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Limitation and Restrictions on the Admission of Postpanamax Container Ships in the Port of Koper

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The recent global container transport increase amounts to about 8-10% on a yearly basis - in the Port of Koper in 2012 it was 570,744 TEU, which brings Koper's increase to 850% over the last 15 years. Despite the global recession, the decline in container transport in 2009 was minimal. A great increase in transport followed in the year 2010 which was partly a consequence of the introduction of a direct line between Asia and the north Adriatic. Further increases in container traffic depend primarily on the technological readiness of the Port of Koper. Therefore, it is necessary to invest in transport mechanization and hinterland connections, but also to provide sufficient draught and a properly shaped channel to ensure a safe approach for larger container vessels calling at the Port of Koper. The paper presents statistics and methods supporting container terminal enlargement and a safety and environmental assessment derived from the use of a ship handling simulator with specific consideration given to the problem of increasing re-sedimentation caused by larger, more intrusive container carriers.

Keywords: *container transport, port development, safety, ship-handling simulator, bottom wash, re-sedimentation*

Ograničenja primanja Post-Panamax kontejnerskih brodova u luci Koper

Izvorni znanstveni rad

Globalni transport kontejnera je u godišnjem porastu od 8 do 10%. U 2012. godinu u luci Koper pretovareno je 570 744 TEU što je ekvivalentno 850% rastu u zadnjih 15 godina. Čak u periodu globalne recesije u godini 2009. pretovar kontejnera nije značajnije poremećen. U godini 2010. uspostavljena je izravna linija između Azije i sjevernog Jadrana zbog čega se promet kontejnera dodatno intenzivira. Bez značajnijih tehničkih unapređenja pristanište u Kopru ne može pratiti potražnje tržišta za primanje i prekrcaj većih kontejnerskih brodova. Zbog toga je pripremljen plan modernizacije transportne mehanizacije u luci. Isto tako izrađen je plan produbljenja plovnog kanala i produženja kontejnerskog terminala za primanje većih brodova. Članak predstavlja pristupe za dizajniranje plovnih putova i primjerenosti veza za brod sa osvrtom na metodu primjene nautičkog simulatora u realnom vremenu s realnom posadom. Dobiveni parametri statistički obrađuju probleme sigurnosti na moru te problem *resuspenzije* materijala na morskom dnu. Naime planirani - veći brodovi na većem gazu - smatraju se sa tog aspekta *intruzivnijim* brodovima za okoliš.

Ključne riječi: *transport kontejnera, razvoj pristaništa, sigurnost na moru, nautički simulator, ispiranje morskog dna, resuspenzija sedimenta*

1 Introduction

Ports play an important role in international trade as interfaces between sea and land transport. In the last 30 years the maritime container industry has grown dramatically and the pressure on ports has been felt from both the land and sea sides. On the land side there is a growing demand for fast and safe transport of containers to the hinterland. On the sea side ports must be able to accept bigger container ships with a greater number of containers.

Including both land and sea legs of transport, containers have a great advantage over other means and the amount of the goods transported in this way continues to grow [1]. This trend has led to increasing numbers and sizes of container ships, changing dramatically over the time analysed here. Container ships have increased in size in order to reduce transport costs.

Table 1 **Trends in the container ship fleet**
Tablica 1 **Razvoj kontejnerske flote**

year	No. of ships	TEU capacity	Average ship size (TEU)
1987	1,052	1,215,215	1,155
2012	5,012	15,406,610	3,074
Growth 1987/2012 (percent %)	**476**	**1,268**	**266**

According to the Review of Maritime Transport (RMT) 2012 [2], total container trade in 2011 was 151 million TEU, 7.1 per cent more than in 2010, while the transport capacity of container ships increased by 6 per cent.

In Table 1 we can see that in 2012 the number of container ships was 476 % higher than in 1987, but the capacity of all ships was 1,268 % higher. That means that larger container ships (with a capacity over 18,000 TEU) are now in service [2].

The introduction of larger ships on mainline routes may be attractive for shipping lines but it could be a problem for the ports. Ports invest a lot of money in transport facilities just to be able to receive vessel calls. Today the maritime industry and market requires ship owners and ports to constantly adapt to new requirements.

In this paper, we analyse the requirements for the admission of postpanamax container ships to minor ports which currently do not have the conditions for receiving such large ships. A detailed case study was made for the Port of Koper.

2 Container traffic in the Port of Koper

The Port of Koper is striving to become the main container terminal in the northern Adriatic. The northern Adriatic ports of Koper, Rijeka, Trieste, Venice and Ravenna operate in a relatively closed system in which the market and customers are limited and therefore the ports are forced to co-operate while at the same time they compete with each other. They are located in three countries, with different transport policies and plans of development. The Port of Koper is Slovenia's only port, and therefore extremely important, contributing significantly to the Slovenian GDP. The state of Slovenia is the largest shareholder and the future development of the port depends on decisions made by the Ministry of Infrastructure. The increase in container throughput in the Port of Koper absolutely requires the reconstruction and extension of the current container terminal. Regarding economic sustainability the extension must be in line with the estimated growth of traffic as well as with the exploitation of present and future terminal capacities. The occasional expansion projects must fulfil environmental and safety requirements. For large container vessels (LOA more than 330 m) calling at the Port of Koper the safety of the berthing and departure conditions must be simulated under various metocean conditions. At the same time manoeuvres should not be intrusive – expected propeller wash or bottom wash phenomena must be carefully analysed.

When large powerful container vessels are manoeuvring in shallow water bottom wash is expected and because sediments at the port are contaminated with mercury some negative environmental influence is expected. The most important expected investment in the container terminal is therefore extending (enlarging) and deepening the berth.

The growth of container traffic in the Port of Koper as well as the beginning of construction of the new container terminal has made the reconstruction and extension of the current container terminal an absolute priority. The extension is in line with the estimated growth of traffic as well as with the exploitation of present and future terminal capacities.

2.1 Development of the container terminal in the Port of Koper

The ports of Koper, Trieste, Venice, Ravenna and Rijeka are located in the northern part of the Adriatic Sea, which penetrates deep into the commercial centre of the European continent, providing the cheapest maritime route from the Far East, via Suez, to Europe, including such economic powers as Germany (Munich, for example is six hours by train from Koper; other large commercial and industrial hubs like Vienna and Milan are even closer). In the past twenty years the total container traffic in the northern Adriatic ports has increased almost exponentially, on average 7% per year, though the rate has varied among the ports (Figure 1). The fastest growth of container traffic was recorded at the Port of Koper, at an average of 14% per year; in Venice the growth was constant; while at Ravenna the traffic barely increased at all [3]. The minimum throughput was and remains at the Port of Rijeka, which lost a great deal of traffic due to the state of war in Croatia; since about 2003 the increase in Rijeka's container throughput has been more in line with that of Koper, Trieste, and Venice.

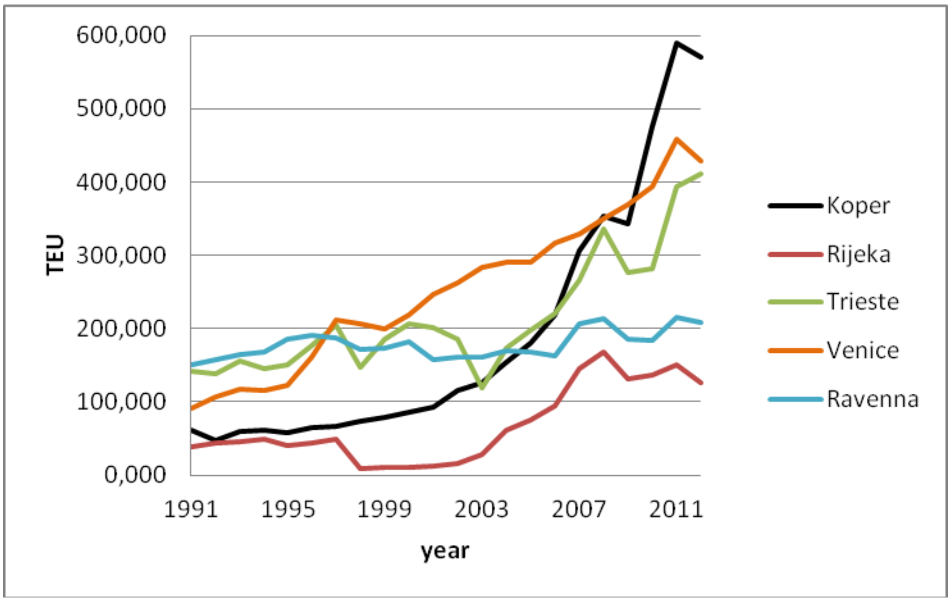

Figure 1 **Container throughput in NAPA ports during 1991-2012 (1,000 TEUs)**
Slika 1 **Kontejnerski promet u *NAPA* lukama u razdoblju od 1991. do 2012. (1,000 TEU)**

The years 2008 and 2009 – the worst years of the global economic and financial crisis – led to some interesting results. In Venice during this period, throughput kept steadily increasing by 5% per year; the other four ports experienced a decrease averaging 15%. The largest drop in traffic was recorded in Trieste, a decrease of more than 58,000 TEUs (17.5%), though by percentage Rijeka fared worse, declining at the rate of 22.5 % (38,000 TEUs fewer).

Because of the expected further increase of container traffic, an extension of 146 m of the first pier in Koper was begun [4]. In 2009 the port obtained two transtainers and four postpanamax cranes (Figure 2). The annual transport capacity increased to 600,000 TEUs with the purchase of new storing bridge cranes with stacking capacity of 4 or 5 containers in height, the repositioning of empty containers to new locations and the acquisition of new areas for full containers; naturally the speed of turnaround was thereby increased.

Figure 2 **The container terminal in the years 2002 and 2010**
Slika 2 **Kontrjnerski terminal u godinama 2002. i 2010.**

2.2 Obstacles on the sea side in the development of the container terminal

The trend in the shipping market is an increase in orders of ships of over 7,500 TEUs, which is why the Port of Koper began to further develop the infrastructure in its container terminal. Significant financial investments in the extension of the container shore, expansion of storage space and the purchase of specialized transport equipment paid off during the increase in transport (despite the global crisis) in 2010. The quantity of transported containers has reached enviable numbers. This very success, though, has at the same time created a problem. The growth of container throughput in the Port of Koper is at the limit of the capacity for the existing container terminal. Therefore, it is necessary to begin construction of a new container terminal and reconstruction and extension of the current container terminal. The extension is in line with the estimated growth of traffic as well as the exploitation of present and future terminal capacities. New projects and potential investments are important steps for the development of the Port of Koper, enhancing its performance and increasing its market share. The figure below (Figure 3) shows on the right the enlargement plan of the Port of Koper where a new pier 3 is foreseen as an additional container terminal, while the existing container terminal shall be extended to accommodate one more berth (berth 7D) [4]; on the left side a large container vessel berthed at the container terminal (berth 7C) is pictured. Because of the limited channel depth, the maximum draught for such vessels is 11.6 m.

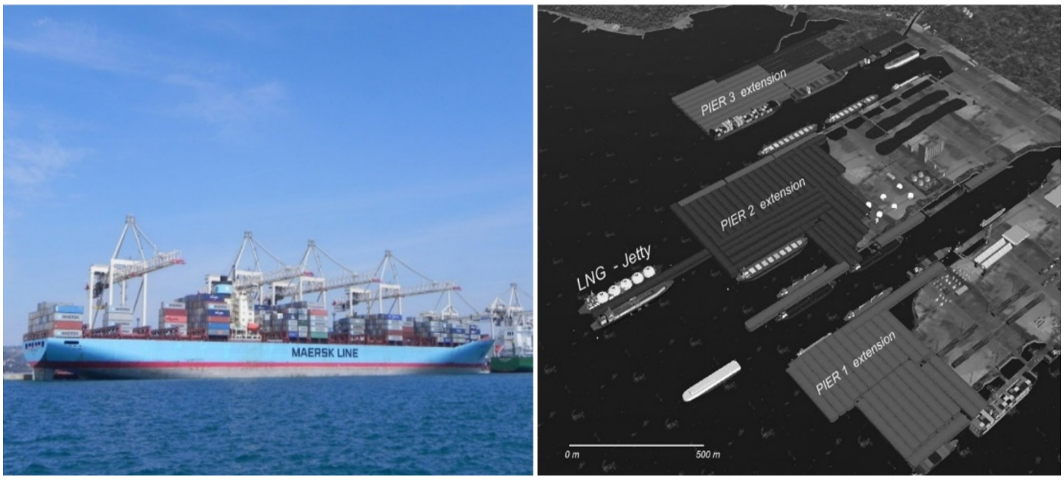

Figure 3 **A container vessel on limited draught alongside the existing container terminal, and the extended container terminal**
Slika 3 **Kontejnerski brod na ograničenom gazu vezan uz postojeći kontejnerski terminal i predviđeni produženi kontejnerski terminal**

Deterministic and semi-probabilistic methods for designing a channel were necessary for the Port of Koper. The minimum width and shape of the channel must be appropriate for safe calling and departure of characteristic container vessels presented at wind conditions up to 5 knots. As a result of the extension of pier 1 the entrance into Basin 1 will narrow, which can affect the safety of approach for the largest cruisers (LOA up to 347 m, draught 14.0 m) calling at berths 1 and 2. The extended plan with a fully loaded berth is presented in Figure 3. The main particulars of the analysed vessel are presented in Table 2.

Table 2 **Main particulars of the studied container vessel**
Tablica 2 **Glavne značajke analiziranog broda**

PILOT CARD					
Ship name	Container ship 4 (Dis.132540t) TRANSAS 2.31.32.0 *			Date	14.09.2011
IMO Number	N/A	Call Sign	N/A	Year built	N/A
Load Condition	Full load				
Displacement	132540 tones		Draft forward	14 m / 46 ft 0 in	
Deadweight	104696 tonnes		Draft forward extreme	14 m / 46 ft 0 in	
Capacity			Draft after	14 m / 46 ft 0 in	
Air draft	60.65 m / 199 ft 6 in		Draft after extreme	14 m / 46 ft 0 in	

Ship's Particulars			
Length overall	346.98 m	Type of bow	Bulbous
Breadth	42.8 m	Type of stern	Transom
Anchor Chain(Port)	14 shackles		
Anchor Chain(Starboard)	14 shackles		
Anchor Chain(Stern)	N/A shackles	(1 shackle =27.5 m / 15 fathoms)	

The initial step was to analyse aspects relative to the safety of an approaching cruiser while the extended container terminal is occupied by a large container vessel (Figure 4). Figure 5 - on the left, shows the approaching trajectory and measurement lines of safe margins, while on the right, the first attempt at designing an entrance to a channel dredged to -15 m (where nautical zero is 63 cm below geodetic zero) and the trajectory of a large container vessel entering Basin 1 are presented.

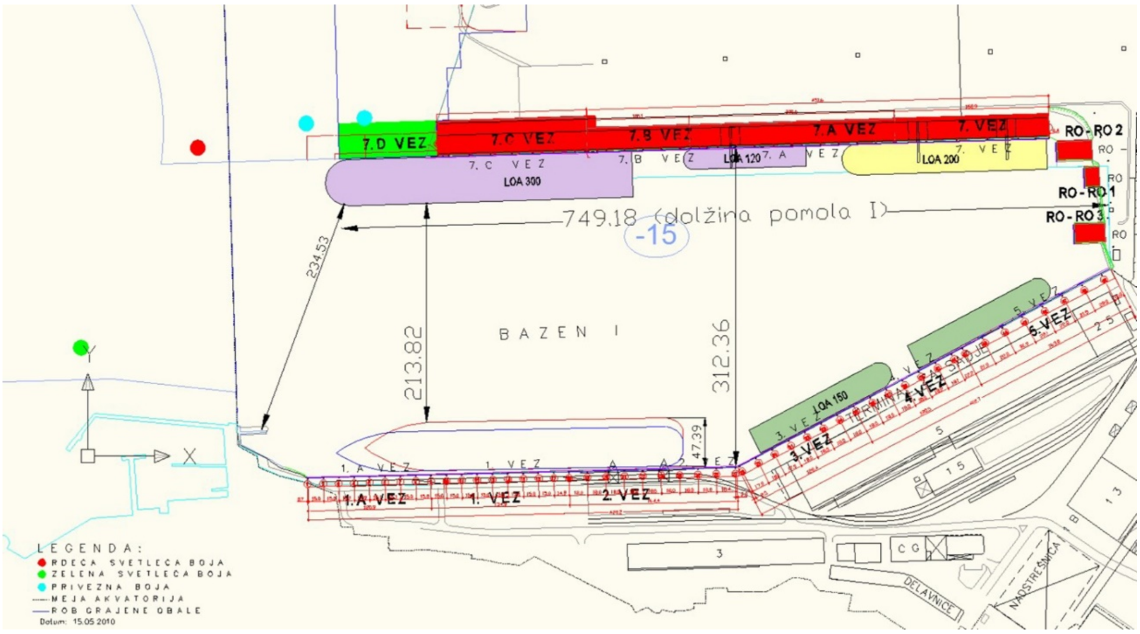

Figure 4 **Basin 1 - fully loaded berths; at the top the extended container terminal (berth 7D)**
Slika 4 **Bazen 1 – potpuno zauzeti vezovi; na vrhu planirano produženje kontejnerskog terminala (vez 7D)**

The designer hoped to make the channel as short as possible to minimise dredging costs, which is why the designed entrance was steep and narrow. Such an approach was also chosen because of the limited amount of landfill capacities. Even brief simulations using a full mission ship handling simulator (Transas NTPro 5000) [5] running with the previously chosen container vessel model clearly shows that such a channel is not an adequately safe approach for large container vessels. Based on those initial simulations further research work was ordered.

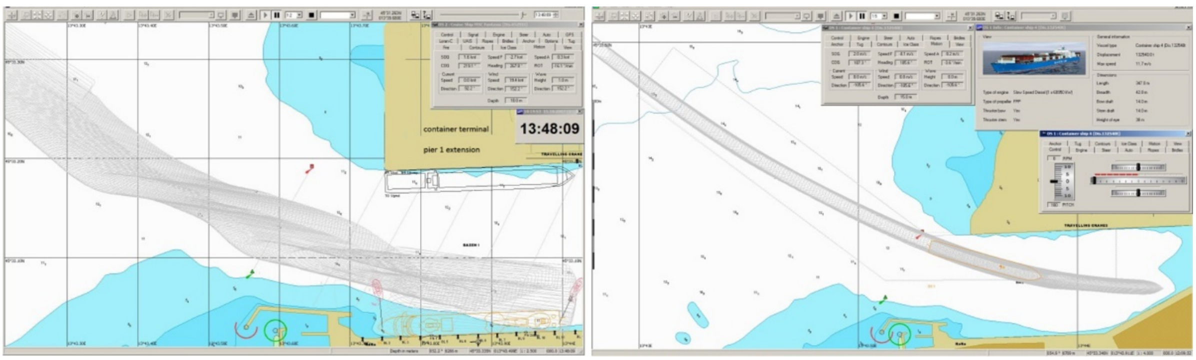

Figure 5 **Basin 1 – approaching trajectories of cruising vessel and container vessel**
Slika 5 **Bazen 1 – prilazne trajektorije putničkih i kontrjnerskih brodova**

3 Methodology for determining nominal channel width

The fundamental criterion for defining and dimensioning elements forming a navigation channel or a harbour basin is safety in manoeuvring and operations carried out within them [6]. The criteria for the geometric layout definition of the following navigation channels and harbour basins: fairways, harbour entrances, manoeuvring areas, anchorages, mooring areas, buoy systems, basins and quays, is based on knowing the spaces occupied by vessels, which depends on: a) the vessel and the factors affecting its movements, b) the water level and factors affecting its variability. The main references for defining those factors are ROM 3.1 “The Recommendations for the Design of the Maritime Configuration of Ports, Approach Channels and Harbour Basins” and PIANC “Permanent International Association of Navigation Congresses" [7]. The key parameters in approach channel design according to PIANC and ROM are alignment, traffic flow, depth, and width. They are all interrelated to a certain extent, especially depth and width. Table 3 lists factors included in the determination of the channel width such as: vessel manoeuvrability (oo), ship speed (a), prevailing cross wind (b), prevailing cross current (c), prevailing longitudinal current (d), significant wave height (e), aids to navigation (f), bottom surface (g), depth of waterway (h), cargo hazard level (i), width for bank clearance (j). The minimum channel width designed for the previously described container vessel turned out to be 162.64 meters for wind conditions 4-6 according to the Beaufort scale. As a particular (gusty) katabatic wind occurs in that area - manoeuvres should not be allowed at winds stronger than 5 according to the Beaufort scale. That limit was confirmed by the simulation (semi-probabilistic) method described in the next paragraph.

Table 3 **PIANC approach – factors determining minimum channel width**
Tablica 3 ***PIANC* pristup – faktori za određivanje minimalne širine plovidbenog kanala**

Basic manoeuvring lane width and additional widths		Factors for multiplying vessel beam (B=42.8)	
00	vessel manoeuvrability (poor)	1.8	
Additional Widths for Straight Channel Sections		wind <4^{0}Bf	wind 4-6^{0}Bf
a	ship speed (slow, less than 5 knots)	0.0	0.0
b	prevailing cross wind	0.1	0.5
c	prevailing cross current (low, 0.2 – 0.5 knots)	0.1	0.2
d	prevailing longitudinal current (low)	0.0	0.1
e	significant wave height	0.0	0.1
f	aids to navigation (moderate with poor visibility)	0.3	0.3
g	bottom surface (smooth and soft, < 1.5T)	0.1	0.1
h	depth of waterway (h/T) 1.25–1.5	0.4	0.4
i	cargo hazard level (low to medium)	0.2	0.2
j	width for bank clearance	0.1	0.1
Sum		**3.1**	**3.8**
The bottom width of the waterway (channel)		**132.68 m**	**162. 64 m**

3.1 Determining nominal channel width through the semi-probabilistic method

Channel geometric design in this procedure is mainly based on statistically analysing the areas swept by vessels in the different manoeuvres considered, which, should a sufficient number of manoeuvre repetitions be available, will enable the resulting design to be associated to the risk present in each case [8], [9]. This method was applied on the basis of real simulator studies. The simulations were performed in different meteorological conditions. Under every type of condition adequate numbers of trials were executed by human navigators. After the simulations, each trial was processed statistically in order to obtain the probability density function of ships' maximum distances from the centre of the waterway and the accident probability calculation in the given conditions. Finally, a safe water area was plotted with consideration of a previously established admissible risk level. The vessel can safely navigate only in such an area where each point satisfies the depth requirement. If such a case exists, the area is referred to as the safe navigable area. The vessel carrying out a manoeuvre in a navigable area sweeps a certain area determined by the subsequent positions of the vessel. The parameters of that area have a random character and depend on a number of factors. Therefore, for fairways and harbour entrances the navigational safety condition can be transformed to this form [10]:

$$D_m(t) \geq d^s_{ijkm} \tag{1}$$

where:

$D_m(t)$	– breadth of the navigable area at the *m-th* point of the fairway at the moment *t*, for which the safe depth condition is satisfied: $h(x, y, t)$ $T(x, y, t) + (x, y, t)$;
d^s_{ijkm}	– breadth of the safe manoeuvring area at the *m-th* point of the fairway for the *i-th* vessel, performing the j-th manoeuvre in *k-th* navigational conditions.
$h(x, y, t)$	– area depth at a point with the coordinates (*x, y*) at the moment *t*,
$T(x, y, t)$	– vessel's draught at a point with the coordinates (*x, y*) at the moment *t*,
$\Delta(x, y, t)$	– under-keel clearance at a point with the coordinates (*x, y*) at the moment *t*.

The breadth of a safe manoeuvring area is a function of the swept path breadth:

$$d^s_{ijkm} = f(d_{ijkm}) \tag{2}$$

where:

d_{ijkm} – swept path of the *i*-th vessel performing the *j*-th manoeuvre in the *k*-th navigational conditions for the *m*-th point of the waterway.

3.2 Simulations and results for the Port of Koper

First it was necessary to build the planned, enlarged port area based on precise bathymetry. The sailing area was created using Transas application Model Wizard [11]. Highly precise bathymetry (Figure 6) (spatial resolution 0.5m x 0.5m) was inserted and the projected manoeuvring area was created. The designed channel layout using the Model Wizard software is shown in Figure 6 – on the right. Figure 7 is a screenshot from the ship handling simulator NTPro5000 instructor station showing a highly precise depth sounding and sailing channel. The real time simulation interactive method with captains, pilots and navigational inspectors engaged in ship manoeuvring trials was applied. This method is assumed to be the most reliable for these kinds of research studies [10]**.** Forty-four simulations were executed in various metocean conditions, while trajectories were processed according to the model previously described. The resulting safe waterway area at a 95% confidence level is presented by Figure 8 ("*dark" area*). Such a confidence level is used most frequently for the design of waterways, whereas in the conditions that are more critical a 99% confidence level may be considered. In port basins, however, the ship's speed is slow enough to significantly reduce the consequences of accidents, which explains the tolerance of 95% as a starting point for more serious considerations and risk analyses.

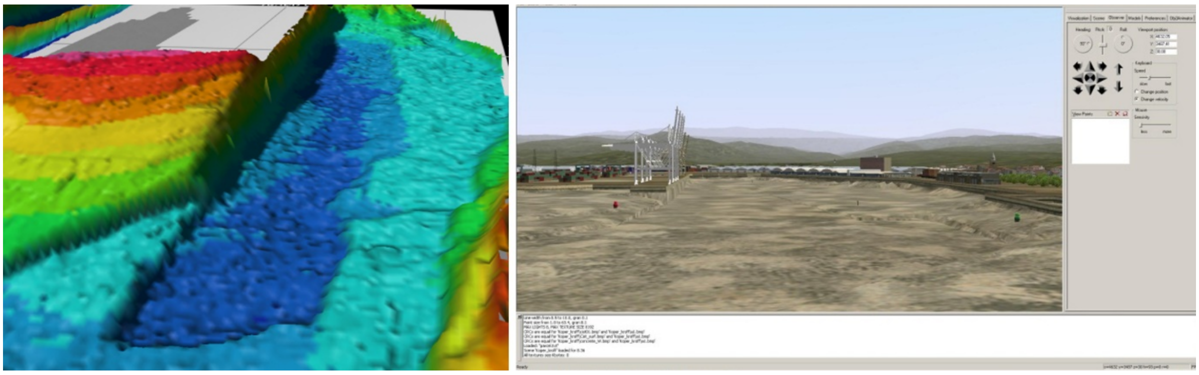

Figure 6 **Existing channel and modified channel created with Transas Model Wizzard tool**
Slika 6 **Postojeći kanal i modificirani kanal kreiran pomoću *Transas Model Wizzard* aplikacije**

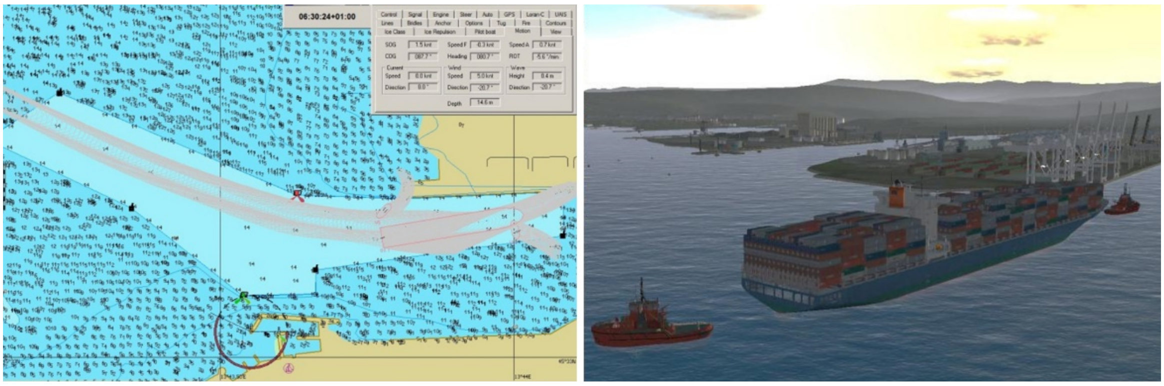

Figure 7 **Fully loaded container vessel (111,626 DWT) approaching terminal with assistance provided by pilot and two tugs – wind 5 knots from 060°**
Slika 7 **Potpuno natovaren kontejnerski brod (111.626 DWT) u prilazu terminalu sa asistencijom pilota i tegljača – vjetar 5 čvorova iz smjera 060°**

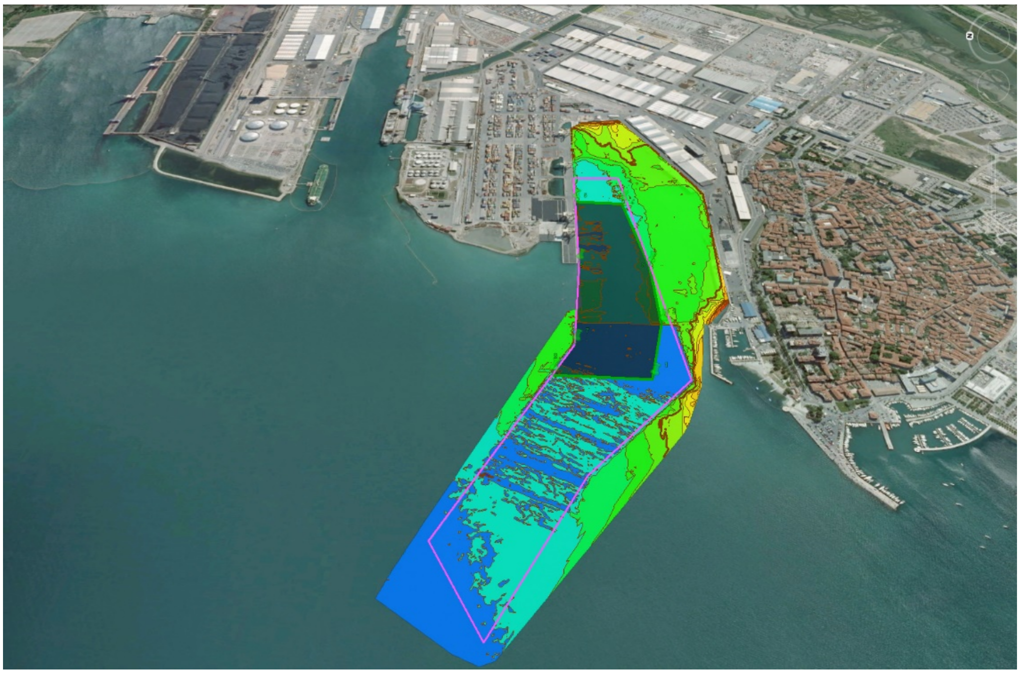

Figure 8 **Final layout – the "dark" area shows the minimum required width based on statistical analyses and a 95% confidence level based on 46 performed manoeuvres using a ship handling simulator set at various metocean conditions.**
Slika 8 **Konačni plan – tamno područje prikazuje minimalnu potrebnu širinu plovidbenog kanala temeljenu na statističkoj analizi provedenih 46 manevriranja brodova na nautičkom simulatoru**

4 Bottom wash issue

Among the many environmental issues concerning transport, one that seems to be largely overlooked is that of re-sedimentation, the effect of maritime vessels on the sea bottom - particularly, of course, in and near ports. The Gulf of Trieste is a semi-enclosed gulf in the north-eastern part of the Adriatic Sea [12], a shallow water area with an average depth of 16 m and a maximum depth of 25 m [13]. This shallow area is subject to special pollution consideration related to bottom wash phenomena. There is a high mercury concentration (*In the town of Idrija, Slovenia, the world's second largest mercury mine was active for 500 years and an estimated 37,000 tons of mercury has in consequence dispersed throughout the environment*) in the subaquatic sediment which rises into the sea column while ships are manoeuvring. This sediment cloud (smaller particles) is then moved by currents for several hours before re-sedimenting, which has a deleterious effect on the aquatic food chain. The process of bottom wash is basically a function of the size, type and speed of propeller, vessel speed, sub-propeller clearance and sediment conditions [14]. It is obvious that the process is dynamic; continuously changing vessel positions result in variable bathymetry and vessel/tug propulsion. This process can be simulated and compared with actual manoeuvring results where telegraph recording data is collected together with vessel dynamics.

4.1 Difference in bottom velocity streams between existing and larger container ships in the Port of Koper

As a vessel moves, the propeller produces an underwater jet of water. This turbulent jet is known as propeller wash and when it reaches the sea floor this effect is known as bottom wash. If this jet reaches the bottom, it can contribute to re-suspension or movement of bottom particles. Velocity distribution behind the propeller, for fully developed turbulent flow [15], is:

$$\frac{v_x}{v_0} = \frac{1}{2\xi} exp\left(1 - \frac{\rho^2}{2\xi^2}\right) \quad \left(\xi > \frac{1}{2}\right) \tag{3}$$

where

$$\xi \equiv \frac{C_1 X}{D_0} \quad \rho \equiv \frac{r}{D_0} \quad (r^r = z^2 + y^2) \tag{4}$$

and v_0 is initial velocity, D_0 propeller diameter, C_1 empirical constant and *x, y, z* are coordinates. The maximal velocity at a given ρ is obtained from the condition

$$\frac{d}{d\xi}\left(\frac{v_x}{v_0}\right) = -\frac{\xi^2 - \rho^2}{2\xi^2} exp\left(-\frac{\rho^2}{2\xi^2}\right) = 0 \tag{5}$$

so

$$\xi = \rho$$

and maximal velocity is

$$\frac{v_{x,max}}{v_0} = \frac{1}{2\rho} exp\left(-\frac{1}{2}\right) \tag{6}$$

At the bottom we have $\rho = \frac{h}{D_0}$ therefore

$$\frac{v_{b,max}}{v_0} = \frac{e^{-1/2}}{2h/D_0} \approx \frac{0.303}{h/D_0} \tag{7}$$

In Propeller Wash Study [14] the maximal bottom velocity is given by

$$\frac{v_{b,max}}{v_0} = \frac{\alpha}{h/D_0} \tag{8}$$

where α is 0.22 for open propellers and 0.3 for ducted propellers.

The simulated berthing procedure described in Figure 7 was analysed for the purpose of bottom wash calculation. Ship position, dynamics and tug forces were recorded with a time resolution of one second [16]. Data were stored and used for the bottom wash model where velocity streams are calculated for the sea bottom level.

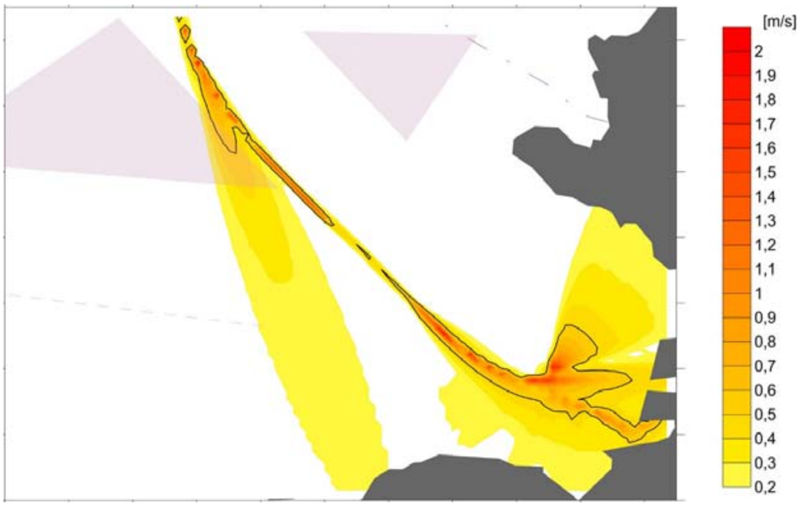

Figure 9 **Bottom wash - maximal bottom velocity (depth between 15 and 22 m)**
Slika 9 **Ispiranje morskog dna – najveće brzine strujanja (dubina mora između 15 i 22 m)**

Figure 9 shows propeller jet streams at the sea bottom for the departing manoeuvre of the analysed container carrier added by two tugboats. Wherever bottom velocity streams exceed 0.5 m/s (marked with black line contour) some re-sedimentation is expected. Further modelling must be done to calculate the total amount of sediment transport divided further into bed-load, suspended-load and wash load, analysed separately for approaching and departure manoeuvres.

At any rate, the next two figures (Figure 10, left and right) demonstrate that there will be no major increase of re-sedimentation for large container vessels calling at the Port of Koper. Installation power of the main engine will increase by 10%, but when analysing bottom wash at zero speed (when the vessel is on stop and start to accelerate, maximum wash is expected) with telegraph command ordered to "*Slow Ahead*", propulsion power is equal to 2,803 kW for larger container carrier compared with 2,545 kW for the existing vessel. The main vessel particulars and propulsion ratings are listed in Table 4.

Table 4 **The main hull and propulsion particulars**
Tablica 4 **Osnovne dimenzije brodskog trupa i značajke propulzije**

	Studied Container Ship	*Existing Container Ship (Figure 2)*
Displacement	132,540 t	120,000 t (estimated)
Engine power	60,950 kW	54,853 kW
Service speed	22.8 kt	25.0 kt
Length o.a.	346.98 m	318.20 m
Breadth m.	42.80 m	42.80 m
Draught	14.00 m	14.00 m (limited to 11.6 m)

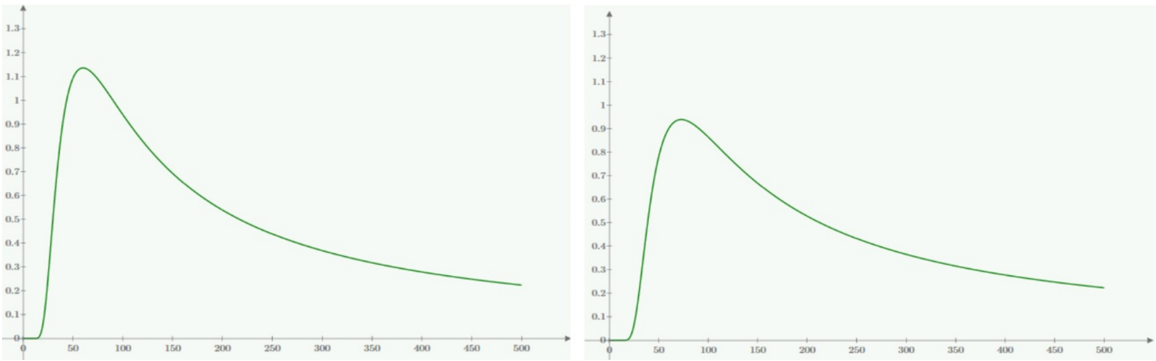

Figure 10 **Bottom velocity streams (m/s) for planned (left side) and existing container ship (graph created with MathCad sw.)**
Slika 10 **Brzina strujanja na morskom dnu (m/s) za planirani (lijeva strana) i trenutačni kontejnerski brod (graf napravljen korištenjem *MathCad* aplikacije)**

Figure 10 shows the bottom velocity streams in the axial direction vessel where the shaft line is under the sea surface -9.9 m and 11.4 m above the sea bottom while the existing vessel has 2.4 meters smaller draught (limited vessel draught of 11.6 m comparing to 14 m draught after the dredging). The studied sea depth is 21.3 m. The main difference in bottom velocity streams between the existing and the larger container ships is mostly due to the increase of the vessel draught. Again such an increase is minor, maximum speed at bottom will only increase by approximately 0.2 m/s (1.13 m/s compared to 0.93 m/s).

4.2 Re-sedimentation

Due to a combination of the force of gravity and the movement of the fluid containing the sediment, three types of flow and sediment transport may be expected: bad-load, sediment-load and wash load. The concentration profile of suspended sediment and mode of transport is defined by the non-dimensional Rouse number, which is the ratio between sediment fall velocity and the upwards velocity on the grain:

$$\mathrm{Ro} \equiv \frac{w_s}{\kappa u_*} \tag{9}$$

w_s - fall velocity

κ - von Karman constant (=0.4)

u_* - shear velocity

Based on Rouse number, 5 different modes of sediment transport are given and described in Table 5 [17]:

Table 5 **Rouse number vs. Transport Mode**
Tablica 5 **Rousov broj u relaciji s načinom transporta sedimenta**

Rouse Number	Mode of Transport
7.5 < Ro	Movement initiation
2.5 < Ro < 7.5	Bed load
1.2 < Ro < 2.5	50% Suspended load
0.8 < Ro < 1.2	100 % Suspended load
Ro <0.8	Wash load

Sedimentation rate or velocity depends on water viscosity and density of sediment:

$$w_s = \frac{1}{28}\left(\sqrt{\left(\frac{36\nu}{d}\right)^2 + 7.5(s-1)gd} - \frac{36\nu}{d}\right) \tag{10}$$

ν – water viscosity

d – particle diameter

g – gravity

$s = \frac{\rho_s}{\rho}$ - relative density of the particle

Share velocity is defined by the relation:

$$u_* = \sqrt{\frac{\tau_b}{\rho}} \tag{11}$$

Where share stress is equal:

$$\tau_b = \rho C_f u^2 \tag{12}$$

C_f - stress factor

$$C_f = \frac{g}{\left(18\log\frac{12h}{k_s}\right)^2} \tag{13}$$

h – water depth

k_s - roughness, approximately: $k_s \approx 100d$

Combining equations (12) to (15) with (11) and considering; $\nu = 10^{-6}\,\mathrm{m^2/s}$, $\rho = 1.050\,\mathrm{kg/m^3}$, $\rho_s = 2650\,\mathrm{kg/m^3}$ and $g = 9{,}81\,\mathrm{m/s^2}$, flowing fluid speed can be defined as:

$$U = f(\mathrm{Ro,h,d}) \tag{14}$$

where Figure 11 shows mode transport boundaries for fine sediments.

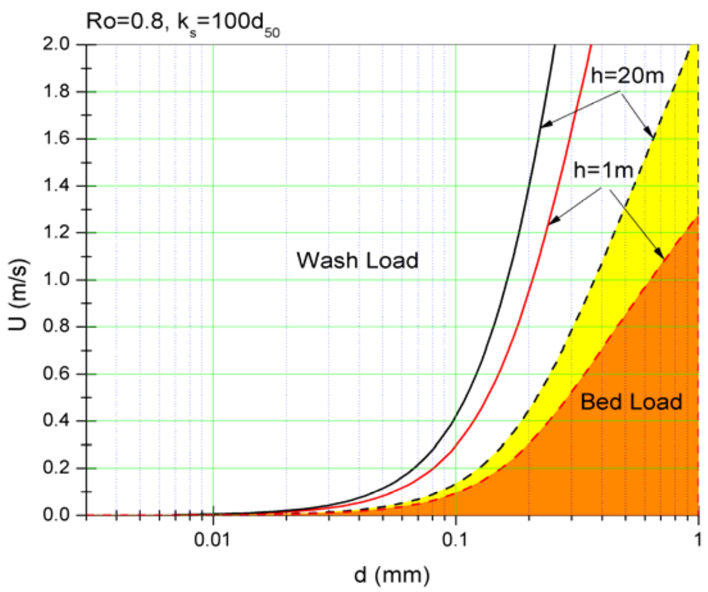

Figure 11 **Flowing velocity speed vs. particle size (graph created with Origin sw.)**
Slika 11 **Brzina strujanja i tip resuspenzije u relaciji s veličinom čestica (graf napravljen korištenjem *Origin* aplikacije)**

Figure 12 describes the modelling approach using Excel software, where 18.1 tons of total sediment transport is calculated for the departure of a large container vessel sailing from Basin 1 up to the position of 45.62553° N, 13.54447° E, and 15.0 tons of transported sediment is calculated for an existing container vessel.

INPUT				
water	density	ρ	1025	kg/m^3
	viscosity	ν	0.000001	m^2/s
flow	speed	U	1.13	m/s
	depth	h	12	m
sediment	density	ρ	2650	kg/m^3
	diameter	d50	0.007	mm
	grain roughness	kr	0.042	mm
	ripple height (reference height)	ks	68	mm
gravity	acceleration	g	9.81	m/s^2

SOLUTION BED-LOAD				
Relative density	s	2.59		
Dimensionles diameter	d*	0.17		
Critical mobility parameter	θ*	1.374		
Critical shear speed	uc*	0.012	m/s	
Critical shear stress	τ*	0.153	N/m^2	
Friction coefficient	f	0.005		
Bottom shear stress	τ	3.56	N/m^2	
Effective friction coefficient	f'	0.001		
Effective botom shear stress	τx	0.93	N/m^2	
dimensionles shear stress	T	5.04		
Thickness of bed-load leyer	δ	0.001	mm	
max volumetric concentration	c0	0.65		
Bed load concentration	cb	3.373	m^3/m^3	51.05002
bed load transport (van Rijn)	qb,c	1.39E-07	m^3/m/s	

SOLUTION SUSPENDED-LOAD			
von Karman constant	κ	0.4	
Fall velocity	ω	0.00003	m/s
Fricton velocity	u*	0.059	m/s
	A	0.006	
Rouse number	z*	0.001	Rerr %
Einstein integral	I1	38.47	0.000
Einstein integral	I2	-37.44	0.000
sediment transport (Bijker)	qS	0.000007	m^3/m/s

Mode of sediment transport (based on Rouse Number)			
Wash Load			
TOTAL SEDIMENT TRANSPORT			
Total transport (Bijker)	qT	0.000007	m^3/m/s
ratio bed/suspended	Q	51.0	m^3/m/s
reference concentration (van Rijn)	ca	0.0000	m^3/m^3
sediment concentration		0.078	kg/m^3
estimated suspension height	hs	3	m
erossion	E	0.234	kg/m^2
area	A	0.084	km^2
Total sediment erosion	S	18.1	ton
Estimated fall time		29.39	h

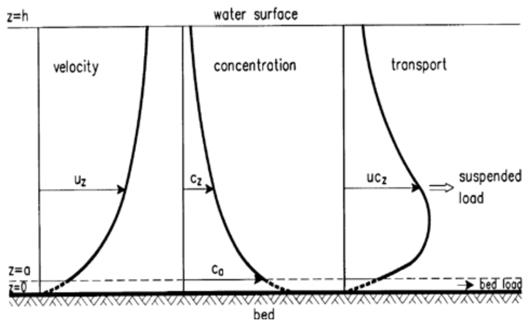

Figure 12 **Screenshot of Excel program implementing Sediment Transport Model**
Slika 12 **Snimak ekrana iz Excel programa za modeliranje transporta sedimenta**

5 Conclusion

The Port of Koper intends to increase cargo operations from the current 16-18 million tons to 30-40 million tons in five to ten years, doubling the cargo capacity, more or less doubling the potential number of vessels calling. Containers continue to increase their share of shipping visits; Ro-Ro’s, another 'intrusive' vessel type, continue to accommodate an increasing traffic in automobiles; and passenger vessels are growing in size, while ports strive to expand to accommodate this increase.

Further development of the Port of Koper will depend on the rate of investment. One of the most important needs is deepening the entrance into Basin 1, because this will permit the arrival of larger container ships to the existing container terminal. According to one estimation, some 80,000 - 100,000 TEUs are lost each year because the container ships of 7,500 TEUs and over are not able to enter the Port of Koper. Therefore, it is necessary to provide a sufficient draught (15 m) and a longer berth. The port's long-term strategy includes the plan to build a third pier with the capacity of 1 mill. TEUs. Such improvements requiring large investments are necessary for the port to maintain competitive, to retain or increase its market share.

For each alteration at the precise point where the land meets the sea at a port, a number of considerations are likely to arise. The two concerns discussed here are safety and potential environmental harm. Not for the first time, we have demonstrated that ship handling simulators can help reconstruct real domain thrust conditions in a variety of circumstances. A number of careful simulations were necessary to determine the best - that is, the safest and the most cost-efficient means for expanding a berth and channel, the extent of dredging required, and the optimal approach for large vessels.

The environmental factor covered here is one that does not seem to attract much research as of yet – the effect of vessel manoeuvres in and near ports in regard to bottom wash and re-sedimentation. The effects of current shipping trends on the seabed must be understood with a long-term view to eliminating environmental damage.

It is thus far unclear whether the maritime transport business will reach a period of something like stasis, when ships are of optimal size for each type of cargo, when ports have reached optimal or maximal capacity, and, perhaps most important of all, when all negative effects on the environment have been eliminated. Until then, perhaps every change must attract careful scientific scrutiny, so that the potential harmful effects of growth in wealth are mitigated.

The result of interactive work with pilots led to determining the berthing tactics that are less intrusive; pilots, for instance, will use more tug force and rely less upon vessel propulsion. But, naturally, this is a first step, as the issue must be known to masters, lest they, after the disembarkation of pilots, tend toward a less controlled acceleration upon leaving the port. A natural suggestion arises that the Port of Koper be known as an environmentally aware port, which yet does not interfere with the quotidian machinations of the land-sea nexus.

Note

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