ČEDOMIR IVAKOVIĆ, D.Sc.
JASNA JURUM, D.Sc.
Faculty of Traffic and Transport Engineering
Fakultet prometnih znanosti
Vukelićeva 4, Zagreb

Tehnologija i organizacija prometa -
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MODEL FOR DETERMINING THE RIVER HARBOURS CAPACITY

SAŽETAK

MODEL ZA ODREĐIVANJE KAPACITETA RIJEČNIH PRISTANIŠTA

U radu je obrađen model za određivanje kapaciteta riječnih pristaništa. Polazne temelje modela određuje veličina akvatorija i mogućnosti postavljanja pristane u bazenu pristaništa kao i njihov broj. Na broj pristana i statički i dinamički kapacitet pristaništa-luke utječu veličine plovnih sredstava planiranih za uplovljavanje. U razradbu su uzete potisnice Europa 1 i 2 i Dunavske teglenice temeljem kojih određujemo dužinu operativne obale koja je vezana uz dužinu željezničkih kolosijeka, cestovnih prometnica i odlagališta tereta.

1. INTRODUCTION

In the European transport flows the river traffic is becoming increasingly important with the opening of the Danube-Rhine-Main channel. By arriving to the banks of the Danube, the Republic of Croatia has the possibility to build the channel Danube-Sava and to include the Croatian fairways of the rivers Drava, Sava, and Kupa into the European fairway network. Apart from the fairways, the basis of a river transport subsystem are the harbours as starting and ending points in the cargo and passenger transport. In harbours with adequate infrastructure there are three transport branches which are: river, road and railway transport. In planning, design and construction all the technical and organisational elements of each of the three branches need to be taken into consideration and co-ordinated in order to avoid interference and achieve smooth operation of the harbour. The size and the capacity of the harbour depend on the traffic requirements and in- and outgoing traffic flows. The harbour aquatorium plays an important part in determining the traffic-technological sizes and number of quays, lengths of railway tracks, roads, lengths of crane tracks, handling and storing areas, warehouses, and other harbour facilities. Large and mid-size harbours today are designed on terminal operation principles, with areas and cargo handling equipment specialised according to types, size, and conditions of cargo. In small harbours the areas and facilities are versatile unless the cargo requires special procedures and equipment such as storing and handling of hazardous substances or refrigerator containers.

2. RIVER HARBOUR AQUATORIUM AND QUAYS

Talking about river harbour aquatorium means the selection of the location closely linked with the traffic flows and the harbour gravitation region. The location of the harbour must be carefully considered to avoid failures that might arise as limiting factors in the future operation of the harbour.

In planning, design and construction of the harbours and terminals, the selection of the location is of special significance since it influences not only the construction expenses but also the operation results.[1] If the quays are located along the river banks, they are considered ship port, and if the port has its own water area, i.e. a dock basin that meets the technical and regarding capacity the exploitation criteria that place it among larger structures, then it is called a river harbour. There are different descriptions and definitions here, so that all quays on rivers and lakes are called ports by some authors, regardless of their capacity and size, and all quays on sea - harbours. Others consider harbours to be all structures that have aquatorium separated from the open sea or river flow, and ports are smaller cargo handling structures located by the sea coast or directly by the river flow. The most important thing is that all harbour i.e. dock structures have to meet the criterion of transport and cargo handling-storing function in coping with all the requirements in cargo flow into and out of the harbour or port. In order to program the larger ports i.e. river harbours, the criteria are more numerous and linked with macro- and micro-location, climatic conditions, level of water inflow, topographical and hydrographic conditions, ground conditions and others. These include wind, precipitation, visibility (fog), heat, dampness, then configuration, water depth, landslides and the existing structures.

The ratio of the water and land areas influences the aquatorium of the port - harbour, and it depends on the purpose of the structure, the transport branches that have to be co-ordinated in it, the facilities i.e. the harbour terminals. According to J. Kirinčić[2] the ratio of the water and land areas is between 0.5 - 3.0 and the ratio of the bank length and the water area varies and can be up to 100 m/ha.

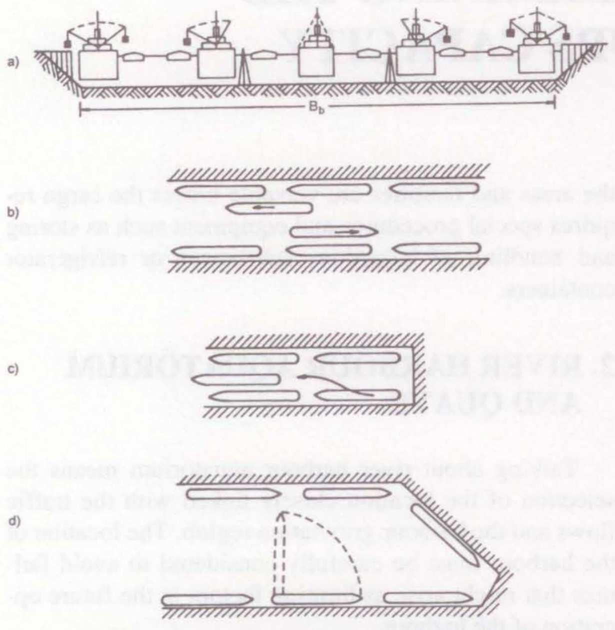

Figure 1 - **Aquatorium of the port - harbour**

Thus the total area i.e. the harbour aquatorium consists of the water area of the access canals, basins and quays. The width and the depth of the canal depends on the size of the ships, barges or push tows planned for navigation on certain fairways, that in turn depends on its category and the allowed draught of the vessel, as well as on the number of navigation directions in and out of the port-harbour basin. The dock basins can have various purposes for turning of vessels and operative purposes (quays and cargo handling). The basin water area must suffice to allow smooth docking, turning, and vessel passing manoeuvres. The position, size, and number of quays in the aquatorium depends primarily on the form and size of the basin, purpose of ships and port-harbour (general cargo, bulk, liquids, containers and others) and the quantity of cargo that is going to be handled daily, monthly or annually.

3. SIZES OF RIVER VESSELS AND THEIR INFLUENCE ON THE NUMBER AND SIZE OF HARBOURS

The size of river vessels on a fairway depends on the fairway category i.e. its navigability regarding depth, width and obstacles on the fairway (transmission lines, bridges, and others). The Commission for the inland fairways of the European Association has defined six classes, determined by the ton capacity of ships:

1st class	250-400 tons	min.depth 1.2-1.5 m
2nd class	400-600 tons	min.depth 1.2-1.8 m
3rd class	650-1000 tons	min.depth 1.5-2.35 m
4th class	1000-1500 tons	min.depth 2.35-2.65 m
5th class	1500-3000 tons	min.depth 2.65-3.50 m
6th class	over 3000 tons	min.depth 3.5 and above

Apart from these minimums the fairway category is also determined by a range of other elements, such as whether the fairway is a natural, engineered or canalised one, whether it has locks etc. The most significant fairways on the rivers Sava, Drava and Danube in the Republic of Croatia range from the 4th class - the Danube and the Drava up to Osijek (14 km), the Sava 3rd class up to Jasenovac, 2nd class up to Sisak, and 1st class from Sisak to Zagreb. Upgrading would require construction of locks on the Drava and the Sava rivers as well as river engineering by eliminating shallow waters and turns.

In river traffic there are single vessels such as motorships, and trains of vessels, barges and push tows.

The pushing technology is a modern exploitation method on the European inland fairways, and its main elements are the push tugs and the push tows that are pushed in front, tied together elastically.

To determine the number and size of the quays i.e. the whole operative coast length, the basic parameter is the size and capacity of push tows and barges adequate for our fairways of the 4th and 2nd class.

Table 1 - **Vessel size and capacity for 4th and 2nd class fairways**

Fairway class	Relevant vessel	Vessel length/width (m)	Vessel capacity (t)	Vessel draught (m)
4th	motorship or 4th cl. Barge	80/9.5	1000 13500	2.0 2.5
4th	push tow E I	70/9.5	0 1000 1350 1500	0.4 2.0 2.5 2.8
	push tow E II	76.5/11.4	1500 1750 3000	2.0 2.5 3.5
2nd	2nd cl. barge	55/12	0 400 650	0.4 1.0 1.3

In Europe most widely used are push tows E I and E II, and the push tugs or tugs for barges are as small as possible at the same time having as much power and as great manoeuvring capabilities as possible.

The basic characteristics of the vessel are:

Capacity: 1500 t	length/width/draught	70/9.5/2.8 (m)
1350 t		70/9.5/2.5 (m)
1000 t		70/9.5/2.0 (m)
0 t		70/9.5/0.4 (m)

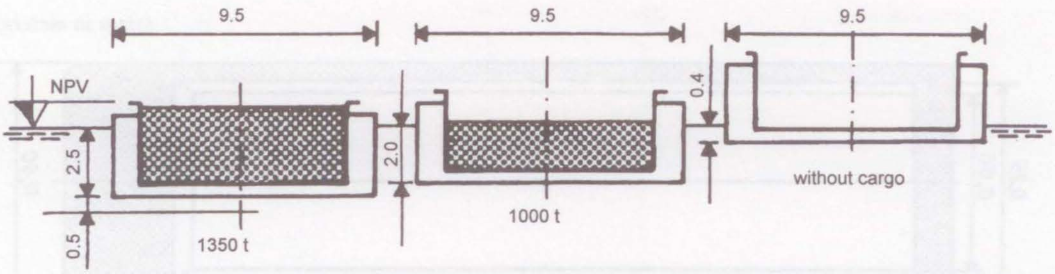

Figure 2 - **Push tow E I - Cross-section**

(sizes in meters)

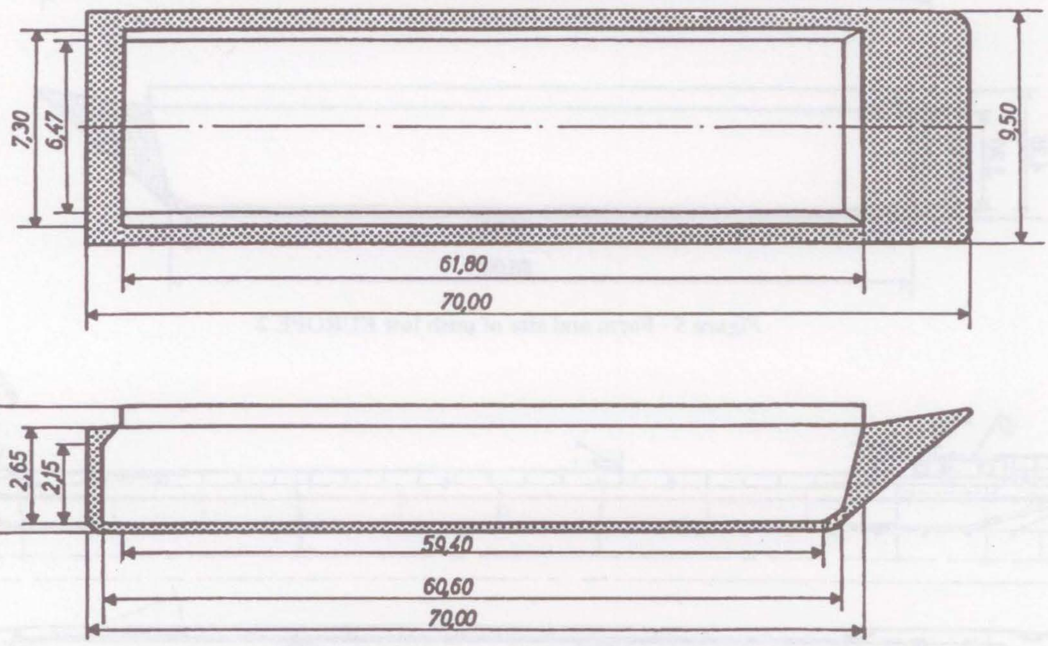

Figure 3 - **Form and sizes of push tow EUROPE 1 (dimensions in metres)**

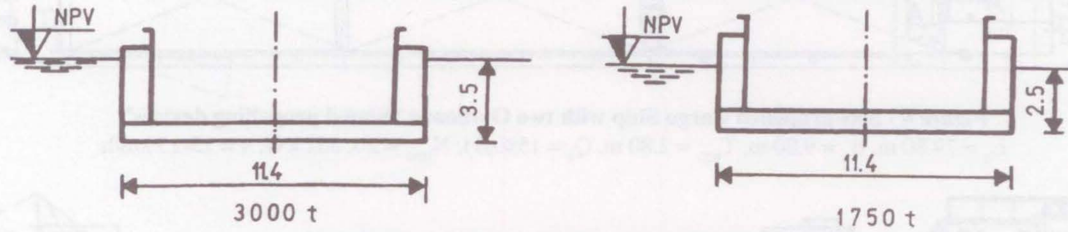

Figure 4 - **Push tow E 2 - Cross-section**

Another significant group of push tows is type EUROPE 2 which is bigger with capacity ranging from 1500 to 3000 t, and with a deeper draught affecting the usage on fairways and ports of the 2nd and 3rd class, and all the more in usage on the fairway Rhine-Main-Danube (mentioned in the ECE classification).

The basic characteristics of the vessel are:

Capacity:	3000 t length/width/draught	76.5/11.4/3.5 (m)
	1750 t	76.5/11.4/2.5 (m)
	1500 t	76.5/11.4/2.0 (m)

Apart from push tows the European navigable waterways accommodate also barges, push tugs, barges and single ships. Barge and push tug assemblies and tug-pushed dumb barges, as well as self-propelled cargo ships determine the number of quays for cargo-handling and the size of the operative harbour or port coastline.

The Danube barge has similar characteristics regarding size.

Since river traffic consists mainly of vessel trains and assemblies which can be tied to the barge or push tug side in a single or double tracks or in rows, their maximally allowed lengths and widths determine the required dimensions of the basin and the aquatorium. The port or the harbour being a complex system, a prerequisite for its smooth operation is linked to all the system elements that have to function in co-ordination, and in order to achieve this the capacity of each of the elements (quay,

(sizes in meters)

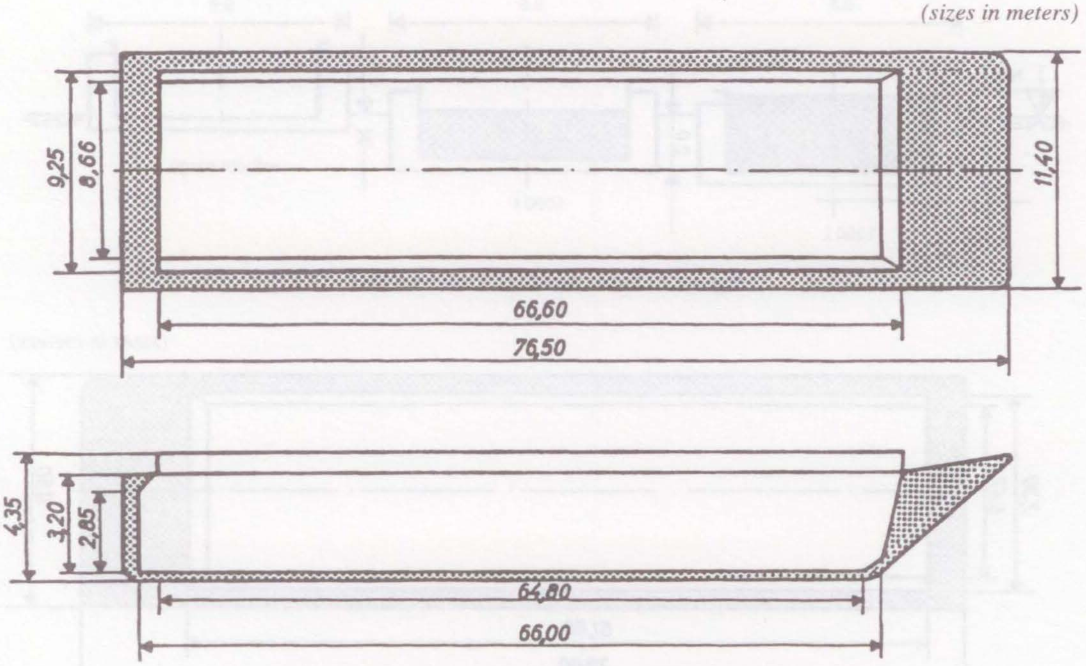

Figure 5 - **Form and size of push tow EUROPE 2**

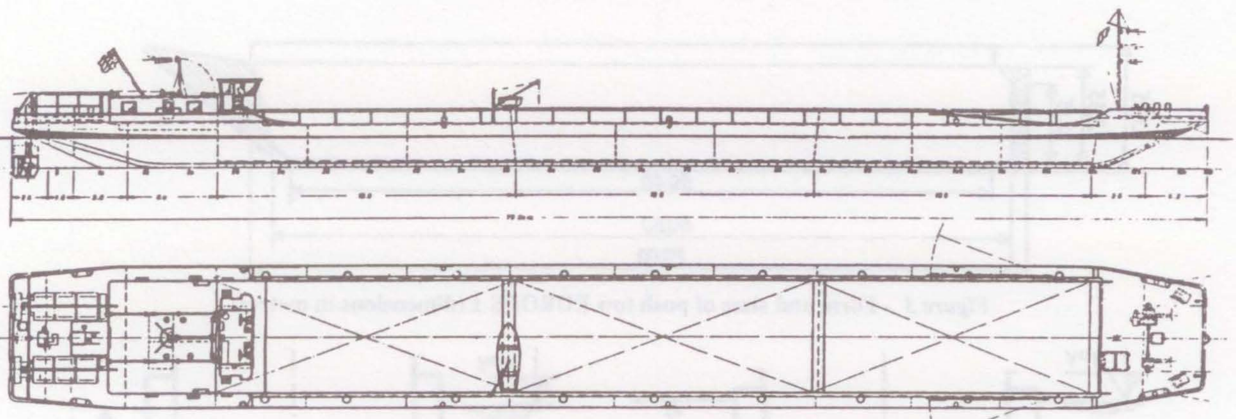

Figure 6 - **Self-propelled Cargo Ship with two Outboard "Shotel propelling devices"**
L_a = 79.80 m, B_a = 9.80 m, T_{km} = 2.80 m, Q_r = 1580,0 t, N_{inst} = 2 × 331 kW, v = 13-15 km/h

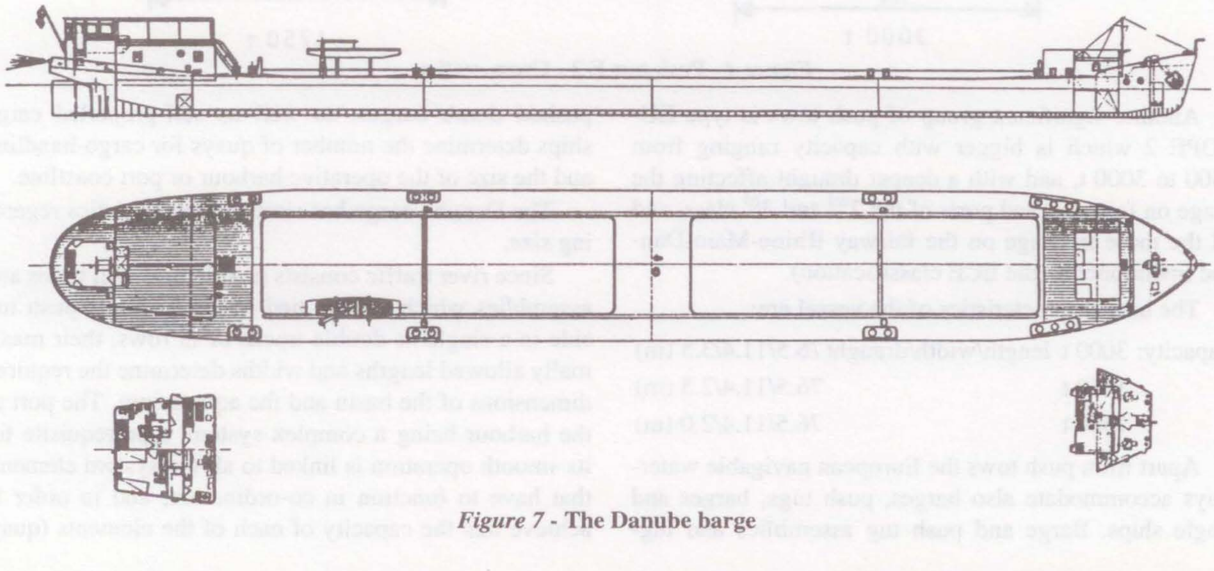

Figure 7 - **The Danube barge**

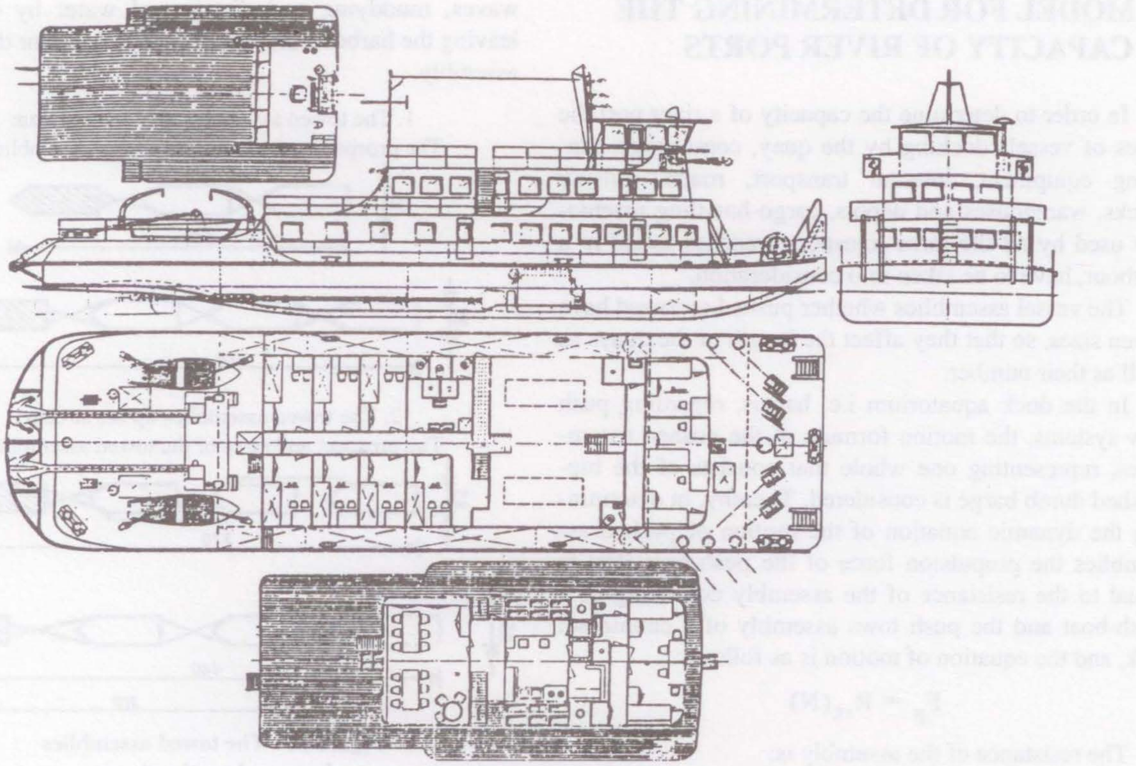

Figure 8 - **The Danube Motor Push tug**

$L_a = 35.50$ m, $B_a = 9.80$ m, $H_k = 2.55$ m, $T_{km} = 1.41$ m, $N_{inst} = 2 \times 363$ kW

terminal, storage and others) has to be equal or larger than the previous one, determined by the formula:

$$x_1 \leq x_2 \leq \ldots \leq x_n$$

Hereby the harbour capacity is in functional correlation with the throughput capacity of single elements of the harbour system and depends on the throughput capacity of the one element within the system which has the poorest dimensions.[3] Thus the throughput capacity of a port or a harbour means the total number of units that pass from one transport form or element (warehouse, storage) to another daily, monthly, or annually.

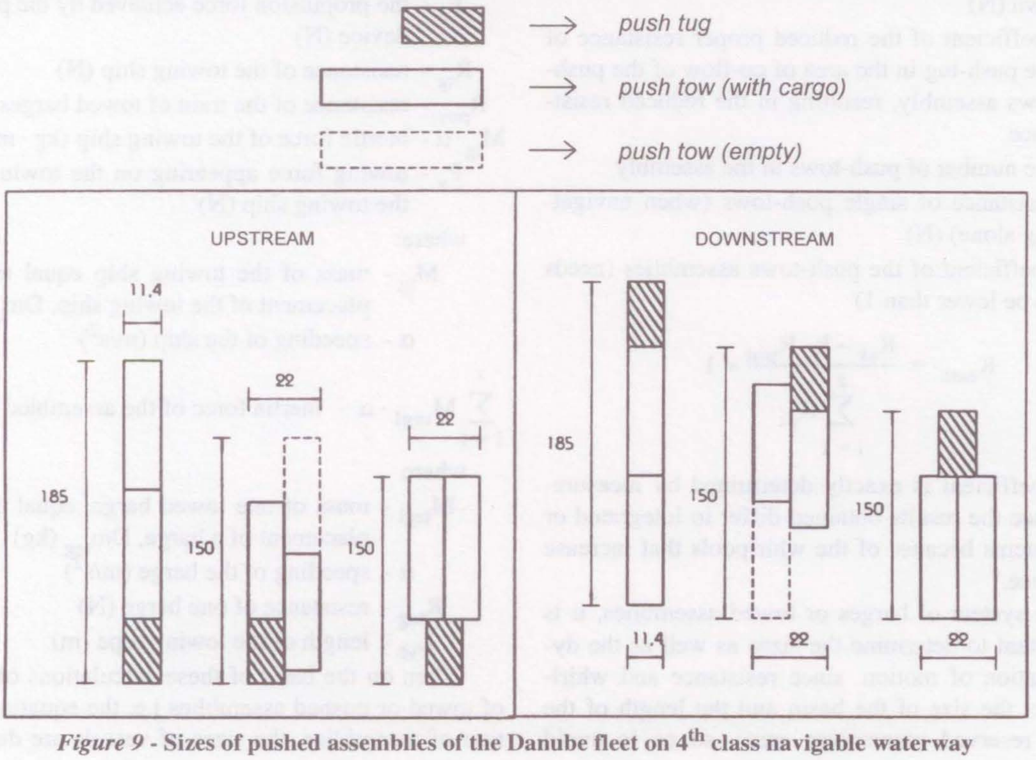

Figure 9 - **Sizes of pushed assemblies of the Danube fleet on 4th class navigable waterway**

4. MODEL FOR DETERMINING THE CAPACITY OF RIVER PORTS

In order to determine the capacity of a river port the sizes of vessels docking by the quay, coast cargo handling equipment, internal transport, roads, railway tracks, warehouses and depots, cargo-handling machinery used by all the three transport branches found in a harbour, have to be taken into consideration.

The vessel assemblies whether pushed or towed have given sizes, so that they affect the length of the quays as well as their number.

In the dock aquatorium i.e. basins, regarding push tow systems, the motion formula of the pushed assemblies, representing one whole that consists of the tug-pushed dumb barge is considered. Thereby, in determining the dynamic equation of the motion of pushed assemblies the propulsion force of the push-boat (Fp) is equal to the resistance of the assembly consisting of a push-boat and the push tows assembly of a certain set Rsk, and the equation of motion is as follows:

$$F_p = R_{sk}(N)$$

The resistance of the assembly is:

$$R_{sk} = k \cdot R_{pot.} + K_{sast.} \cdot \sum_{i=1}^{z} R_{pt}(N)$$

where

- R_{sk} - is the resistance of the assembly (tug-pushed dumb barge) (N)
- R_{pot} - the resistance of the push-boat navigating on its own (N)
- k - coefficient of the reduced proper resistance of the push-tug in the area of co-flow of the push-tows assembly, resulting in the reduced resistance
- z - the number of push-tows in the assembly
- R_{pt} - resistance of single push-tows (when navigating alone) (N)
- K_{sast} - coefficient of the push-tows assemblies (needs to be lower than 1)

$$K_{sast.} = \frac{R_{sk} - k \cdot R_{pot}}{\sum_{i=1}^{z} R_{pt}} < 1$$

This coefficient is exactly determined by measurements, since the results obtained differ in integrated or section systems because of the whirlpools that increase the resistance.[4]

For the system of barges or towed assemblies, it is also important to determine the sizes as well as the dynamic equation of motion, since resistance and whirlpools affect the size of the basin and the length of the quay, i.e. reserved manoeuvre areas, so as to avoid waves, muddying and dirtying of water by docking, leaving the harbour and turning of the barge or the whole assembly.

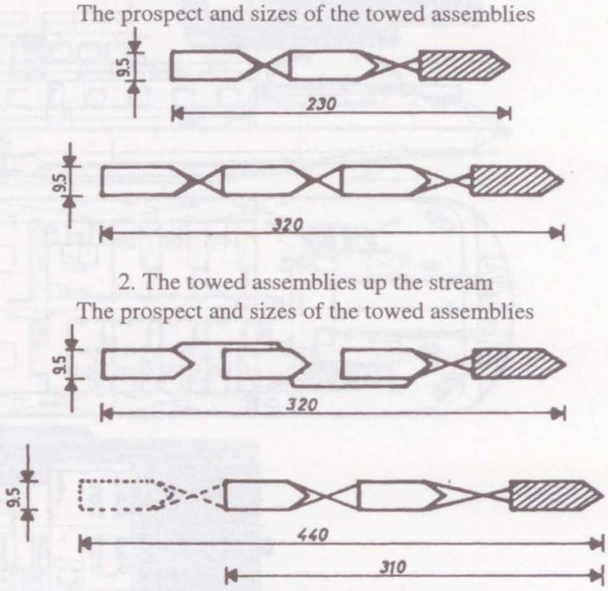

Figure 10 - The towed assemblies down and up the stream

The general dynamic equation of motion of the towed assemblies has the following formula:

$$F_p = R_{tg} + \underset{(P_v)}{R_{pov}} + M_{tg} \cdot \alpha + \sum_{i=1}^{z} M_{tegl} \cdot \alpha(N)$$

where

- F_p - the propulsion force achieved by the propulsion device (N)
- R_{tg} - resistance of the towing ship (N)
- R_{pov} - resistance of the train of towed barges (N)
- $M_{tg} \cdot \alpha$ - inertia force of the towing ship ($kg \cdot m/s^2$)
- P_v - towing force appearing on the towing rope of the towing ship (N)

where:

- M_{tg} - mass of the towing ship equal to the displacement of the towing ship, Dm_{tg} (kg)
- α - speeding of the ship (m/s^2)

$\sum_{i=1}^{z} M_{tegl} \cdot \alpha$ - inertia force of the assembled barges

where

- M_{tegl} - mass of one towed barge, equal to the displacement of a barge, Dm_{teg} (kg)
- α - speeding of the barge (m/s^2)
- R_{teg} - resistance of one barge (N)
- $L_{vč}$ - length of the towing rope (m)

When on the basis of these calculations of the sizes of towed or pushed assemblies i.e. the equations of motion of assemblies, the sizes of vessels are determined, then the length of the operative coastline and the number of quays depends on the length of railway tracks i.e. trains that deliver the cargo into the port (harbour). Therefore, the length of the train affecting the length of the operative coastline is calculated according to the formula:

$$L_v = N_v \cdot L_k + L_e(m)$$

where

N_v - number of cargo vans

L_k - length of the cargo van

L_e - length of the locomotive or the shunting engine

The length of the railway tracks ranges from 271 m, 372 m and 431 m which allows for 1, 2 or 3 quays along the operative coastline. The length of the railway tracks is related to the length of the roads, i.e. tracks and travel of the quayside cranes.[5]

Based on the obtained parameters we can calculate the throughput capacity of the quay "P_m" in tons according to the formula:

$$P_m = \frac{L_{mk} \cdot P_s \cdot n}{\gamma \cdot L_k \cdot \beta} \ (t)$$

while the throughput capacity of the quay "P_t" expressed in number of barges or push tows is calculated according to:

$$P_t = \frac{T_r \cdot n_k}{t_p + t_i + t_{ui}} \ \text{(barges, push tows)}$$

where

n_k - average number of barges or push tows per delivery

t_p - docking time of barges or push tows

t_i - time necessary for pulling of barges or push tows

t_{ui} - time necessary for cargo handling (unloading or loading)

β - interval coefficient between barges or push tows

Apart from these elements of ports harbours, the capacities of the depots, warehouses, cargo handling machinery and other facilities may be calculated.

The static capacity of the port or harbour depends on the number of quays, length of the depot, number of depot lanes, use factor of the depot lanes lengthways, length of the barge or push tow in metres, and the following formula is used:

$$N_k = \frac{n \cdot l \cdot y}{L_k}$$

where

N_k - number of barges or push tows that can dock along a quay

n - number of depot lanes by the quay

l - length of the lane for depositing the cargo

y - use factor of the lane lengthways

L_k - length of the barge or push tow in m

The dynamic capacity is the throughput capacity of the port - harbour, and is calculated according to the formula:

$$P_s = m \cdot P_n \ \text{(barge, push tow)}$$

where

P_s - throughput capacity, i.e. dynamic capacity of the port - harbour

m - planned number of barges, push tows at the quay

P_n - probability that during the operation of the port (t) "n" barges or push tows are determined

The probability is calculated according to the formula:

$$P_n(t) = e^{-\mu t} \cdot \left(\frac{\mu t}{n}\right)^n ; \ n = 0, 1, ...$$

where:

μ - the serving density (exit of barges, push tows from the serving system)

n - number of barges, push tows handled per hour

t - time necessary to handle "n" barges or push tows

These mathematical models have found their application in determining the size of the port and in planning its development, depending on the cargo and transport flows directed towards the port in delivery to and from the port.

5. CONCLUSION

The basic elements for determining the capacity include the aquatorium, depth of the navigable waterway, size of the vessels and the level of transport demand. By simulating various parameters and sizes of these basic elements, the operative coastlines are determined first. The size of vessels affects the number of quays that can be located along the operative coastline. Using the mathematical model we determine the lengths of railway tracks, roads and depots located along the operative coastline, i.e. the quays. The transport demand determined by the geotraffic location, gravitation region and transport flows, affects the number of railway tracks, roads, depot lanes and cargo handling areas. The results of these calculations affect the number and capacities of cargo handling equipment, storage area, towing and transport devices. The capacities of river ports or terminals in them can be defined from a static and dynamic aspect. The static capacity represents the maximum load on all the port and terminal facilities in a certain time period, and it is the upper limit i.e. the ideal capacity. The dynamic capacity takes into account all the delays and disruptions in the operation of single segments of the port or terminal and it actually stands for its throughput capacity. This model is very significant for planning and designing of ports and terminals in them, awaiting the river transport in the near future from the Vukovar, Osijek and other ports i.e. river harbours.

SUMMARY

This paper deals with the model for determining the capacity of a river port. The basic parameters of the model are determined by the size of the aquatorium and the possibilities of locating quays in the dock basin as well as their number. The number of quays and the static and dynamic capacity of the port - harbour depend on the sizes of the vessels planned for docking. The analysis considers the push tows Europe 1 and 2 and the Danube barges on the basis of which the length of the operative coastline is determined which in turn is related to the length of the railway tracks, roads, and cargo depots.

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