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Original scientific paper

Minimisation of Propeller-Induced Sediment Resuspension with Rip-Rap System

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Abstract: Sediment resuspension caused by the movement of propellers during manoeuvring is a major problem in daily port operations. Negative impacts include: Marine flora and fauna, sediment erosion that weakens berth structures, sediment deposits that require dredging. Later, this leads to delays in port operations. Several authors have proposed different methods to cope with this problem. This paper presents methods and tools to determine the critical propeller jet velocities, which are the most important parameter to determine the size of the bank stabilisation system. The tool is a bridge simulator that can be used to simulate the intrusive departure manoeuvre of a ship. The ship motion data are analysed to determine the critical shear stress of the sediment particles. The critical velocity induced by the propeller jet is determined using the German method.

Keywords: Sediment resuspension, Full Mission Bridge Simulator, Critical propeller jet bottom velocity, Rip-rap system.

1. Introduction

The Port of Koper faces a global shipping problem to accommodate ever larger ships and remain competitive in the global port market. The Port of Koper (PK) is reaching its limits to accept deep draft vessels in length, width and gross tonnage. The first parameter is limited by sea depth, and the others present manoeuvring challenges for pilots and tug operators.

The focus of the article is on deep draft vessels calling at our port with under keel clearance (UKC) of less than 1m. Negative impacts are seen in sediment resuspension caused by the propeller rotation. The latter negatively impact marine flora and fauna, erosion around the berthing structure, deposition of sediment particles in certain areas of the port, and the need for dredging operations, leading to challenges in port logistics [1].

Scientific research addresses the problem of finding appropriate methods to determine the interaction between ship propellers and the

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seabed. There are mainly two methods to reduce the impact of sediment resuspension: different seabed protection techniques in port and alternative ship manoeuvres. The article deals with the outbound manoeuvre of a container ship from Basin I, Berth 7 D/C. The Full Mission Bridge Simulator (FMBS) was used to simulate the outbound manoeuvre of container ships expected to call at the port in the near future. The corresponding ship motion data were recorded and later analysed to determine the maximum velocities of the propeller jets on the seabed and to determine an appropriate technique to protect the port bottom.

2. Simulation tool to recreate ship departure manoeuvre

Port Authority is concerned about future ships that grow in size. Where is the upper limit, and how can it be predicted? The main concern is the implementation of safe departure and arrival manoeuvres so as not to endanger the marine habitat, the ships in the vicinity and the port infrastructure. The article's topic is reducing the current caused by the ship's propeller rotation. The useful simulation tool to determine the optimal departure/arrival manoeuvre and to obtain ship motion data for further analysis to predict the ship propeller jet bottom velocities is FMBS. The following Table 1 shows the static data of the simulator ship that is expected to enter Basin I in the near future. The simulated vessel has a UKC of 0.5 m, the lowest value allowed [2].

Table 1 - *Simulator Container ship 31 data.*

Ship Type	**Container Ship 31 TRANSAS version 2.31.32.0**
Displacement	232 005 t
Length Overall	400 m
Breadth (moulded)	59 m
Draft (midship)	14.5 m
Max engine power	61 042 kW
Ship propeller type	FPP (Fixed Pitch Propeller)
Propeller diameter (D_p)	10.3
Propeller immersion (S_t)	9.15 m
Bow thruster capacity	5 000 kW

The largest container ship displaced 165,000 tons, measuring 353 meters in length and drafted 14.2 meters. Figure 1 below shows the configuration of port Basin I with the corresponding position for the container ship's departure manoeuvre.

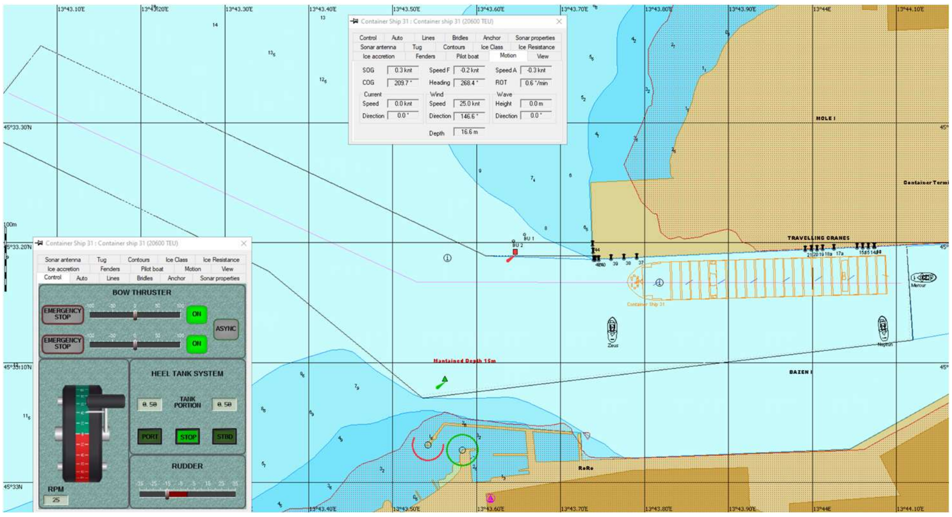


Fig. 1 - *FMBS container 31 departure manoeuvre from Port of Koper Basin 1, berth 7 D/C.*

The FMBS simulation was used to recreate departure manoeuver in real time and place. During the manoeuvre, relevant ship dynamic data were recorded at a frequency of 1 Hz: ship position, speed over ground, course over ground, heading, propeller rates per minute, thrust, rudder angle and other [3].

3. Methods to determine ship propeller jet bottom velocities

Determining the maximum velocity of the propeller jet bottom velocities ($V_{b,max}$) is the most important parameter for determining the correct rip-rap technique. The authors [4] presented ship propeller efflux velocity (V_0). It is an important variable in sediment resuspension analysis because all semi-empirical equations use it as a dependent variable.

$$V_0 = C_3 \left(\frac{P_{app.}}{\rho_{w} D_p^2} \right)^{\frac{1}{3}} \; [{}^{m}/_{s}] \qquad (1)$$

where is; applied power (P_{app}), water density (ρ_w) in (PK) is 1027 kg/m^3, propeller diameter (D_p) and coefficient (C_3):

- C_3 = 1.17 for ducted propellers (propellers with nozzle),
- C_3 = 1.48 for free propellers.

The equation applies to the ship's speed ($V_{0;v=0}$); the applied propeller speeds per minute (RPM_{app}) are recorded during the ship manoeuvre with a time step of 1 Hz; Parameter maximum propeller rates per minute (RPM_{max}). Applied power (P_{app}) is calculated using the following equation.

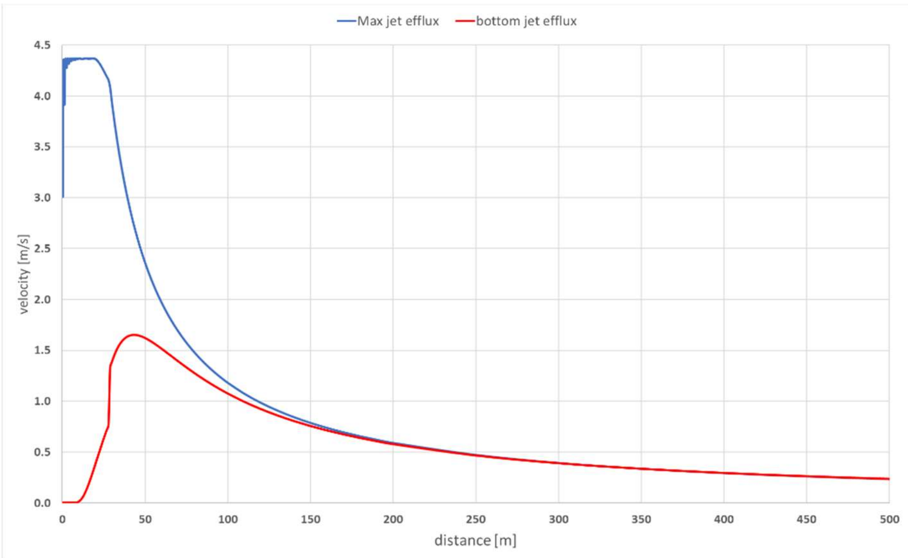
$$P_{app} = \left(\frac{RPM_{app}}{RPM_{max}}\right)^3 P_{max}\ [W] \tag{2}$$

The increasing speed of the ship requires a different approach in calculating the outflow velocity of the ship's propeller for a non-zero ship speed ($V_{0;v\neq0}$), since the propeller slip and the vessel speed are related to the thrust equation.

$$\mathbf{V_{0;v\neq0}} = \mathbf{V_0}\left(\mathbf{1} - \frac{\mathbf{v_s}}{\mathbf{D_p\ n}}\right)\ [m/s] \tag{3}$$

The equation consists of the following parameters: vessel speed (V_s) and propeller rotation per second (n). The maximum bottom jet velocity of the ship's propeller ($V_{b,max}$) determines the critical jet velocity at which sediment particles reach the upper limit of bottom shear stress and detach from the seafloor, resulting in erosion, advection, and deposition of sediment particles [5].

$$V_{b,max=0} = E\ V_{0;v\neq0}\left(\frac{D_p}{h_t}\right)^b\ [m/s] \tag{4}$$



Graph 1 - *Container ship maximal jet efflux and bottom velocity.*

Graph 1 presents the container ship propeller maximal jet efflux and bottom velocity; originating from the propeller face. The maximum propeller jet outflow velocity (V_0) reaches a value of 4.4 m/s, and the maximum jet velocity ($V_{b,max}$) reaches 1.65 m/s; at a distance of 41 m from the propeller face.

Coefficient (E) and (b) used to determine the rudder influence (E = 0.71, b = 1.0, ships with rudder); (E = 0.42, b = 0.275, ships without rudder). The simulation ship has the rudder influence. The parameter (H_t) contributes (Figure 2) most to high jet bottom velocities and is correlated with the ship (UKC) and propeller diameter (D_p).

$$H_t = C + \frac{D_p}{2} \ [m] \tag{5}$$

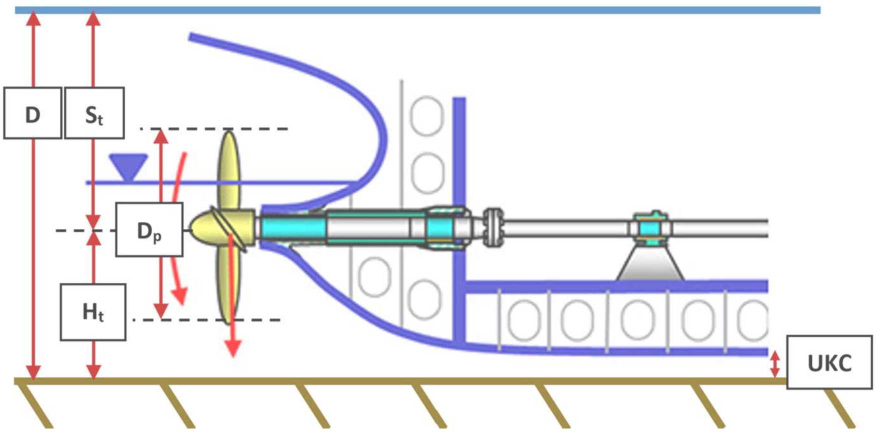


Fig. 2 - *Parameters influencing maximal jet bottom velocity.*

Port of Koper depth (D) set in the numerical calculations to 15 m and the axial distance of the ship's propeller to the seabed (H_t) to 5.85 m; which gives a maximum jet bottom velocity ($V_{b,max}$) of 1.65 m/s.

3.1 Port bottom Rip-Rap technique to prevent sediment scouring

The market for sediment resuspension prevention technology offers several sea bottom overlaying material types. The type of scour protection material is influenced by: cohesive (mud) and non-cohesive (sediment particles), sediment size and density, bathymetry of the sea bottom [6].

The installation of a rip-rap system has negative impacts on port economics, such as primary costs due to the implementation of the system, vessel traffic delays in the port, and removal of the rip-rap system prior to dredging in case of deepening of the port bottom channel.

There are several types of sediment scour prevention techniques: Rip-rap (basalt, granite, syenite, quartzite, limestone); rip-rap impregnated with asphalt primer; rip-rap impregnated with underwater concrete; wired concrete block mats; concrete slabs; concrete-filled fabric mattresses; stone-filled fibre-reinforced bitumen mattresses; geosynthetic bags, mattresses, tubes and containers filled with sand, gravel [7].

The first method uses the following equation to determine the rock size (D_{85}); 85% of rocks are smaller than this size) rip-rap protection technique [8].

$$V_{b,max} = B_{cr}\sqrt{D_{85} g \Delta}\ \left[{}^{m}/_{s}\right] \tag{6}$$

Rearranging ($V_{b,max}$) equation yields required rock size(D_{85}).

$$\mathrm{D}_{85} = \frac{\mathrm{V}_{\mathrm{b,max}}^2}{\mathrm{B}_{\mathrm{cr}}^2\ \mathrm{g}\ \Delta}\ [m] \tag{7}$$

$$\Delta = \frac{\rho_s - \rho_w}{\rho_w}$$

Coefficient (B_{cr}) is between 0.9 and 1.25 (calculated value 1.0), (g) is acceleration due to gravity, (Δ) is relative density, (ρ_s) is density of sediment, and (ρ_w) is the surrounding water density [9].

Koper port has an average seawater density of 1027 kg/m3, a sediment density of 2650 kg/m3, and a calculated relative density (Δ) of 1.58. The rock size equation (D_{85}) recommended for use in (PK) yields a value of 0.18 m.

The second method of preventing sediment stir-up is to cover the seabed with concrete field mattresses or concrete slabs. Their thickness (D_M) is determined by the following equation.

$$D_M > \frac{C_L V_{b,max}^2}{2 g \Delta} \tag{8}$$

The coefficient (C_L) is between 0.50 and 0.75 (chosen value 0.70). The equation recommends a thickness of at least 0.06 m.

The scour protection area near the operational critical side depends on the width of the bottom area from the pier berthing structure to minimize sediment erosion around the mooring and the transverse area affected by bow or stern thrusters. The figure below shows the width of the bottom protection area (b_{pr}) measured perpendicular to the pier. The prediction is based on the following equation.

$$b_{pr} = b_q + 0.5\ b_s + 0.5\ S_p + 0.5\ D_p + 5.0\ [\mathrm{m}] \quad (9)$$

The following variables are present: Distance between the ship and the pier wall (b_q), the ship's width (b_s) and, in the case of two propellers, the distance between the propeller shafts (S_p).

In most cases, the bottom protection will be less than the ship's width; an additional 5 m will ensure the stability of the structure.

The second method to determine bottom protection width (b_{pr}) from the pier is based on German equations [10].

Equation for ships with one propeller.

$$\mathrm{b_{pr}} = (3 \ldots 4)\mathrm{D_p} + 3.0 - 5.0\ [\mathrm{m}] \quad (10)$$

Equation for ships with two propellers.

$$\mathrm{b_{pr}} = 2\ (3 \ldots 4)\mathrm{D_p} + 3.0 - 5.0\ [\mathrm{m}] \quad (11)$$

The largest expected container ship (PK) measures 400 m in length and 61.5 m in width. According to these values, the scour width can be calculated using the equation for a ship with one propeller. The equations give a bottom protection of about 40 m.

The scour protection of the seabed along the pier can be determined with the rule of thumb: Ship length plus 50 m at the bow and stern. Depending on arrival and departure manoeuvres, the protection area may extend by a certain value.

If the berthing position of the largest vessel expected to call at a given berth in the port does not change, the following equations are used.

$$L_m = (6 \ldots 8)D_p + 3.0 - 5.0\ \ [\mathrm{m}] \quad (12)$$

$$L_{m,2} = 3\ D_p + 3.0 - 5.0\ \ [\mathrm{m}] \quad (13)$$

$$L_t = (3 \ldots 4)D_p + 3.0 - 5.0\ \ [\mathrm{m}] \quad (14)$$

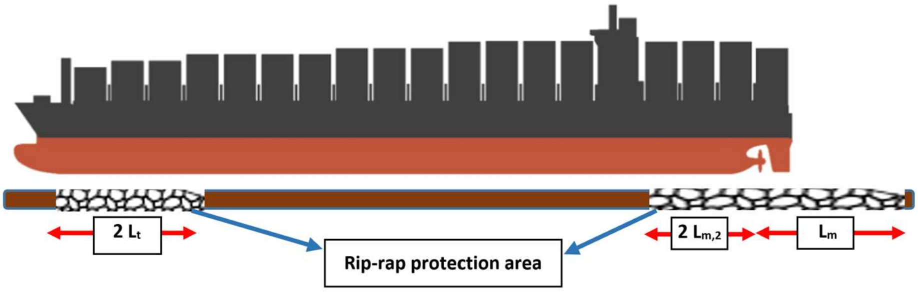


Fig. 3 - *Ship side and front view to determine bottom protection area.*

Equation (12) determines the length of 70 m; measured from the ship's propeller in the aft direction, equation (13) the value of 29 m; measured from the ship's propeller in the forward direction and with equation (14) the value 39 m, the area length around the bow thruster is determined.

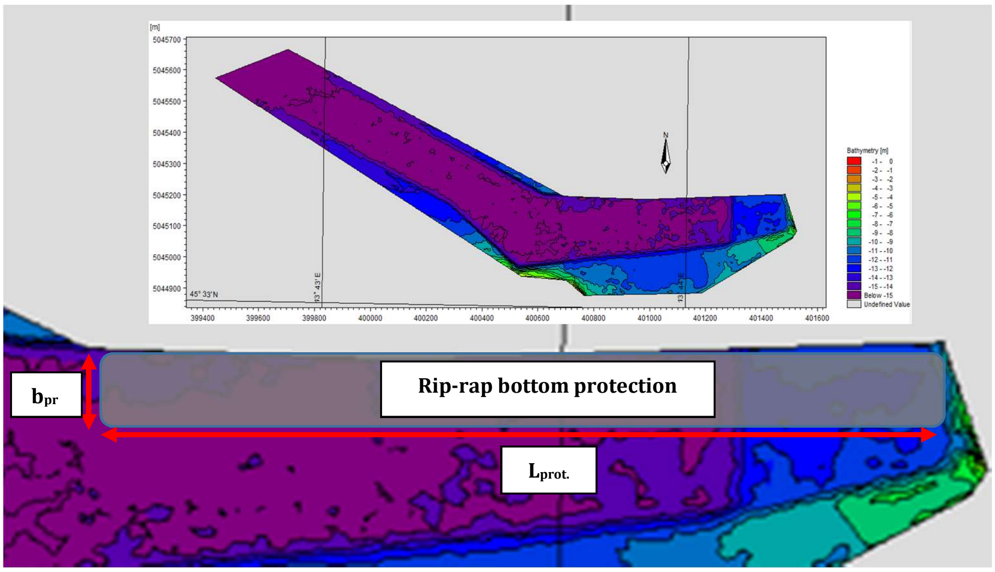


Fig. 4 - *Port of Koper Basin 1, Bathymetry and recommended bottom protection area.*

Figure 4 shows the area to be protected along the container terminal at South Pier I. The article recommends protection by rip-rap in the lateral direction from the pier (b_{pr}) of 40 m and a longitudinal protection distance ($L_{prot.}$) of 710 m along the entire container terminal. Figure 3 shows the partially protected ship bottom, which depends on the ship's berthing position, the main propulsion system and the position of the bow thruster.

4. Conclusion

Shipping global trade encounters problem excepting deep draft vessels in ports, resulting in sediment stir-up that negatively affects marine flora and fauna and damages mooring structures. The article describes the rip-rap technique for the port of Koper, in which the seabed is covered with various materials, such as: Rock fill (basalt, granite, syenite, quartzite, limestone) and Concrete block mats.

The Full Mission Bridge Simulator was the main tool used to simulate the departure manoeuvre of intrusive container ship and to obtain dynamic data used to calculate the jet efflux velocity (V_0) induced by the ship's propeller motion and to determine the maximum jet bottom velocity ($V_{b,max}$). The later value is used to calculate the rock size for the rip-rap protection technique and the thickness of the concrete block mats.

The solution could be used in the port of Koper positioned in the northeastern Mediterranean Sea. The port is strongly affected by sediment uplift from ship propellers due to shallow bathymetry.

The implementation of alternative ship manoeuvres to minimise sediment resuspension will be the focus of future research.

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