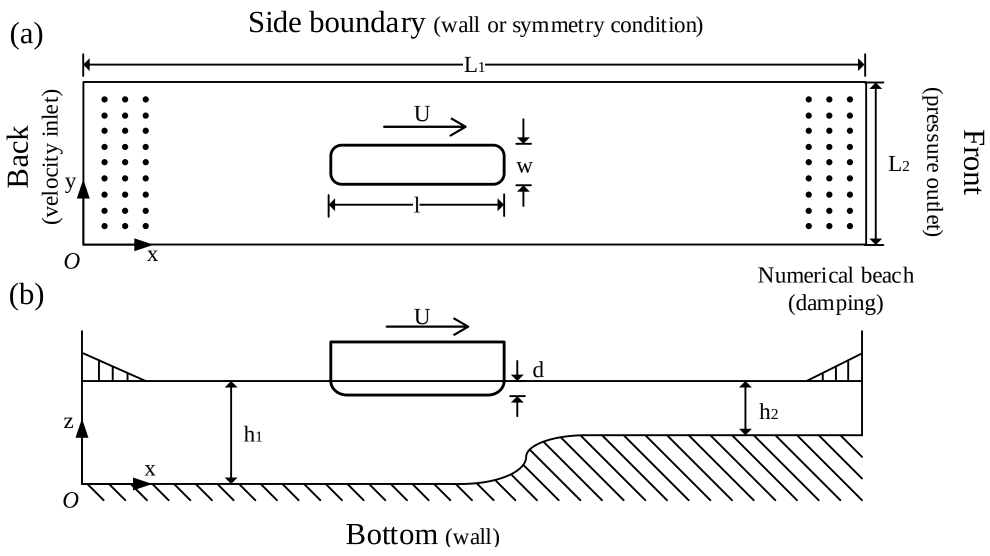

Figure 1: The sketch of the numerical model and coordinate system. (a) topview, Oxy plane; (b) sideview, Oxz plane

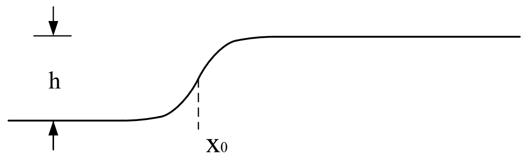

Figure 2: Bottom cross section (showing only the depth change area)

and $d = 1.31$ m. The blue curve $\eta_{max}/h = 2.0Fr^{3.2}$ is the fitted line in Grue (2017). The red circles represent the present results, corresponding to depth Froude number of 0.258, 0.345 and 0.431.

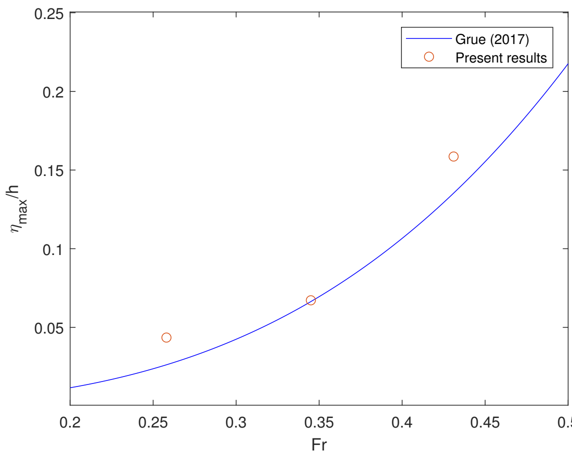

Figure 3: Maximum upstream elevation η_{max} versus Fr for a ship moving from deep to shallow waters

As can be observed, in general, the present results match quite well with the solutions in Grue (2017) generally, although there is a little bit difference for $Fr = 0.258$ and 0.431. This confirms that the present numerical model is able to simulate the generation of upstream long wave due to depth change.

Next, we tested a group of models with different parameters to examine how the elevation of mini-tsunamis varies with these parameters. The parameters of the base model are: $h_1 = 0.6$ m, $h_2 = 0.2$ m, $l = 1.5$ m, $w = 0.25$ m, $L_1 = 60$ m, $L_2 = 2.5$ m, $d = 0.05$ m and $U_0 = 0.8$ m/s. We choose to change different parameters and the results are shown in Fig. 4. Fig. 4(a) shows the result under base conditions; (b) the draught doubles $d = 0.10$ m; (c) the maximum ship speed increases by 0.2 m/s, $U_0 = 1.0$ m/s; (d) the width of the tank is narrowed to $L_2 = 1.25$ m.

As shown in Fig. 4(a), the upstream long wave (mini-tsunami) is rather obvious with several secondary waves being propagating behind the main peak. The main peak is about 0.002 m with mean water level being

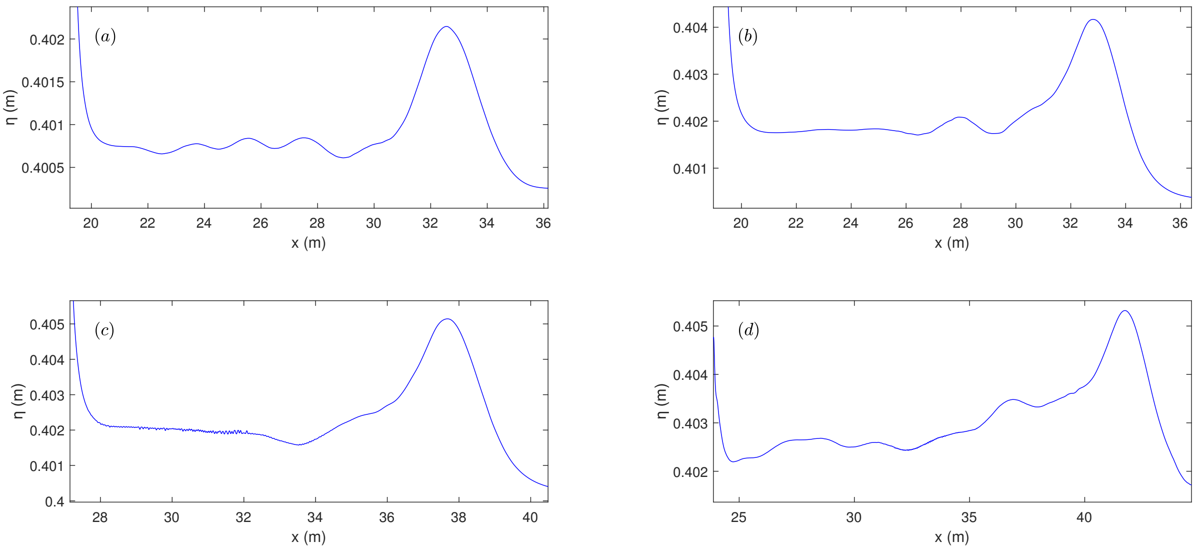

Figure 4: The sensitivity of the maximum upstream elevation η_{max} to draught, ship speed and ship width, ($t = 50$ s for all cases); (a) base case: $U_0 = 0.8$ m/s, $d = 0.05$ m, $L_2 = 2.5$ m; (b) the draught doubles $U_0 = 0.8$ m/s, $d = 0.10$ m, $L_2 = 2.5$ m; (c) the maximum ship speed increase by 0.2 m/s, $U_0 = 1.0$ m/s, $d = 0.05$ m, $L_2 = 2.5$ m; (d) the numerical tank is narrowed, $U_0 = 0.8$ m/s, $d = 0.05$ m, $L_2 = 1.25$ m.

0.4 m. As can been seen from Fig. 4(b), when we increase the draught, maximum evelation η_{max} almost doubles. But we also notice that the average elevation of the secondary wave area, where some small waves emerge after the main peak of mini-tsunami, also increases by nearly the same amplitude as η_{max}. With the elevation of the upstream region being about 0.402 m , a step-like structure with amplitude of 0.002 m is formed in addition to the mini-tsunami when a ship travels across a depth change to the shallow water. As shown in Fig. 4(c), the step exists but the secondary waves is not obvious any more. The maximum elevation of mini-tsunami η_{max} in Fig. 4(d) is the largest among the four test cases.

The generation of steps is probably due to the depth of the shallow water or deep draught. Therefore, we performed another group of simulations to understand the physics. A narrow tank is adopted to enhance the phenomenon of the step. Boundary conditions for the two sides are changed to symmetry condition in order to reduce the wave reflection. We select the following base model: $h_1 = 0.3$ m, $h_2 = 0.15$ m, $l = 1.5$ m, $w = 0.6$ m, $L_1 = 60$ m, $L_2 = 2$ m, $U_0 = 0.742$ m/s, the initial water level is on $z = 0.3$ m. Two damping zones with length of 5 m are placed at the back and front of the tank. The control parameter is the draught of the ship. We also discussed the cases without depth changes. The generation of mini-tsunami in the case of $d = 0.10$ m is visualized in Fig. 5. Since the depth change area is just ahead of the ship in Fig. 5(a), mini-tsunami has not been generated and cannot be observed yet. The little black arrows in Fig. 5(b) and (c) point out the position of mini-tsunami. The numerical results are presented in Fig. 6. Fig. 6(a) shows the result for $d = 0.10$ m; (b) the draught is varied to $d = 0.05$ m; (c) the depth change is removed with water level on $z = h_1$, $d = 0.05$ m; (d) the depth change is removed and water level is on $z = h_2$, $d = 0.05$ m.

As shown in Fig. 6(a), the elevation of secondary waves is higher than the initial water level on $z = 0.3$ m. This indicates that the upstream wave is a superposition of mini-tsunami and a rather small step. But when the draught is decreased, as shown in Fig. 6(b), the step reduces. It could be assumed that the bottom effects are from depth change region and two flat regions. Because mini-tsunami is mainly triggered by the depth change part, it is natural to believe that the flat region causes the step. In the following two cases without depth change but in different water depths, mini-tsunamis disappear. There is almost no waves or observable step-like structure in upstream region in Fig. 6(c). However, in Fig. 6(d), there is a step at $x = 32$ m, resembling the structure at the same position in (b). This indicates that the step may not be caused by depth changes and only appear in shallow water region.

4 Conclusion

The present results obtained from CFD simulations share a lot in common with Grue's results, which confirms that the present CFD model is valid and can serve as a reference for future experiments. Increasing draught or ship speed does enhance the elevation of mini-tsunami, but also results in a growth of a step-like structure whose size may be comparable to the mini-tsunamis. The upstream wave is dispersive. For ship generated solitons in a shallow water channel a higher, transcritical speed is required as discussed by Mei (1986). We observe in the numerical calculations that water is piling up in front of the ship. Further, the piling up becomes more substantial as ship width or draught increases. In forthcoming simulations we will detail the mini-tsunami

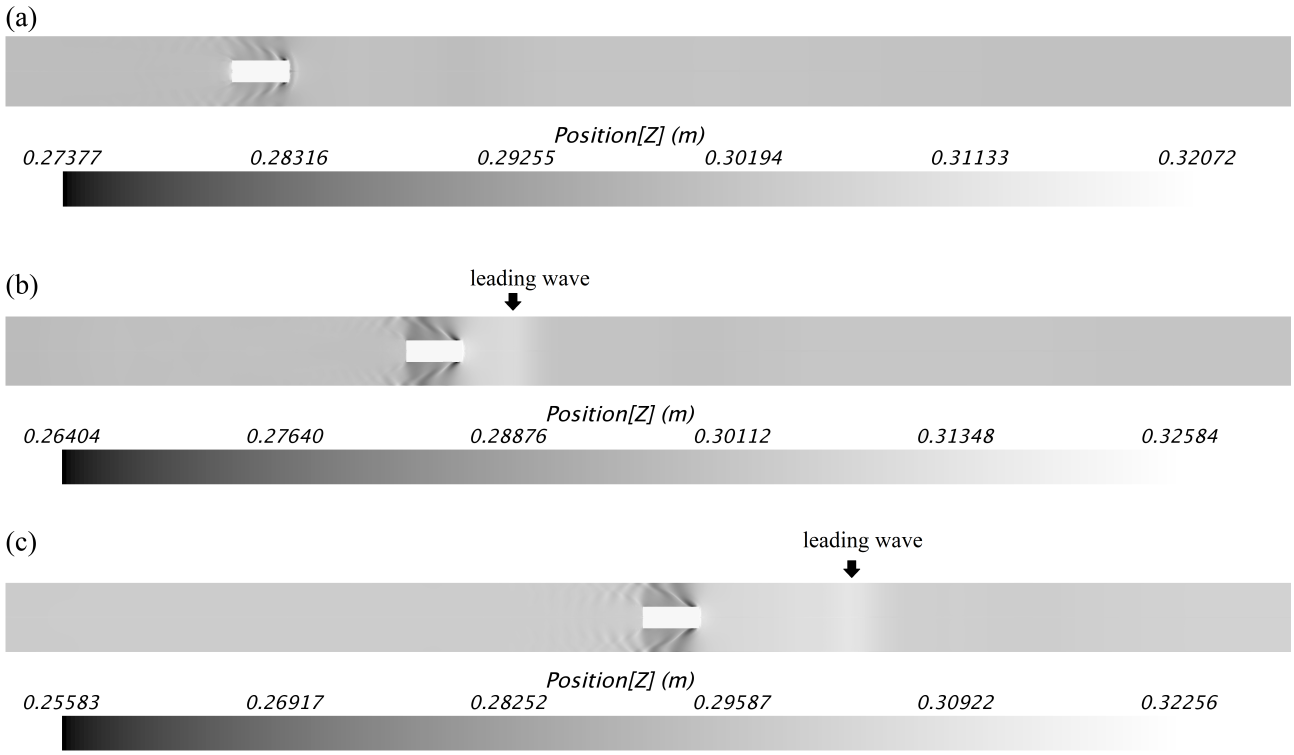

Figure 5: The process of mini-tsunami's generation in a narrow tank. The figures represent the elevation (Position[Z] is the free surface elevation) of the water surface at different time: (a) $t = 34$ s ; (b) $t = 40$ s ; (c) $t = 48$ s.

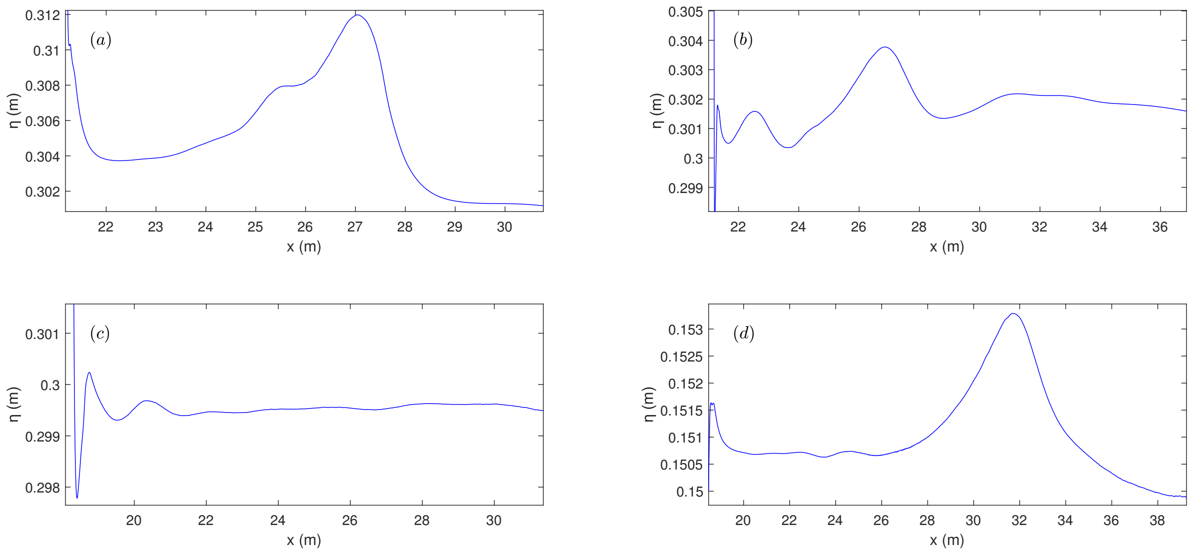

Figure 6: The generation of upstream step ($t = 52$ s for all cases); (a) result with $d = 0.10$ m; (b) the draught becomes $d = 0.07$ m; (c) the depth change is removed and water level is on $z = h_1$, $d = 0.05$ m; (d) the depth change is removed and mean water level is on $z = h_2$, $d = 0.05$ m.

generation and the piling-up effect, and study this effect by varying the ship speed and tank width.

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