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Modelsko ispitivanje uplovljavanja i isplovljavanja plovnih sastava u kanal Dunav - Sava

Stručni rad

Prikazano je modelsko ispitivanje manevra uplovljavanja i isplovljavanja guranih i tegljenih sastava u kanal Dunav – Sava. Svrha ispitivanja bila je donošenje zaključka o prikladnosti, odnosno neprikladnosti, projektirane konfiguracije ušća kanala sa gledišta sigurnosti manevara riječnih brodskih sastava. U radu su opisani fizički model kao i zadovoljeni uvjeti sličnosti glede modela vodotoka i modela sastava brodova. Nadalje je objašnjen izbor mjerila modela, te primijenjeni mjerni postupci, osobito mjerenje koordinata sastava u ovisnosti o trajanju manevra pomoću TV opreme. Prikazani su i komentirani dobiveni i obrađeni rezultati ispitivanja.

Ključne riječi: *gurani sastav brodova, kanal Dunav – Sava, manevriranje, modelsko ispitivanje, tegljeni sastav brodova.*

Model Testing of Entry and Exit Manoeuvre of Push and Tow Vessel Combinations into the Danube – Sava Canal

Professional paper

Model testing of push and tow vessel combinations' entry and exit manoeuvre into the Danube – Sava Canal is presented. The objective of the testing was to determine adequacy or inadequacy of the canal confluence configuration design with respect to the safety of the manoeuvre of the vessel combinations. The physical model and fulfilled similarity conditions for the river and canal model and for the vessels combinations model are described. Also, the choice of the model scale and applied experimental methods are explained. Finally, the measured and evaluated results are presented and discussed.

Keywords: *Danube – Sava Canal, manoeuvre, model test, push vessel combination, tow vessel combination*

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1. Uvod

Brodarski institut je za *Institut građevinarstva Hrvatske*, kao naručitelja, proveo modelska ispitivanja manevra uplovljavanja i isplovljavanja guranih i tegljenih sastava brodova na modelu dijela korita Dunava i ušća budućega kanala Dunav – Sava [1]. Svrha ispitivanja bila je provjera prikladnosti predloženog oblika ušća kanala za sigurno uplovljavanje u kanal i isplovljavanje iz kanala sastava brodova. Modelska ispitivanja provedena su krajem 1998. godine, te u prvoj polovici 1999. godine.

2. Fizički model i uvjeti sličnosti

Jedan je od najosjetljivijih problema kod modelskih ispitivanja hidrodinamičkih pojava utvrđivanje relevantnih zakona sličnosti i definiranje mjerila modela, pa zato treba ovoj problematici posvetiti najveću moguću pozornost. To u posebno velikoj mjeri vrijedi za ovakav tip istraživanja, jer je riječ o istodobnom

1 Introduction

Brodarski Institute conducted for the customer *Civil Engineering Institute of Croatia* model tests of the entry and exit manoeuvre of push and tow vessel combinations into the canal on the model of the part of the Danube River and the confluence of the planned Danube – Sava Canal [1]. The objective of the testing was to verify the adequacy of the suggested canal's confluence shape for safe canal entry and exit manoeuvre of vessel combinations. Model tests were conducted at the end of 1998 and in the first half of 1999.

2 Physical model and similarity conditions

One of the most sensitive problems of hydrodynamic model testing is the determination of relevant similarity laws and model scale, so this issue should be addressed with greatest care. This particularly applies to the considered investigation, because it ispitivanju i modela hidrotehničkoga sustava i modela broda, preciznije rečeno modela sastava brodova.

Kao i uvijek polazi se od *geometrijske sličnosti* modela i objekata u naravi, koja može biti ili stroga sličnost (s jednakim mjerilom duljina u svim smjerovima) ili afina sličnost kod koje se za razne smjerove uzimaju različita mjerila.

Prvi zahtjev od kojega se nije moglo odstupiti jest da oba modela budu izvedena u istome mjerilu. Distorzija mjerila, zbog svojih neospornih prednosti, često primjenjivana na fizičkim modelima hidrotehničkih objekata ovdje nije dolazila u obzir, jer se modeli brodova ne smiju izvoditi kao distordirani, pa zato ni model vodotoka nije smio biti distordiran.

Sljedeći uvjet koji je trebalo zadovoljiti bila je *kinematička sličnost*. Taj je zahtjev u ovom konkretnom slučaju značio da, prvo, postoji sličnost polja brzina strujanja na modelu i polja strujanja u naravi i, drugo, da su omjeri brzina strujanja i brzine modela broda jednaki takvim omjerima u naravnoj veličini. Treba naglasiti da se to odnosi i na kutne brzine, pri čemu se posebno misli na kutne brzine prebacivanja kormila.

Konačno trebala je biti zadovoljena i *dinamička sličnost*, to jest jednakost omjera po svojoj fizičkoj suštini različitih sila (sila tlaka, trenja, inercije, gravitacije …). Nužan je uvjet za ostvarenje dinamičke sličnosti postojanje geometrijske i kinematičke sličnosti. Budući da su kod dinamičkih pojava bitna inercijska svojstva onih tijela koja u tim pojavama sudjeluju, to treba zadovoljiti sličnost masa i s masom povezanih veličina, kao što su dinamički momenti tromosti masa u odnosu na pojedine osi. Premda nas kod ovih ispitivanja nisu zanimale konkretne vrijednosti pojedinih sila koje se javljaju pri odvijanju promatranih pojava, ipak je važno zadovoljiti i dinamičku sličnost, da bi (neustaljena) gibanja bila slična.

2.1. Sličnost modela vodotoka

S obzirom da se ispitivanje provodilo na modelu otvorenog vodotoka, gdje je za strujanje bitno gravitacijsko polje zemlje (jer upravo zbog djelovanja gravitacije i nastaje strujanje), morao se zadovoljiti uvjet jednakosti Froudeova broja, to jest:

$$F_n = \text{idem}$$

Taj uvjet neposredno daje odnose brzina na modelu i u naravi u ovisnosti o izabranomu mjerilu linearnih dimenzija modela, a isto tako i odnose korespondentnih vremena.

Što se tiče ostvarivanja potpune dinamičke sličnosti strujanja javlja se niz problema. Naime, pri modeliranju pojava kod kojih je utjecaj viskoznosti malen, kao što su prelijevanje, istjecanje i slično, dostatno je zadovoljiti samo Froudev zakon sličnosti, dok se kod strujanja kod kojih je velik utjecaj viskoznosti mora zadovoljiti i jednakost koeficijenta otpora strujanja, koji ovisi o Reynoldsovom broju i o hrapavosti stijenki. U načelu nemoguće je istodobno zadovoljiti uvjete F_n = idem i R_n = idem, a u praksi je, posebno kada su mjerila modela mala, vrlo teško na modelu točno reproducirati relativnu hrapavost iz naravi. Mnogo je jednostavnija situacija ako se može napraviti model u dostatno velikomu mjerilu, tako da se na modelu postižu natkritične vrijednosti Reynoldsova broja, pa je uz F_n = idem dostatno zadovoljiti još samo uvjet jednakosti relativne hrapavosti. U ovo se može uvjeriti promatranjem Moodyevog dijagrama za strujanje kroz hrapave cijevi. No osim ovih, postojali su još neki problemi. Kao prvo sam hidraulički model mogao je obuhvaćati

includes simultaneous testing of a hydraulic model and a ship model, more precisely the model of the vessel combination.

As always the starting point is *geometric similarity* of the model and the real objects, which can be strict (with equal length scale in all directions) or distorted where different scales are applied for the horizontal and the vertical.

The first condition that could not be deviated from was to construct both models in an equal scale. Scale distortion, often applied to physical hydraulic models due to its indisputable advantages, could not be considered here, because the ship models had to be constructed in a non-distorted scale, so the river model also could not have been distorted.

The next condition to be satisfied was *kinematic similarity*. This condition in this specific case meant that: first, there is similarity of flow velocity field on the model and prototype; and second, ratios of flow velocities to ship model velocity are equal to these ratios on the prototype. It should be pointed out that this also applies to angular velocities, specifically to rudder angular velocity.

Finally, *dynamic similarity* was to be satisfied, i.e. equality of ratios of different forces (pressure, friction, inertia, gravity,). Necessary condition for dynamic similarity is the presence of geometric and kinematic similarity. Since inertial properties of those bodies that participate in dynamic phenomena are important for these phenomena, it is necessary to satisfy similarity of mass and physical quantities related to mass, like dynamic moments of inertia of mass concerning the respective axes. Although in this testing we were not concerned with specific values of individual forces acting during the observed phenomena, nevertheless it was also important to satisfy dynamic similarity, to achieve the similarity of (unsteady) motion.

2.1 River model similarity

Due to the fact that tests were conducted on an open river model, where the flow is caused by Earth's gravitational field, Froude number equality condition had to be fulfilled, i.e.:

$$F_n = \text{idem}$$

This condition directly determines velocity ratios on the model and prototype depending upon the chosen linear scale, as well as the corresponding time ratios.

Regarding the fulfilment of complete dynamic similarity of flow, a series of problems arises. Namely, when modelling phenomena where viscosity effects are low, like overflow, outflow and similar, it is sufficient to fulfil only the Froude law of similarity, whereas for flows with high viscosity effects we also have to achieve the equality of flow resistance coefficient, which depends upon Reynolds number and wall roughness. In principle it is impossible to fulfil conditions F_n = idem and R_n = idem at the same time, and in reality, especially in small model scales, it is very difficult to reproduce on the model exactly the full-scale relative roughness. We have much simpler situation if the model is made in a large enough scale, so Reynolds numbers above the critical value are achieved on the model, and then besides F_n = idem it is sufficient only to fulfil the relative roughness equality condition. This can be verified by observing the Moody diagram for flow through rough pipes. However, besides these, some other problems were confronted. First, the hydraulic model itself could cover only the part of the Danube river where the canal entry and the canal exit manoeuvre were expected to occur. Namely, the upstream part of the river, which was not modelled, affects tek dio toka Dunava u kojem se predviđa manevar uplovljavanja, odnosno isplovljavanja iz kanala. Naime, uzvodni dio korita, koji nije modeliran, djeluje na karakter strujanja na nizvodnim profilima, pogotovo što je riječ o zakrivljenom dijelu toka rijeke u kojemu se javljaju sekundarna strujanja, koja se odražavaju i na nizvodne profile brzina. Nadalje je za stvaranje ustaljenoga graničnog sloja potrebna dostatno duga sekcija vodotoka, što pri modelskom ispitivanju uglavnom nije moguće ostvariti. Iz tih razloga bilo je nužno ugradnjom odgovarajućih usmjerivača strujanja, odnosno nekih drugih prepreka oblikovati na zanimljivom presjeku vodotoka (to je dio vodotoka u blizini samog ušća kanala, gdje se odvija najosjetljiviji dio manevra uplovljavanja odnosno isplovljavanja) profil brzina koji je sličan odgovarajućem profilu u naravi.

2.2. Sličnost modela sastava brodova

Sličnost modela sastava brodova mora zadovoljavati dobro poznate uvjete sličnosti koji se postavljaju na modele brodova. To je opet kao prvo geometrijska sličnost, nadalje kinematička sličnost i konačno dinamička sličnost.

Glede geometrijske sličnosti treba reći da u ovom slučaju modeli vijaka nisu bili geometrijski slični vijcima broda u naravi iz praktičnih razloga. Naime na tržištu se nude samo vijci s određenim omjerom uspona *P*/*D*. Zato se odstupilo od kinematičke sličnosti izražene koeficijentom napredovanja tj. omjerom $J = v_a/(n{\cdot}D)$, a brzina vrtnje modela vijka određena je tako da se ostvari sličnost poriva.

Budući da je, kao što je već ranije rečeno, za modeliranje strujanja u vodotoku nužno zadovoljiti uvjet F_n = idem, to kinematička sličnost, tj. jednakost omjera brzine broda i brzine struje, automatski ostvaruje i jednakost Froudeovih brojeva za sastav brodova i njegov model. Takvo ispunjenje uvjeta F_n = idem za brod znači da će sličnost sila na trup, uronjaja i trima u uvjetima plitke vode i ograničene širine akvatorija biti sačuvana. Uz jednakost gustoće fluida, što je ovdje bilo ispunjeno (i u naravi i kod modela radilo se o istoj tekućini – slatkoj vodi), geometrijska sličnost gazova vodi na sličnost masa. Međutim, za postizanje sličnosti momenta tromosti mase sastava brodova za os kroz težište trebalo se posebno pobrinuti. To znači da su se mase (tereti) na modelu rasporedili na način da polumjeri tromosti mase sastava brodova i njegovog modela budu u odnosu koji je zahtijevalo mjerilo linearnih dimenzija.

Kada se ispituju modeli uz uvjet F_n = idem linearne brzine se odnose kao korijen iz mjerila, $v_m = v/\sqrt{\lambda}$, a isti je omjer i vremena proteklih na modelu i u naravi za pređeni odgovarajući put, odnosno za jednaki kut. To znači da se kutne brzine, odnosno frekvencije povećavaju u omjeru $\sqrt{\lambda}$. Ova je činjenica važna zato jer se kod ovog ispitivanja u regulacijskom krugu pojavljivao čovjek. Naime za izvršenje iste operacije na modelu stoji na raspolaganju $\sqrt{\lambda}$ kraće vrijeme. U slučaju sporih objekata, kao što su sastavi guranih i tegljenih brodova, kormilaru preostaje i na modelu dostatno vremena za reagiranje, tako da se na temelju modelskih pokusa može ustanoviti izvedivost pojedinih manevara. Na brodu u naravi je brzina prebacivanja kormila, tj. njegova kutna brzina određena konstrukcijom kormilarskoga stroja. Budući da pokazatelji upravljivosti bitno ovise o toj kutnoj brzini, to je na modelu bilo potrebno primjereno povećati kutnu brzinu kormila.

the flow on the downstream profiles, especially since this part of the river is curved, thus causing secondary flows, which are also reflected on the downstream velocity profiles. Furthermore, to achieve a steady boundary layer, a river section of sufficient length is necessary, which is usually not possible to accomplish in model testing. It was therefore necessary to implement appropriate flow directioning devices, respectively some other obstacles to produce a velocity profile on the examined river section (it is the part of the river near the canal's confluence, where the most sensitive part of the entry/exit manoeuvre occurs) similar to the corresponding profile on the prototype.

2.2 Vessel combination model similarity

The vessel combination model has to fulfil well known similarity conditions which are applied to ship models. First, it is again geometric similarity, then kinematic similarity, and finally dynamic similarity.

Regarding the geometric similarity it is necessary to say that the propeller models were not geometrically similar to the prototype ship propellers for practical reasons. Namely, market offers only propellers with certain pitch to diameter ratios *P*/*D*. Therefore there was deviation from kinematic similarity expressed by the advance coefficient, i.e. ratio $J = v_a/(n{\cdot}D)$, and the propeller model rotation velocity was set to achieve similarity of thrust.

As it was previously said, due to the fact that to model river flow it is necessary to fulfil the condition F_n = idem, the kinematic similarity, i.e. equality of ship velocity to flow velocity ratio also automatically fulfils the Froude number equality for the vessel combination and its model. This fulfilment of the condition F_n = idem for the ship means that similarity of forces acting on the hull, draught and trim in shallow water and limited water surface will be preserved. Beside the equality of fluid density, which was fulfilled in the considered case (in the case of both the prototype and the model the same fluid – fresh water was in question), the geometric similarity of draught leads to similarity of mass. However, to achieve the similarity of the vessel combination mass moment of inertia for the axis passing through centre of gravity it was necessary to take special measures. This means that masses (loads) on the model were distributed in such a way to produce the ratio of radii of inertia of the vessel combination and its model that was governed by the linear scale.

When models are tested under the condition F_n = idem, the ratio of linear velocities is equal to the scale square root, $v_m = v/\sqrt{\lambda}$, and the same is the ratio of times passed on the model and prototype for corresponding displacement, that is for the same angle. This means that angular velocities, that is frequencies are increased in the ratio $\sqrt{\lambda}$. This fact is important because in the considered testing the man was present in the regulation circle. Namely, to execute the same operation on the model $\sqrt{\lambda}$ times shorter time is available. In case of slow moving objects, like the push-tow combinations, the coxswain on the model has also enough time to react, and thus on the basis of the model tests, the manoeuvring ability can be determined. The prototype ship rudder changeover velocity, i.e. its angular velocity is determined by steering equipment. Since the manoeuvring indicators largely depend on this angular velocity, it was necessary to increase the rudder angular velocity on the model accordingly.

2.3. Izbor mjerila

Izbor mjerila uvijek je kompromis suprotstavljenih zahtjeva. Za veliko mjerilo, to jest za velike vrijednosti omjera $1/\lambda$, lakše je vjerno reproducirati neke pojedinosti modela, kao na primjer vijak ili hrapavost vodotoka, manji je "utjecaj mjerila" na otpore strujanja, jer je Reynoldsov broj veći, sile i momenti su veći, pa je i točnost njihovog mjerenja veća. S druge strane veliko mjerilo traži velike modele, kojima je veličina ograničena dimenzijama raspoloživih laboratorija, kao i kapacitetima pumpi kojima se raspolaže, a i cijena bitno raste s veličinom modela.

Analiziranjem zahtjeva ispitivanja i laboratorijskih ograničenja, te uvidom u literaturu [2], gdje se navodi da mjerilo 50 još upravo omogućuje dobivanje pouzdanih podataka o upravljivosti modela brodova, premda se u tom slučaju više ne može govoriti o pouzdanomu mjerenju snage i prognozi brzine, usvojeno je mjerilo $\lambda = 50$. Na taj se način osigurala mogućnost modeliranja dostatno velikog dijela Dunava uzvodno i nizvodno od ušća kanala i pouzdano zaključivanje o ostvarivosti sigurnih manevara uplovljavanja i isplovljavanja iz kanala.

U tablici 1 prikazani su omjeri pojedinih veličina na modelu i u naravi.

Tablica 1 **Omjeri veličina na modelu i u naravi**

Veličina	Narav	Model	Za mjerilo $\lambda = 50$
Linearne dimenzije	L	$L_m = L / \lambda$	$L_m = L / 50$
Ploštine	A	$A_m = A / \lambda^2$	$A_m = A / 2500$
Linearne brzine	v	$v_m = v / \sqrt{\lambda}$	$v_m = v / 7{,}07$
Vremena	t	$t_m = t / \sqrt{\lambda}$	$t_m = t / 7{,}07$
Kutne brzine	ω	$\omega_m = \omega \sqrt{\lambda}$	$\omega_m = 7{,}07\ \omega$
Sile	F	$F_m = F / \lambda^3$	$F_m = F / 125000$
Momenti	M	$M_m = M / \lambda^4$	$M_m = M / 625000$
Snage	P	$P_m = P / \lambda^{7/2}$	$P_m = P / 883883$
Protoci	Q	$Q_m = Q / \lambda^{5/2}$	$Q_m = Q / 17678$
Reynoldsovi brojevi	R_n	$R_{n,m} = R_n / \lambda^{3/2}$	$R_{n,m} = R_n / 353{,}6$

Iz tablice 1 može se vidjeti da je uz zadovoljenje jednakosti Froudeova broja, koji je ovdje najmjerodavniji uvjet sličnosti, Reynoldsov broj modela više nego 350 puta manji od toga broja u naravi, što je uzrok takozvanog "utjecaja mjerila".

2.4. Model dijela Dunava i ušća kanala

U okruglom bazenu *Brodarskog instituta* izrađen je u mjerilu 1:50 model Dunava između kilometra 1334+050 i kilometra 1335+310, te dio budućega kanala u duljini od 430 metara. Model je izrađen uobičajenom tehnologijom izgradnje hidrauličkih modela, pri čemu je postignuta točnost unutar granica odstupanja ±0,002 m. Ostvarena je hrapavost modela koja se normalno postiže pri primjeni takve tehnologije, a kako hrapavost korita Dunava nije poznata, nije niti bilo potrebno težiti ostvarenju sličnosti mikrogeometrije modela, to jest sličnosti hrapavosti.

Strujanje vode u modelu osigurano je pomoću pumpi, koje su prebacivale vodu iz retencije u okruglom bazenu u bazen 3. Regulacija protoka ostvarena je prigušivanjem. Brzine strujanja

2.3 Choice of scale

Choice of scale is always a compromise of contradictory demands. For a large scale, i.e. for large values of $1/\lambda$ ratio, it is easier to truly reproduce individual details of the model, like for instance, the propeller or the river bed roughness, the "scale effect" on flow resistance is smaller because of higher Reynolds number, forces and moments are larger, so the precision of their measurement is higher. On the other hand, a large scale demands large models, whose size is limited by available laboratory space, as well as by available pumping capacities. Also, the cost significantly grows with the model size.

After analysing testing requirements and laboratory limitations, and after overviewing referent literature [2], where it is stated that scale 50 still provides reliable data for ship model manoeuvring ability evaluation, although in that case power measurement and velocity prediction are not reliable, scale $\lambda = 50$ was adopted. In this way it was possible to model a sufficiently long part of the Danube upstream and downstream from the canal confluence and to reliably evaluate the safety of the canal entry/exit manoeuvre.

The ratios of individual quantities on the model and prototype are given in Table 1.

Table 1 **Ratios of quantities on the model and prototype**

Quantity	Prototype	Model	For scale $\lambda = 50$
Linear dimensions	L	$L_m = L / \lambda$	$L_m = L / 50$
Areas	A	$A_m = A / \lambda^2$	$A_m = A / 2500$
Linear velocities	v	$v_m = v / \sqrt{\lambda}$	$v_m = v / 7.07$
Times	t	$t_m = t / \sqrt{\lambda}$	$t_m = t / 7.07$
Angular velocities	ω	$\omega_m = \omega \sqrt{\lambda}$	$\omega_m = 7.07\ \omega$
Forces	F	$F_m = F / \lambda^3$	$F_m = F / 125000$
Moments	M	$M_m = M / \lambda^4$	$M_m = M / 625000$
Powers	P	$P_m = P / \lambda^{7/2}$	$P_m = P / 883883$
Flows	Q	$Q_m = Q / \lambda^{5/2}$	$Q_m = Q / 17678$
Reynolds numbers	R_n	$R_{n,m} = R_n / \lambda^{3/2}$	$R_{n,m} = R_n / 353.6$

It can be seen from Table 1 that when fulfilling the Froude number equality condition, which is the most important condition of similarity here, the Reynolds number on the model is 350 times smaller than this number on the prototype, which is caused by the so called "scale effect".

2.4 Model of Danube section and canal confluence

In the circular basin of *Brodarski Institute* a model of the Danube between kilometre 1334+050 and kilometre 1335+310 and a part of the planned canal 430 m long was constructed in a scale 1:50. Standard hydraulic model construction technology was applied with accuracy within the range ±0.002 m. Normal surface roughness of the model was achieved for this kind of construction technology, and since the surface roughness of the Danube river bed is unknown, it was not necessary to strive to attain the similarity of the model microgeometry, i.e. roughness similarity.

su na modelu mjerene na tri profila. Usmjeravanjem vode pomoću cijevi i šupljih opeka ostvareni su profili brzina koji su odgovarali onima u naravi. Visina razine vode na modelu ostvarena je postavljanjem uspora na mjestu istrujavanja iz modela u retenciju u okruglom bazenu.

2.5. Modeli sastava

Standardni gurani i tegljeni sastavi koji su predviđeni za plovidbu kanalom sastoje se od gurača i dvije potisnice tipa Europa II, odnosno tegljača i dvije tegljenice. Treba napomenuti da je kao tegljač iskorišten postojeći model gurača, uz nužne adaptacije na vezovima za vuču tegljenica. Glavne izmjere plovila nalaze se u tablici 2.

Tablica 2 **Glavne izmjere plovila**

Plovilo	Duljina L_{pp}, m		Širina B, m		Gaz T, m	
	Narav	Model	Narav	Model	Narav	Model
Gurač/tegljač	32,00	0,640	11,40	0,228	1,60	0,032
Potisnica	76,50	1,530	11,40	0,228	2,80	0,056
Tegljenica*	72,20	1,440	10,20	0,204	1,95	0,039

* standardna tegljenica u sastavu *Dunavskog Lloyda* Sisak

Modeli gurača/tegljača, potisnica i tegljenica izvedeni su od staklenim vlaknima ojačane poliesterske smole. Granice točnosti modela procijenjene su na cca 1 posto. Model gurača opremljen je s dva vijka u sapnicama i ima tri kormila, što odgovara propulzijskoupravljačkom sustavu uobičajenom na brodovima dunavske flote. Vijci su pogonjeni elektromotorima putem reduktora, a kormila su spregnuta i zakretana pomoću servomotora. Sustavom daljinskog upravljanja omogućeno je mijenjanje smjera i brzine vrtnje vijaka, kao i mijenjanje kuta zakreta kormila. Nadalje, modeli tegljenica opremljeni su neovisno upravljanim kormilarskim sustavom. Modeli gurača i potisnice s uređajem za daljinsko upravljanje prikazani su na slici1. Model guranoga sastava plovila s guračem i dvije serijski spojene potisnice tijekom ispitivanja prikazan je na slici 2.

The flow of water in the model was provided by pumps, which transferred the water from retention in the circular basin to basin No. 3. The flow was regulated by damping. Flow velocities on the model were measured on three profiles. By directing water using pipes and hollow bricks the velocity profiles corresponding to the prototype were achieved. Water depth on the model was ensured by weir discharge from the model into the retention in the circular basin.

2.5 Vessel Combination Models

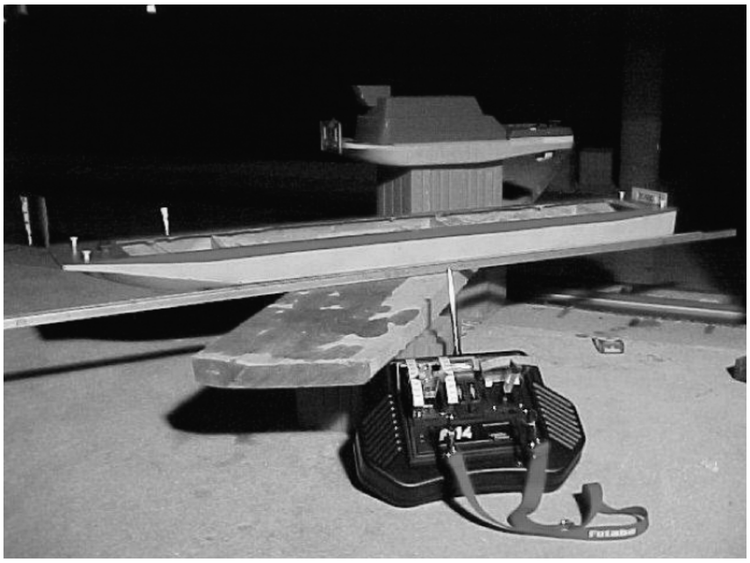
Standard push and tow combinations anticipated to navigate the canal consist of a push tug and two push barges of Europa II type, that is of a tug and two tow barges. It should be noted that the existing push tug model was also used as a tow tug, with the necessary modifications concerning towlines required for barge towing. The main vessels' dimensions are given in Table 2.

Table 2 **Main vessel dimensions**

Vessel	Length L_{pp}, m		Width B, m		Draught T, m	
	Prototype	Model	Prototype	Model	Prototype	Model
Tug	32.00	0.640	11.40	0.228	1.60	0.032
Push barge	76.50	1.530	11.40	0.228	2.80	0.056
Tow barge*	72.20	1.440	10.20	0.204	1.95	0.039

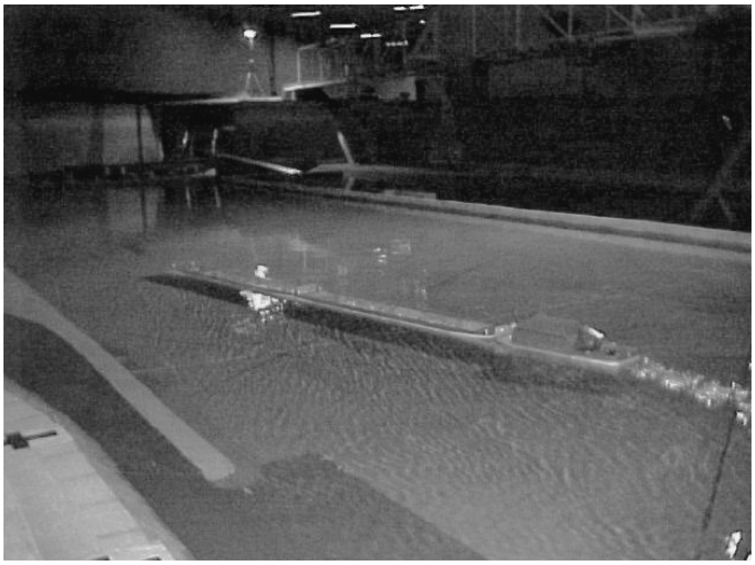
* standard barge in the fleet of *Danube Lloyd* Sisak

The tug, push barge and tow barge models were constructed of glass fibre reinforced polyester resin. The accuracy of the models was estimated to be ca 1%. The tug model is equipped with two nozzle propellers and three rudders, which matches the propulsion and steering system usually employed on the ships of the Danube fleet. Propellers are powered by electric motors through reduction gear, and rudders are coupled and rotated by servomotor. A remote control system enables change of direction and velocity of propeller rotation, as well as rudder angle regulation. Furthermore, the tow barges are equipped with independently operated steering system. The push tug and push barge models with the remote control unit are shown in Figure 1. The Pushed vessel combination model with the push tug and two serially connected push barges during testing is shown in Figure 2.



Slika 1 **Modeli gurača i potisnice s uređajem za daljinsko upravljanje**

Figure 1 **Push tug and push barge models with remote control unit**



Slika 2 **Model sastava gurača i dvije serijski spojene potisnice tijekom ispitivanja**

Figure 2 **Push vessel combination model with push tug and two serially connected push barges during testing**

3. Mjerne metode i oprema

Osnovni podatak kojega je trebalo dobiti pri provođenju pokusa bila je putanja sastava brodova, u odnosu na granice akvatorija, kao funkcija vremena. Da bi se ispunili kinematički uvjeti sličnosti trebalo je realizirati profile brzina koji vladaju na Dunavu, zbog čega se provodio iterativni postupak mjerenja i prilagođivanja (pomoću usmjerivača) brzina strujanja.

3.1. Mjerenje prostornih i vremenskih koordinata primjenom televizije

Postavljeni zadatak podrazumijevao je masovno mjerenje prostornih i vremenskih koordinata modela tijekom plovidbi u raznim režimima, ukupno oko 60000. Stoga je bilo nužno automatizirati akviziciju podataka tijekom ispitivanja, a također i naknadnu obradu.

Tijekom slobodne plovidbe modeli su snimani televizijskom kamerom, a signal kamere bilježen je na magnetsku traku. Za svaki pokus digitalizirana je sekvenca slika s razdobljima akvizicije od 500 do 1200 ms, ovisno o tipu pokusa. Digitalne slike pohranjene su na tvrdi disk računala, a u naknadnoj obradi su pojedinačno pozivane, te je na njima izvršeno mjerenje slikovnih koordinata i pretvorba u njihove geodetske ekvivalente u lokalnom (desnom) koordinatnom sustavu.

Konačna obrada izmjerenih uzastopnih položaja sastava provedena je na računalu pomoću programa napisanog u sustavu Mathematica©; grafički prikaz putanja ostvaren je pomoću istoga programa [8].

Snimanje pokusa obavljeno je televizijskom kamerom smještenom ispod kupole bazena u kojem se provodilo ispitivanje. Apscisa slike postavljena je približno po uzdužnoj osi Dunava, s pozitivnim smjerom uzvodno, a ordinata je postavljena poprečno na tok s pozitivnim smjerom prema obali na hrvatskoj strani (desni koordinatni sustav). Radi omogućavanja zahvaćanja cijelog modela u format slike, kamera je nagnuta u odnosu na apscisu i u odnosu na ordinatu. Na taj je način obuhvaćeno područje kanala i Dunava po gotovo čitavoj površini izgrađenog modela.

3 Measurement methods and equipment

The basic information required from these tests was the path of the vessel combination, related to water surface limits, as a function of time. To fulfil kinematic similarity conditions it was necessary to achieve the velocity profiles which are present on the Danube. Therefore, iterative procedure of flow velocity measurement and regulation (using flow directioning devices) was performed.

3.1 Spatial and time coordinate measurement by television application

The imposed task implied a mass measurement of spatial and time coordinates of the model during navigation under different modes of operation, approximately 60000 overall. Therefore it was necessary to automate data acquisition during testing, as well as subsequent data processing.

During free navigation the models were captured with a television camera, and the camera signal was recorded on a magnetic tape. For each test a sequence of images was digitized with acquisition time from 500 to 1200 ms, depending on the type of test. Digitized images were saved to a computer hard disk, subsequently individually processed, and used for measurement of image coordinates and conversion to their geodetic equivalents in the local (right) coordinate system.

Final processing of the measured consecutive vessel combination positions was conducted on a computer using a program written in Mathematica© software; graphic representation of the paths was accomplished with the same program [8].

Tests were recorded using a television camera installed under the dome of the basin where the testing was conducted. Image abscissa was approximately aligned with the Danube longitudinal axis, with upstream oriented positive direction, and ordinate was set transversely to the flow with positive direction towards the Croatian bank of the Danube (right coordinate system). In order to be able to capture the whole model into image format, the camera was inclined in reference to the abscissa and in reference to the ordinate. In this way it was possible to capture the canal and the Danube almost over the whole surface of the model.

Spomenuti nagibi kamere proizveli su nezanemariva perspektivna izobličenja u oba smjera [3], [4], a na njih se superponiralo još i sferno izobličenje širokokutnog objektiva. Drugim riječima, mjerilo slike mijenjalo se od točke do točke po složenim nelinearnim funkcijama. Stoga je bilo nužno prethodno ustanoviti analitički oblik algoritama izobličenja i izvršiti odgovarajuća umjeravanja na realnom sustavu. Kada su ustanovljeni svi korekcijski čimbenici za realan sustav, načinjen je programski modul pomoću kojega su koordinate očitane na slici prevođene na njihov geodetski (metrički) ekvivalent. Konačno, načinjena je opsežna provjera postignutog rješenja i ustanovljena je zaostala sustavna pogrješka koja je ocijenjena prihvatljivo malom.

Korekcija perspektivnih izobličenja za navedene kutove nagiba provedena je na način kako se opisuje u standardnoj fotogrametrijskoj literaturi, uz napomenu da je korištena inačica algoritma razvijena u *Brodarskom institutu* za potrebe balističkih ispitivanja, a koja se odnosi na određivanje koordinata u naravi iz digitalizirane televizijske slike. Ova inačica potanko je dokumentirana i usvojena od Državnog zavoda za normizaciju i mjeriteljstvo u sklopu ovlaštenja [5].

Sferna distorzija objektiva izmjerena je na etalonskoj rešetki u laboratoriju. Na temelju tih podataka nađena je prva aproksimacija kvadratičnoga polinoma za korekciju izobličenja. Zatim je polinom rotiran u polarnom sustavu po polju za umjeravanje na realnomu modelu, a iterativnim postupkom provedeno je precizno podešavanje korekcijskih koeficijenata.

Radi bolje razlučivosti, na rubnim točkama modela sastava plovila postavljene su svijetleće diode, LED.

3.2. Mjerenje polja brzina strujanja

Brzine strujanja Dunava na modelu mjerene su na tri mjerna presjeka postavljena kao što je prikazano na slici 3. Mjerne točke na tim presjecima bile su određene tako da pokriju čitavu širinu plovnoga puta. Brzine strujanja mjerene su hidrometrijskim krilom SEBA (*propeller no*. 50.93) promjera 50 mm.

Slika 3 **Položaj mjernih presjeka i mjernih točaka za nadzor polja brzina u akvatoriju ulaza u kanal Dunav – Sava**

The mentioned camera inclinations produced perspective distortions in both directions [3], [4] that could not be disregarded, and wide-angle lens spherical distortion was additionally also present. In other words, the image scale was changing from point to point according to complex nonlinear functions. Therefore it was first necessary to determine the analytic shape of distortion algorithms and perform corresponding calibration on the actual system. When all corrective coefficients for the actual system were determined, a program module was made for transformation of image coordinates to their equivalent geodetic (metric) coordinates. Finally, a comprehensive verification of the accomplished solution was carried out, and the identified residual systematic error was considered to be acceptably small.

Correction of perspective distortions for the mentioned inclination angles was conducted in a manner described in standard photogrammetric literature, with a note that the applied algorithm version was developed in *Brodarski Institute* for ballistic testing purposes, and it is concerned with coordinate measurement from digitized television records. This version has been documented in detail and adopted by the State Standardisation and Metrology Institute within accreditation [5].

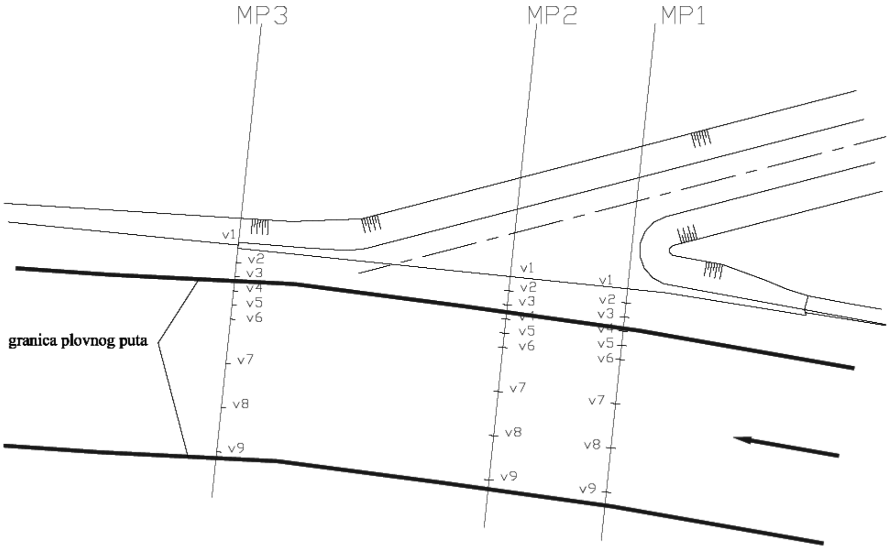
Spherical distortion of the lens was measured on a calibration grid in a laboratory. Based on this data, the first approximation of quadratic polynomial for distortion correction was established. Then the polynomial was rotated in a polar system over the calibration field on the actual model, and iterative procedure was carried out for accurate adjustment of correction coefficients.

For better resolution, light emitting diodes (LED) were installed on limiting points of the vessel combination models.

3.2 Flow velocity field measurement

Flow velocities of the Danube on the model were measured on three measurement sections as shown in Figure 3. Measurement points on these sections were determined to cover the whole waterway width. Flow velocities were measured with hydrometric propeller SEBA (no. 50.93) having a 50 mm diameter.

Figure 3 **Positions of measuring sections and measuring points for flow velocity field control in the Danube – Sava Canal confluence area**



4. Program ispitivanja

Ispitivanja su provedena uz sustavno mijenjanje većega broja parametara. Ispitan je utjecaj visine razine Dunava, vrste guranoga/tegljenog sastava, te utjecaj udaljenosti od obale prigodom ulaska u manevar uplovljavanja. Budući da je uspješnost manevra osim o konfiguraciji ušća kanala (u prvom redu o kutu osi kanala prema strujanju Dunava) i o manevarskim svojstvima sastava ovisna i o čovjeku koji provodi manevar, tj. o njegovoj umješnosti, izvježbanosti i koncentraciji, to je rezultat, izražen bilo kao binarni ishod uspjeh/neuspjeh, odnosno izražen najmanjom, kritičnom udaljenošću sastava od obale, u velikoj mjeri slučajna veličina. Zato je bilo potrebno upotrijebiti statistički pristup, koji se sastojao u tome da je isti tip manevra uz iste osnovne parametre u okviru jednoga pokusa izveden veći broj puta. Uglavnom se provodilo deset plovidbi u svakom pokusu, a manje samo onda kad je ustanovljeno da su manevri vrlo sigurni bez naznake bilo kakvog rizika.

Ispitani su modeli tri različita gurana [6] i tri različita tegljena sastava [7], a njihovi opisi prikazani su u tablici 3.

Tablica 3 **Ispitani modeli različitih sastava plovila**

Sastav	Oznaka
Gurač i jedna potisnica	G-1
Gurač i dvije serijski vezane potisnice (jedna iza druge)	G-2
Gurač i dvije paralelno vezane potisnice (jedna pored druge)	G-3
Tegljač i jedna tegljenica vučena užetom	T-1
Tegljač i dvije tegljenice vučene užetom	T-2
Uplovljavanje: tegljač i jedna tegljenica kruto vezana uz njegov desni bok Isplovljavanje: tegljač i jedna tegljenica kruto vezana uz njegov lijevi bok	T-3

Pretpostavlja se da su manevri uplovljavanja/isplovljavanja sastava G-1 usporedivi s manevrima broda s vlastitim pogonom ("samohotke").

Vodostaji Dunava koji su modelirani prigodom ispitivanja prikazani su u tablici 4.

Tablica 4 **Modelirani vodostaji Dunava**

Vodostaj	Oznaka	Nadmorska visina, m n.m.	Primjedba
Niski plovni vodostaj	NPV	76,64	Vodostaj od kojega se manji javlja u prosjeku u 5% vremena trajanja
Srednji plovni vodostaj	SPV	78,35	Statistička srednja vrijednost vodostaja
Visoki plovni vodostaj	VPV	80,20	Vodostaj od kojega se veći javlja u prosjeku u 10% vremena.

Budući da se manevri obavljaju samo na desnoj polovini Dunava, to nije bilo potrebno, a iz praktičnog razloga – ograničenoga kapaciteta crpki, i nije se moglo, ostvariti sličnost brzine strujanja na čitavoj širini modela Dunava.

5. Rezultati ispitivanja i njihova obrada

Primjer grafičkoga prikaza rezultata ispitivanja modela sastava G-3 u manevru uplovljavanja u kanal pri VPV nalazi se

4 Test program

The tests were conducted with systematic variation of larger number of parameters. The influence of the following parameters was examined: Danube water level, type of push/tow combination and distance to the bank during the canal entry manoeuvre. Since the manoeuvre successfulness apart from the canal confluence configuration (primarily the angle of the canal axis in reference to the Danube flow) and vessel combination manoeuvrability also depends on the person conducting the manoeuvre, i.e. on his skill, aptness and concentration, the result, expressed either as a binary outcome success/failure or as a minimum, critical distance of the vessel combination ship composition to the bank, is mostly a stochastic variable. Therefore it was necessary to apply a statistical approach, by repeating the same type of manoeuvre under the same basic conditions within one test more times. Generally, ten rides were conducted in every test, and less only if it was ascertained that manoeuvres were very safe without indication of any risk.

Three different push [6] and three different tow combinations [7] were tested, and their descriptions are presented in Table 3.

Table 3 **Tested models of different vessel combinations**

Vessel Combination	Code
Push tug and one push barge.	G-1
Push tug and two serially connected push barges (one behind the other).	G-2
Push tug and two paralelly connected push barges (one besides the other).	G-3
Tug and one barge towed by towline.	T-1
Tug and two barges towed by towline.	T-2
Canal entry: Tug and one barge rigidly tied to its starboard. Canal exit: Tug and one barge rigidly tied to its portside.	T-3

It is assumed that the canal entry/exit manoeuvres of G-1 combination are comparable to the manoeuvres of a self-propelled ship.

The Danube water levels modelled during the tests are presented in Table 4.

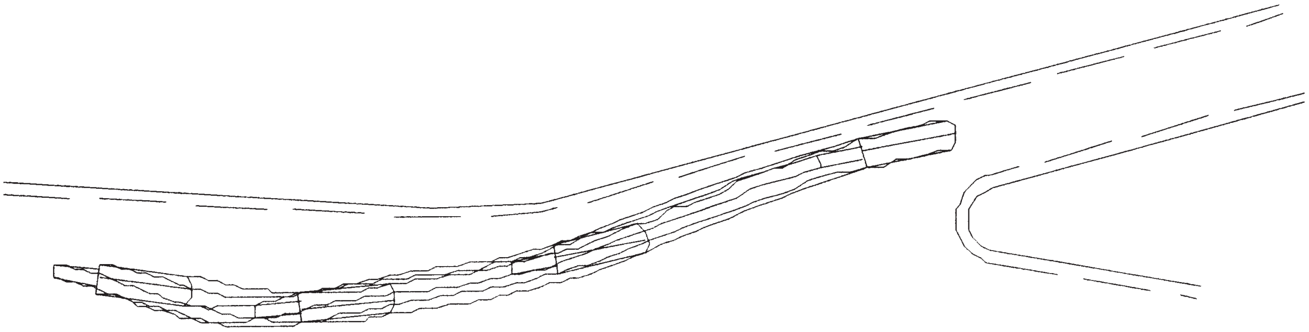
Table 4 **Modelled Danube water levels**

Water level	Code	Altitude, m ASL	Remark
Low water level	NPV	76.64	Water level lower than this occurs on average 5% of the time.
Mean water level	SPV	78.35	Statistical water level average.
High water level	VPV	80.20	Water level higher than this occurs on average 10% of the time.

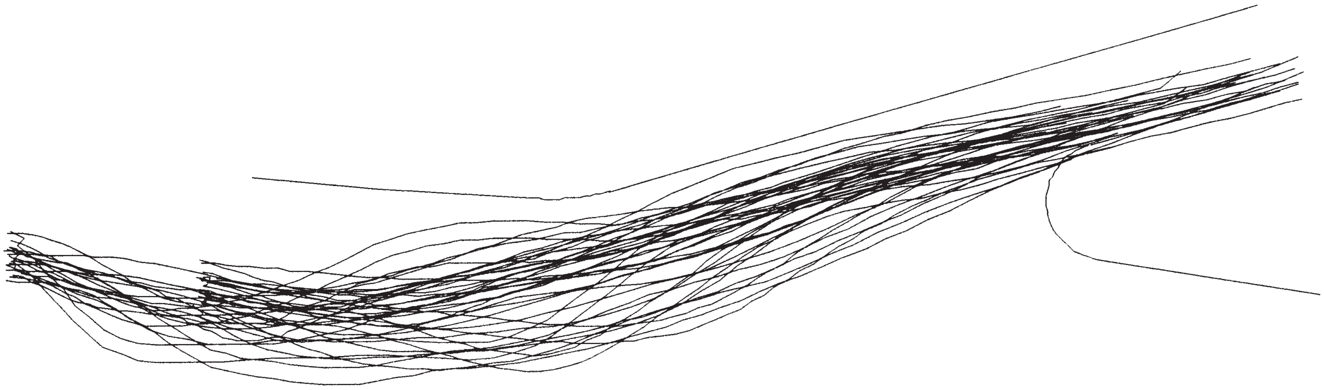
Since the manoeuvres are performed only on the right side of the Danube, it was not necessary, and for practical reasons – limited pumping capacity, it was not possible, to achieve the similarity of flow velocity over the whole Danube model width.

5 Test results and their processing

An example of the graphical representation of the test results for G-3 combination model in the canal entry manoeuvre for na slici 4. Za svaki pojedini manevar praćene su četiri istaknute točke guranoga sastava, odnosno šest istaknutih točaka tegljenoga sastava, za koje se pretpostavljalo da će najvjerojatnije doći u neposrednu blizinu obale. Kao što se vidi na slici 4, pored putanja karakterističnih točaka sastava prikazane su i konture sastava. Za pojedine pokuse analizirane su i skupne putanje svih šest istaknutih točaka, što je na primjeru sastava G-3 u manevru uplovljavanja u kanal pri VPV prikazano na slici 5.



Slika 4 **Putanje četiri istaknute točke guranoga sastava pri jednom od pokusnih manevara uplovljavanja u kanal**



Slika 5 **Skup putanja istaknutih točaka guranoga sastava za svih deset provedenih pokusnih manevara uplovljavanja**

Statistička je obrada rezultata u dogovoru s projektantima napravljena na sljedeći način. Duž linije obale na modelu na razmaku od, u pravilu, 2 m (tome odgovara u naravi 100 m) zamišljeni su okomiti presjeci. Ti su presjeci dani svojom relativnom stacionažom, pri čemu je 472,5 m relativne stacionaže na 1334+700 dunavskom kilometru. Položaj pravaca relativnih stacionaža na kojima je kontrolirana udaljenost referentne točke sastava od obale nalazi se na slici 6.

Kako se gotovo pri svim manevrima guranoga sastava obali najviše približavala krma gurača, to je kao karakteristična točka za ovaj prikaz odabrana točka na sredini krme gurača u kojoj se nalazila svijetleća dioda (LED). Pri gotovo svim manevrima tegljenoga sastava obali se najviše približavala krma tegljenica, pa je stoga kao karakteristična točka za ovaj prikaz odabrana točka na sredini krme tegljenice u kojoj se nalazila svijetleća dioda. Za svaki su pokus određene jednadžbe interpolacijskih funkcija koje

VPV is shown in Figure 4. For each individual manoeuvre four limiting points of the push combination were monitored, i.e. six limiting points of the tow combination that were assumed to come nearest to the bank. As can be observed in Figure 4, besides the paths of characteristic points of a vessel combination, the vessel combination contours are also shown. Grouped paths of all six limiting points were also analysed for individual tests, as is shown in Figure 5 on the example of G-3 combination model in the canal entry manoeuvre for VPV.

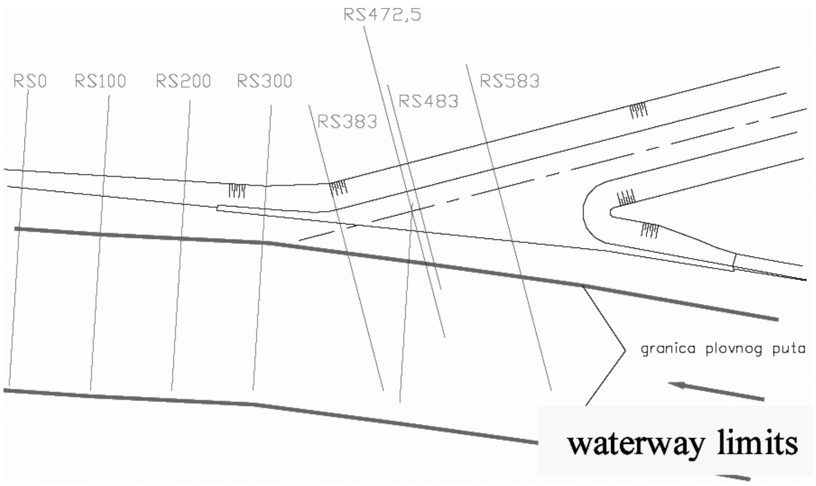
Figure 4 **Paths of four limiting points of a push combination for one of the tested canal entry manoeuvres**

Figure 5 **Grouped paths of limiting points of a push combination for all ten test canal entry manoeuvres**

Statistical data processing was done in agreement with the designers in the following way. Along the model river bank perpendicular sections with typically 2 m spacing (100 m spacing on the prototype) were imagined. These sections were specified as relative stations, with the relative station 472.5 m corresponding to the Danube kilometre 1334+700. The positions of relative stations, on which distance to the river bank of ship composition referent point was verified, are shown in Figure 6.

Since during almost all of the push combination manoeuvres the push tug's stern came closest to the river bank, a point located in the middle of the push tug's stern, with light emitting diode (LED) installed, was selected as the characteristic point for this representation. During almost all of the tow combination manoeuvres the barge's stern came closest to the river bank, therefore a point located in the middle of the barge stern, with light emitting diode installed, was selected as the characteristic opisuju putanje karakteristične točke pri pojedinim plovidbama. Numeričkim rješavanjem jednadžbi putanja i jednadžbi pravaca presjeka dobilo se udaljenosti od obale na kojima prolazi krmena dioda. Najmanja, najveća i srednja vrijednost udaljenosti za sastav G-3 u manevru uplovljavanja u kanal pri VPV prikazane su u tablici 5, odnosno dijagramu 1. U dijagramu 1 je na osi apscisa označena udaljenost mjerena duž obalne crte – to jest relativna stacionaža.

point for this representation. Interpolation function equations, which describe the paths of the characteristic points during individual manoeuvres, were determined for each trial. Distances of the stern diode to the river bank were provided by numerical solution of path equations and section line equations. Minimum, maximum and average distance values for the G-3 combination in the canal entry manoeuvre for VPV are presented in Table 5, i.e. in Chart 1. The abscissa of Chart 1 represents the position measured along the river bank – i.e. the relative station.

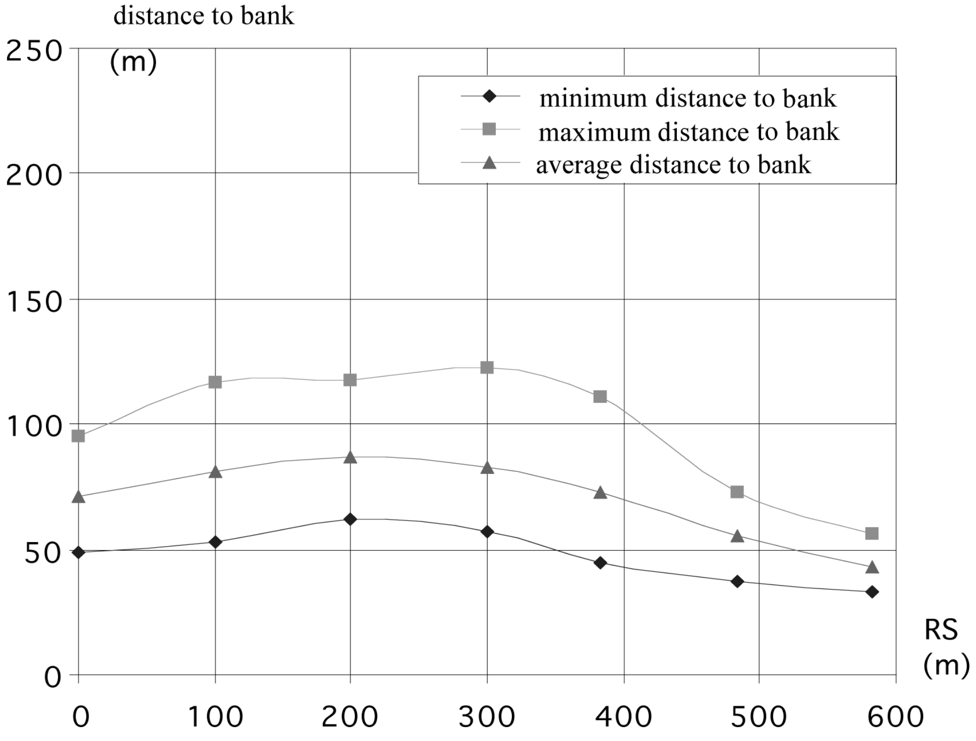


Slika 6 **Položaj pravaca relativnih stacionaža na kojima je kontrolirana udaljenost referentne točke sastava od obale**

Figure 6 **Positions of relative stations where distance of the vessel combination's referent point to the river bank was verified**

Dijagram 1 **Udaljenosti karakteristične točke sastava G-3 u manevru uplovljavanja u kanal pri VPV**

Chart 1 **Distances of the characteristic point of the G-3 combination in the canal entry manoeuvre for VPV**



Tablica 5 **Udaljenosti karakteristične točke sastava G-3 u manevru uplovljavanja u kanal pri VPV**

Relativna stacionaža RS (m)	Najmanja udaljenost od obale (m)	Najveća udaljenost od obale (m)	Prosječna udaljenost od obale (m)
0	48,7	95,2	70,9
100	52,9	116,9	80,8
200	62,3	117,6	86,5
300	57,5	122,3	82,6
383	45,0	110,8	72,8
483	37,5	73,2	55,8
583	32,8	56,3	42,9

6. Zaključak

Važno je uočiti da je pored objektivne, kvantificirane, brojkama izražene procjene prikladnosti predložene konfiguracije ušća kanala vrlo važna i subjektivna stručna procjena osobe koja dobro poznaje tehniku navigacije na rijekama. Zato su zatraženi stručna procjena i mišljenje kapetana Željka Radića (*Dunavski Lloyd*), koji ima bogato praktično iskustvo u upravljanju riječnim sastavima.

Uspoređujući ponašanje modela riječnoga sastava pri manevriranju s ponašanjem stvarnih sastava dolazi se do zaključka da model vrlo vjerno oponaša gibanje sastava u prirodnoj veličini. To znači da se zaključke o prikladnosti, odnosno neprikladnosti, neke konfiguracije ušća kanala do kojih se došlo ispitivanjem na modelima može pouzdano primijeniti i na objekt u naravi.

Razmatranje rezultata modelskih ispitivanja navodi na zaključak da je ušće kanala Dunav – Sava kod Vukovara dobro oblikovano i da omogućuje siguran manevar uplovljavanja, a da se ne govori o neusporedivo lakšem isplovljavanju. U skladu s očekivanjima, manevar tegljenim sastavom, posebno pri uplovljavanju u kanal, pokazao se bitno zahtjevnijim od ostalih. Uočeno je da je manevriranje guranim sastavom na višem plovnom vodostaju mnogo lakše, jer je širina vodnog lica u kanalu veća pri višem vodostaju (pokos je 1:3), bez obzira što je pri višoj razini vode brzina strujanja veća. S druge strane, upravljanje modelom tegljenoga sastava pokazalo se lakšim kod nižeg vodostaja, dakle pri nižim brzinama strujanja.

Table 5 **Distances of the characteristic point of the G-3 combination in the canal entry manoeuvre for VPV**

Relative station RS (m)	Minimum distance to river bank (m)	Maximum distance to river bank (m)	Average distance to river bank (m)
0	48.7	95.2	70.9
100	52.9	116.9	80.8
200	62.3	117.6	86.5
300	57.5	122.3	82.6
383	45.0	110.8	72.8
483	37.5	73.2	55.8
583	32.8	56.3	42.9

6 Conclusion

It is important to note, that besides having an objective, quantified and in numbers expressed adequacy assessment of the suggested canal confluence configuration, it is also important to have a subjective expert assessment from a person who has knowledge on river navigation. Therefore an expert assessment and opinion was sought from captain Željko Radić (*Danube Lloyd*), who has rich practical experience in river navigation.

Comparing the behaviour of the vessel combination model during manoeuvre with the behaviour of actual compositions it can be concluded that the model very truly imitates the movement of a full-scale vessel combination. This means that the conclusions about adequacy or inadequacy of a certain canal confluence configuration based on model tests can also be reliably applied to the actual object (prototype).

Consideration of the model test results leads to the conclusion that the Danube – Sava Canal confluence at Vukovar is well shaped and ensures safe entry manoeuvre, not to speak of incomparably easier exit. As expected, the tow combination manoeuvre, especially during canal entry, proved to be considerably more demanding than the others. It was noticed that the push combination manoeuvre was much easier for high water level, because the canal water face width is greater during high water level (slope is 1:3), regardless of higher water flow velocity. On the other hand, the tow model navigation proved to be less difficult at lower water level, i.e. lower flow velocities.

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