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**Doychev, Svetlana; Söhngen, Bernhard**

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# Impact of ship size on induced waves and currents in confined water

S. Doychev[a] and B. Söhngen[a]

[a] Federal Waterways Engineering and Research Institute, Karlsruhe, Germany

## Summary

In this report ship induced waves and flow velocities caused by modern inland vessels in small canals will be calculated by numerical simulations. The main question of the study is whether these ships can cause more damages to canal banks than common smaller vessels. For this, the straight centric and off-centre motion of two ships in different trapezoidal canals was investigated at varied ship speeds. For the present investigation a depth-integrated 2D Boussinesq model for the numerical simulation of ship induced waves is applied. It provides the surface elevation and the flow velocities induced by a steadily driving ship in a prismatic channel. The model is based on the potential theory and uses the slender body theory to derive the water displacement caused by the ship motion. Thereby the ship is free to heave and pitch.

## Nomenclature

| | |
|---|---|
| $b_s$ | Ship beam (m) |
| $D_{50}$ | Average stone size (m) |
| Fr | Froude Number based on $h_C$ and $v_S$ (-) |
| g | Acceleration due to gravity (m $s^{-2}$) |
| h | Local water depth (m) |
| $h_0$ | Water depth on ship position (m) |
| $h_C$ | Reference water depth (m) |
| $H_S$ | Transversal stern wave height (m) |

| | |
|---|---|
| $L_s$ | Ship length (m) |
| m | Reciprocal bank slope (-) |
| s | Sinkage (squat) (m) |
| S | Transverse section area of the ship below still water level ($m^2$) |
| $S_f$ | Transverse section area of the ship below current water table ($m^2$) |
| $t_s$ | Ship draft (m) |
| $v_{crit}$ | Critical or limit ship speed (km h-1) |
| $v_s$ | Ship speed (km $h^{-1}$) |
| $\zeta$ | Local surface elevation (m) |
| $\zeta_0$ | Surface elevation at ship position (m) |
| $\theta$ | Trim angle (rad) |
| $\rho_S$ | Density of riprap stones (kg m-3) |
| $\rho_W$ | Water density (kg m-3) |
| $\varphi$ | Potential function (-) |

## 1. Introduction

Especially because of operational economical reasons, the size and the installed motor power of modern ships increase steadily compared to the ships in the past. But for different reasons, e.g. because of presently low traffic density, smaller existing canals, e.g. in the eastern part of Germany's canal system, will not be adapted accordingly. Nevertheless, there is an increasing demand to permit passages of vessels in very small existing canals. The question arises, whether this is acceptable and under which conditions, especially because of increasing ship induced impacts and corresponding damages of the undersized bank protection of these small canals.

There are many factors which affect the ship induced loads onto the bank. In this study we leave the most parameters fixed and just vary the ship size, the ship position and the ship speed to analyse their impacts separately. Furthermore, we just investigate ship induced impacts coming from the primary wave field of the ship, not from propeller induced currents. These will be investigated in a separate parameter study, using 3D numerical models.

For the present investigation a depth-integrated 2D Boussinesq model for the numerical simulation of ship induced waves is applied. It provides the surface elevation and the flow velocities induced by a steadily driving ship in a prismatic channel. The model is based on the potential theory and uses the slender body theory to derive the water displacement caused by the ship motion [1]. The model considers the viscous effects at the ship hull and at the channel bed.

These simplified approach compared e.g. to 3D calculations, field investigations or scale model tests, seems appropriate for the main task of the study to compare the effect of different boundary conditions on relevant ship induced loads, because the number of variants under consideration is very large. The present paper deals with some ongoing parametric studies, which will be performed at the Federal Waterways Engineering and Research Institute by order of the German Federal Ministry of Transport, Building and Urban Development as a part of different investigations for German waterways with low traffic density.

## 2. Test scenarios

### 2.1 Background

The German Küsten-Kanal (KK) was taken as a first example for the investigation of ship induced waves in strongly confined water. The Küsten-Kanal is a part of Germany's northwestern canal system. It diverts in the East from the River Hunte and ends in the West in the Dortmund-Ems-Kanal. At present, ships with maximum length of 100 m, beam of 9.65 m and draft of 2.5 m are permitted to use the Küsten-Kanal. But on the river Hunte the ships of length up to 110 m and beam up to 11.4 m are already permitted. Also Dortmund-Ems-Kanal is intended to be upgraded for vessels of similar dimensions. This means that in the future the Küsten-Kanal will be surrounded by waterways, which are designed for lager ships. This report deals with the hypothetical question of how the larger vessels might amplify the ship induced waves and currents at different speeds and different driving positions.

### 2.2 Ship and canal data

The study was carried out with two ships of different dimensions, but similar bow and stern shapes. The smaller ship S1 has a length of 100 m, a beam of 9.65 m and a draft of 2.5 m. The larger ship S2 has the dimensions of 100 m x 11.4 m x 2.8 m.

Calculations were carried out for two sections. The first one is between KK-km 41 and KK-km 64. The cross section of the navigation channel has a trapezoidal profile. The width of channel bed is approximately 24 m and the water table width is 45 m (Fig. 1 (a)). The channel is symmetric with a bank slope of about 1:3. The water depth along the channel bed is about 3.5 m.

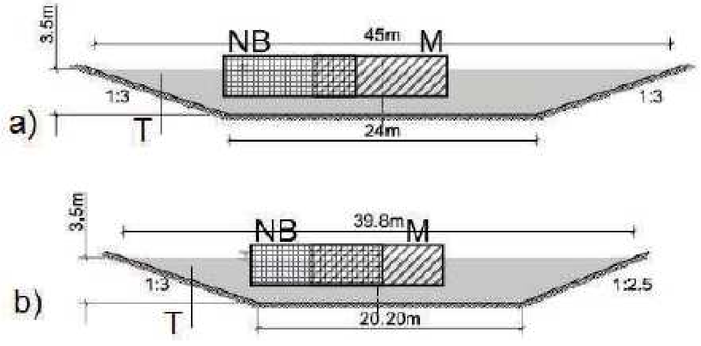

Figure 1: Channel cross section and ship positions a) between KK-km 41 and KK-km 64 and b) between KK-km 5 and KK-km 26

The second profile is between KK-km 5 and KK-km 26. The channel profile is also trapezoidal with bank slopes of 1:3 and 1:2.5 (Fig. 1 (b)). The width of the channel bed is 20.2 m and the water surface width is 39.8 m. The water depth of 3.5 m is unchanged compared to the previous profile.

Since this report deals with a channel, the flow velocity was neglected in the computations. The equivalent sand roughness of the canal bed was set to 0.03 m.

Two typical ship positions in the canal were investigated: in the middle of the water surface (M) and close to the bank (NB). At position NB, the ship centreline was 5 m away from the toe of the bank slope. Figures 1 (a) and (b) show the dimensions of channel cross-sections and the two ship positions. Ship induced loads were analysed at position (T) on the bank slope, halfway of the water depth.

## 2.3 Summary of evaluated data

A driving ship deforms the water surface around itself by displacing the water toward the sides, downwards and backwards. The corresponding ship induced velocities cause the primary wave system, consisting of a strongly deformed water surface at bow and stern (bow and stern wave system) and a nearly constant drawdown in the middle part of the ship hull, especially in case of long vessels in very small canals. Figure 2 illustrates the definition of different wave patterns at the bank.

The primary system is formed by low-frequency waves with large amplitudes. They are superimposed by highfrequency waves, called secondary waves, which are able to propagate at long distances away from ship, but with generally small amplitudes compared to waves of primary system for the considered case of usual cargo ships sailing in extremely restricted canal cross sections. Secondary waves will not be evaluated in this study.

However bow and stern wave heights are important characteristics for designing bank revetments, especially for the necessary riprap stone size. In accordance with [3] the average stone size $D_{50}$ can be estimated from the transversal stern wave height $H_S$ as follows:

$$D_{50} \geq \frac{H_S}{1.5 \cdot \left( \frac{\rho_S - \rho_W}{\rho_W} \right) m^{1/3}}, \tag{1}$$

with *m* = reciprocal bank slope.

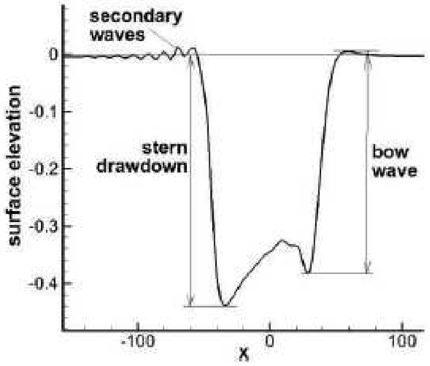

Figure 2: Description of waves

In this study we evaluate the bow waves, the water level drawdown at the stern and the return current velocities, especially in the range of critical ship speeds.

## 3. Computational methods

### 3.1 Governing Equations

The theoretical model is based on technique of matched asymptotic expansion, which uses the Slender-Body-Theory for the near field and applies shallow water wave theory for the far field [1].

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#### 3.1 (a) Far Field Condition

The far field condition is described by a transport equation for potential function j and can be written as

$$2Fr\cdot\varphi_{xt}+\left[h-\left(Fr^2+\frac{3}{2}\varphi_x^2\right)\right]\varphi_{xx}+\left(h+Fr\cdot\varphi_x\right)\varphi_{yy}+\frac{Fr^2h^2}{3}\varphi_{xxxx}+3Fr\cdot\varphi_x\varphi_{xx}+2Fr\cdot\varphi_{xy}\varphi_y+h_y\varphi_y=0$$

Here Fr denotes the depth Froude number based on the reference water depth $h_c$ and ship speed $v_s$ and is defined as $\mathrm{Fr} = v_s/\sqrt{g * h_c}$. Indices x and y denote the derivatives with respect to the longitudinal and transversal canal directions (Fig. 3).

The surface elevation ζ is then computed as

$$\zeta = Fr\cdot\left[1-\frac{1}{3}h^2\nabla^2\right]\varphi_x-\frac{1}{2}\nabla\varphi\cdot\nabla\varphi-\frac{1}{2}Fr\cdot\nabla h^2\cdot\nabla\varphi_x,$$

with the gradient operator Δ.

### 3.1 (b) Ship Boundary Condition

The ship boundary condition, which describes the transverse dynamic displacement of water caused by the ship motion, is defined in [2] as

$$\left.\frac{\partial\varphi}{\partial y}\right|_{y=\pm 0}=\mp\frac{1}{2(\zeta_0+h_0)}\frac{d}{dx}\left[\left(Fr-\varphi_x\right)_0 S_f(x)\right],$$

where $h_0$ denotes the water depth and $\zeta_0$ the surface elevation, both at the ship position (index 0). Here $S_f(x)$ denotes the dynamic wetted ship cross sectional area at ships position x (rib at position x). The efficiency of this equation was shown even in extreme cases, as the steady drive in a lock, by comparison with well known return current velocities.

Depending on the local dynamic free surface elevation, the ship's reaction on the water level deformation at ship hull, the sinkage (squat) s and trim angle θ are computed in each time step by means of the quasi-steady vertical force balance [1]. Using those values the dynamic crosssectional area can be calculated as follows

$$S_f(x)=S(x)+b(x)(s-x\theta)+b(x)\cdot\zeta\cdot h,$$

where S(x) is the transverse section area of the ship below still water level. This modification allows the ship to heave and pitch.

### 3.1 (c) Wave-Run-up Model

The Wave-Run-up Model is based on the Wet-Slope-Strategy [4], whose main idea is to extend the computational domain up to several meters onshore and assume this area to be wet, i.e. to be covered by a thin and strongly viscous water film. The equations are then solved on water and on land nodes together. However, on the water nodes the water depth is defined by the channel topology and viscosity equals the water viscosity.

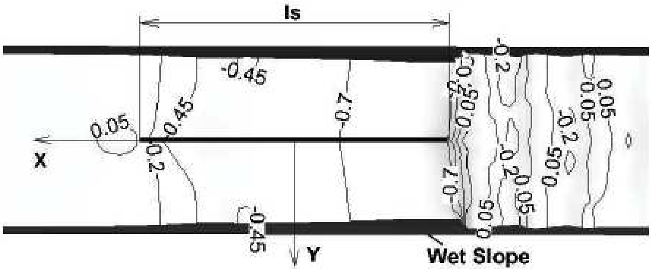

Figure 3: Example of computed water surface elevation

### 3.2 Computational conditions and numerical setup

For all computations the grid size of 2.625 m was set in the moving direction. In the cross sectional direction the grid size of 1 m was used, but to resolve the shore line properly the grid size in the bank area was gradually refined to 0.5 m.

For the discretization in space the central difference scheme on rectangular grid is used. The numerical solution was carried out by fractional step method, which splits up the two-dimensional equation in two one dimensional problems. Thereby the equation is first solved in the x-direction by applying the Crank-Nicolson method (CN) and then the obtained result is used for the solution in y-direction again by the CN. This combination provides the accuracy of second order in space and in time. This approach leads to a five-diagonal equation system for the solution in x-direction and three-diagonal equation system for y-direction. Both can be solved very efficiently. Hence, the computational time for each case was less than three minutes.

The numerical model has been validated using data from field observations. The results of the simulations agreed well with experimental data. The model predicted the heights of primary waves and the return current velocities with deviation of less than 15%. However the heights of secondary waves were strongly underestimated. The results are currently in the publishing process. In future the numerical program will be a part of the professional revetment design tool GBBSoft.

## 4. Results and discussion

### 4.1 Channel profile at KK-km 41-64

Since the wave pattern strongly depends on the ship squat, we at first discuss the dynamics of the ship movement for the four cases. Figure 4 shows the trim of both ships on the two positions for different ship speeds. In case of ship S1 driving on the centreline at speed lower than 5.5 km/h (Fr=0.26) the ship trims by the bow. The trim angle in this case takes negative, but very little values. With growing ship speed the trim angle grows as well and becomes positive, which means that the ship trims stern-heavy. Close to the critical ship speed (i.e. the speed, that a displacement vessel generally cannot

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overtop in restricted water), the trim angle increases rapidly. Ship S2 shows a similar trend, but because of a higher blockage the trim angle grows much faster compared to S1. The switch from trimming by the bow to trimming by the stern for ship S1 at off-centre motion happens at higher speed than at the centreline motion. The trim of the bigger ship at position NB shows no dependency on the ship speed. For all speeds the ship remains slightly down by bow.

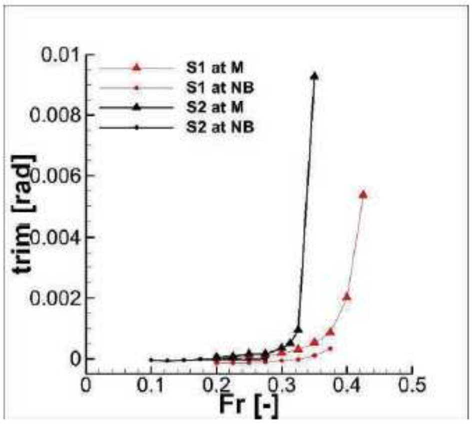

Figure 4: Computed trim of the ships. Positive trim means stern down.

Figure 5 shows the computed bow wave heights at the bank position T, induced by a centric and an off-centric motion at different ship speeds. Figure 6 shows the computed stern drawdown for the same cases. Since the blockage coefficient for the bigger ship is higher, its critical speed is lower.

For the centreline motion the critical speed of the ship S1 is approximately 9 km/h (Fr=0.43). At this speed the generated bow wave height is 0.49 m and stern drawdown at halfway water depth at the bank is 0.67 m. At the critical speed of approximately 7.4 km/h (Fr=0.35) the ship S2 induces the bow wave and stern drawdown respectively of 0.43 m and 0.87 m. Because of the strong trimming close to and at the critical ship speed, the stern drawdown is in both cases more significant than the bow wave and is high enough to cause considerable damage on the bank revetments. The criteria on revetment design can be found in [3]. According to experience, the most inland cargo ships drive at a speed of approximately 90% of the critical ship speed. In this case the bow waves and the stern drawdown at the bank of both ships are approximately 0.3 m, which may be an acceptable wave height for older under-dimensioned revetments.

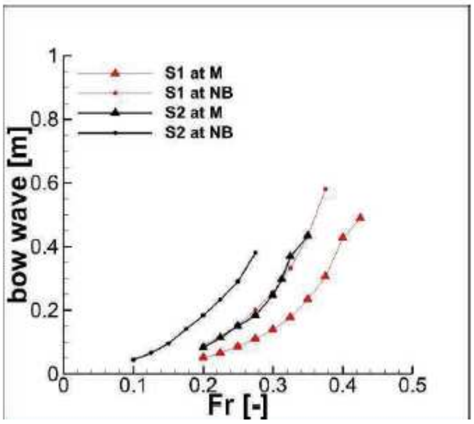

Figure 5: Computed bow wave heights at bank position T

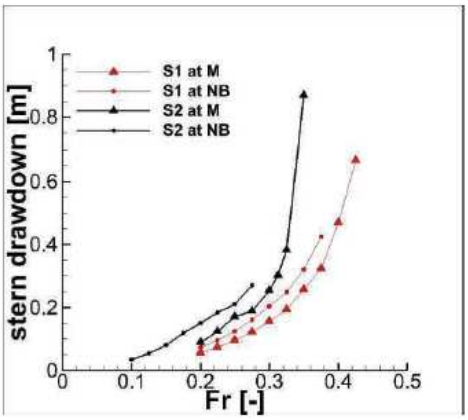

Figure 6: Computed stern drawdown at bank position T

The stern drawdown at the bank is for both ships slightly higher during the off-centre motion than during the centreline motion. However the bow waves show a significant difference between both positions. A ship driving in shallow water displaces the water particularly sidewards. The water is then flowing in the opposite direction to the vessel. In case the clearance between the ship and the bank is limited, the water accelerates, causing a strong bow wave as the results at the position NB show. Because of the smaller blockage coefficient the ship S1 is able to reach higher speed and so generates higher bow waves than the ship S2.

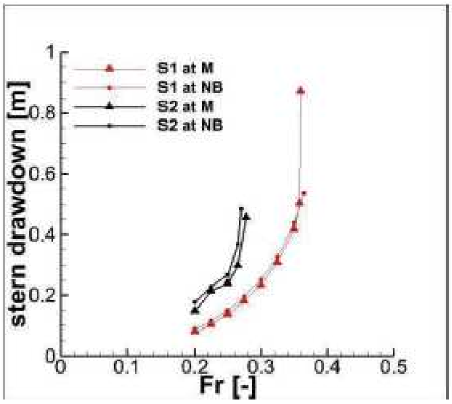

Figure 7: Computed maximum return current velocity at bank position T

Figure 7 shows the maximum ship induced velocities relative to the banks on the bank position T. For the study it was not distinguished, whether the maximum values appeared on bow or stern area or in the middle of the ship. Both, the driving position and the ship size, have a strong influence on the return current velocities. The highest backflow velocity was caused by the ship S2 during the centreline motion.

## 4.2 Channel profile at KK-km 5-26

Figures 8 and 9 show computed values for bow waves and stern drawdown at different ship speeds and different ship positions for second, smaller canal cross section. Since the channel profile is very narrow, the difference of ship induced waves at centre and off-centre motion at subcritical speed is insignificant for both ships. Also the critical speed, which can be detected on sudden trimming by stern or abrupt increase of return flow velocity, for each ship respectively at centre and off-centre motion was almost the same.

However, the ship size crucially influences the surface elevation. At equal speeds the waves of ship S2 are almost two times higher than those of ship S1. But in spite of this, the highest waves are still induced by the smaller ship at around the critical speed! The reason for this fact is, that it has a smaller rib area, which enables S1 to reach higher speeds. More precisely, the critical speed of ship S1 is approximately 7.5 km/h (Fr=0.36) and of ship S2 is only about 5.6 km/h (Fr=0.26). Near the critical speed ship S1 induces a stern drawdown of up to 0.9 m at centre motion and 0.6 m at off-centre motion. Both are precarious for existing revetments in the Küsten-Kanal and generally for many small canals in Germany. On the other hand the stern drawdown of ship S2 close to the critical ship speed is only about 0.5 m, which may be acceptable in many cases.

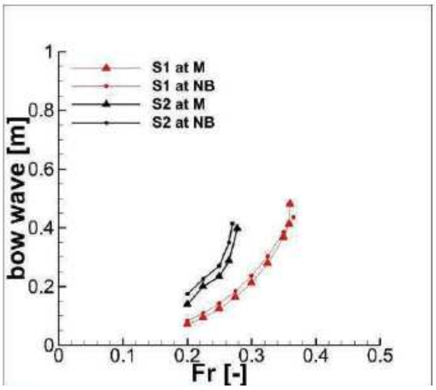

Figure 8: Computed bow wave heights at bank position T

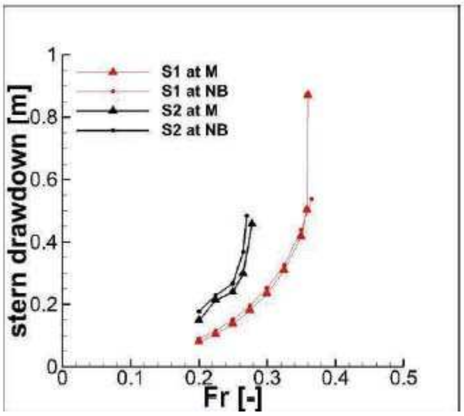

Figure 9: Computed drawdown at ship stern at bank position T

The computed maximum backflow velocities at the position T show a similar behaviour (Fig. 10). The difference between centre and off-centre motion at subcritical speed is insignificant for both ships. However, in all cases the backflow velocity increases rapidly near the critical speed. Comparable to stern drawdown, the return current velocities induced by a bigger ship are approximately two times higher than those induced by a smaller ship. The highest values of maximum velocity of the return current are for both ships approximately 2.5 m/s. These values were reached by the bigger ship at 5.6 km/h (Fr=0.26) and by the smaller ship at approximately 7.5 km/h (Fr=0.36).

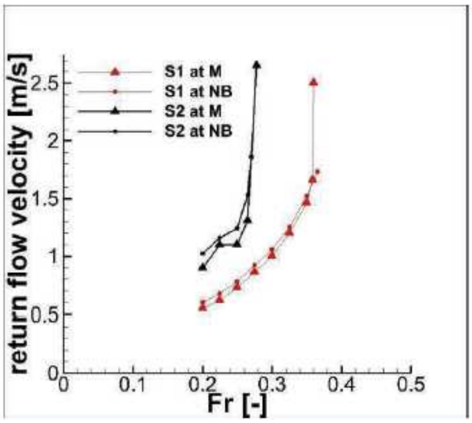

Figure 10: Computed maximum return flow velocity at bank position T

## 5. Conclusions and outlook

The ship induced waves and backflow velocities of two different sized ships were investigated in two different sections of the Küsten-Kanal, Germany. Thereby the driving positions and the ship speeds were varied.

Although the breadth of the water surface and the width of the channel bottom of the second canal profile was only 5 m smaller than of the first one, the difference in the wave pattern was significant, especially in regard to eccentricity. In the first profile ship induced waves and return current velocities were higher at the near bank motion. However, the highest reachable ship speed was smaller, which led to smaller bow and stern waves. At the second profile no significant differences in ship induced loads between centre and off-centre motion at subcritical speed were calculated. Also the critical ship speeds at both driving positions were approximately equal. The discussion of eccentricity in this section applies for both ships.

In both profiles the bigger ship generated up to two times higher waves and return flow velocities than the smaller ship. But because the highest reachable speed of the bigger ship is lower, the corresponding hydraulic loads are in certain cases smaller. This occurs especially when the distance to the bank is small, e.g. at off-centre motion in the first profile or at both driving positions in the second profile.

The study shows, that the ship size is a decisive but not exclusive factor in generation of ship induced loads. Moreover it is the interaction between ship size, ship speed, channel geometry and driving position. Even small changes in the channel profile show crucial differences in ship induced loads. This makes a general statement difficult and each profile has to be investigated individually for several ships.

Possibilities to reduce the ship induced loads are the restriction of driving position or the limitation of ship speed. Both have their drawbacks. The limitation of the ship speed is difficult, because it should be different for smaller or empty vessels and larger or deep draught ships. Further, at a low ship speed the propeller-induced impacts may increase because of a more or less permanent manoeuvring condition, forcing the helmsman to use the bow thruster or to sail with varying engine power. The study has also shown that the restriction of the sailing positions may only be reasonable if the channel is wide enough. Also because of overtaking and meeting of ships this solution is less practicable in many cases.

This study concentrates on uniformly loaded ships. A ship, which is loaded uneven, has an initial trimming. This trimming has a strong influence on the resulting squat and consequently is able to change the wave pattern entirely. Especially for a ship, which is trimmed stern-heavy, the critical ship speed is expected to be smaller than in case of a uniformly loaded vessel. Also the hull shape, especially at bow and stern, may strongly influence the ship induced waves and currents. These two aspects should be investigated in future studies.

## 6. Acknowledgements

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## 8. Authors biography

**Svetlana Doychev** is a research associate in the Department of Hydraulic Engineering at Federal Waterways Engineering and Research Institute, Karlsruhe, Germany. She works on developing and implementing the numerical algorithms for hydrodynamics.

**Dr. Bernhard Söhngen** is professor at the University of Darmstadt and the head of the Section Ship-Waterway at Federal Waterways Engineering and Research Institute, Karlsruhe, Germany. His research concentrates on ship hydrodynamics and ship induced loads.