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METODE IZRAČUNA DODATNOG ZAGAŽAJA BRODA I NJEGOVO PREDVIĐANJE KORISTEĆI AIS U VTS SLUŽBI

METHODS OF CALCULATING THE SHIP'S SQUAT AND ITS PREDICTION USING AIS IN VTS

SAŽETAK

Predmet ovoga rada je predstavljanje i komparacija metoda izračuna dodatnog zagažaja broda, te njihovo korištenje u VTS službama za predviđanje opasnosti od nasukanja broda. Analizom i komparacijom do sada upotrebljavanih empirijskih formula za izračun dodatnog zagažaja, navodi se koje metode su pogodnije za određene vrste brodova i karakteristične plovne putove. VTS službe raspolažu detaljnim podacima o plovnim putovima područja nadležnosti, a koristeći AIS sustav dostupni su svi statički i dinamički podaci broda. Na temelju navedenog u radu se iznosi mogućnost integracije empirijskih formula za izračun dodatnog zagažaja, brodskih podataka iz AIS sustava te vektorskih elektroničkih karata. Osnovni cilj rada je ukazati da VTS službe mogu aproksimativno određivati dodatni zagažaj broda u plovidbi te predviđati nastupanje opasnosti od nasukanja radi smanjivanja dubine s donje strane kobilice ispod kritične vrijednosti. Predlažu se izračuni i uvjeti za predviđanje i alarmiranje kritične dubine ispod kobilice u realnom vremenu.

Ključne riječi: *dodatni zagažaj, dubina ispod kobilice, VTS, AIS*

SUMMARY

This paper aims at presenting and comparing the methods of calculating ship's squat, and their possible application in VTS services for predicting the danger of grounding. Analyzing and comparing the existing empirical formulas, various methods and their suitability for different types of ships and waterways are discussed. VTS services have detailed information regarding the waterways within the area of jurisdiction, and all static and dynamic ship data are available using the AIS system. Based on the above mentioned, the paper presents the possibility of integrating squat empirical formulas, the necessary ship's data retrieved from AIS system, and vector electronic charts. The Main goal is to point out that VTS services can approximately determine the squat of the ship underway, and predict imminent danger of grounding due to reducing under keel clearance below the critical value. Calculations and conditions are proposed for predicting and alarming the critical under keel clearance in real time.

Keywords: *Squat, under keel clearance, VTS, AIS.*

UVOD

S razvitkom tehnologije u današnje doba, može se reći da gotovo ne postoje granice pri gradnji brodova različitih namjena. Brodovi se grade u dimenzijama koje prije nekoliko desetljeća nisu bile zamislive. Luke i terminali diljem svijeta često teško prate trend gradnje sve većih brodova, stoga nerijetko zbog svojih ograničenja, posebice dubine i širine prilaznih putova te mjesta priveza, ne mogu primiti velike brodove novijeg godišta. Da bi se taj problem umanjio luke i prilazi se jaružaju i preuređuju te se često primaju brodovi s vrlo malom dubinom ispod kobilice (UKC – Under keel clearance). Tijekom rizične navigacije ograničenim plovnim putovima takvi brodovi su izloženi opasnosti od nasukanja uslijed efekta dodatnog zagažaja. Taj efekt se donekle može izračunati i predvidjeti, međutim, u praksi se nerijetko zanemaruje.

Razvojem sustava za nadzor i upravljanje pomorskim prometom (VTS – Vessel traffic service) obalnih država povećava se stupanj sigurnosti na moru. Kombinacijom elektroničkih karata, radara, automatskog identifikacijskog sustava (AIS – Automatic identification system), kamera te ostalih sustava i senzora, takve službe mogu detaljno nadzirati i djelomice upravljati pomorskim prometom. Jedan od sljedećih pravaca razvoja računalne, tehnološke i organizacijske podrške VTS službi jest predviđanje opasnih situacija na moru te upozoravanje sudionika u pomorskom prometu prije nastanka takve kritične situacije.

Cilj ovoga rada je prikazati i razmotriti integraciju metoda izračuna dodatnog zagažaja i dubine ispod kobilice broda u stvarnom vremenu s postojećim sustavima u VTS službi i AIS-om kao primarnim izvorom podataka. S time bi se dobila mogućnost predviđanja nastanka efekta dodatnog zagažaja, smanjenja minimalno potrebne dubine ispod kobilice te opasnosti od nasukanja. Za sve navedeno VTS služba trebala bi biti u stanju predvidjeti, neovisno o komunikaciji s brodom, odnosno automatski, da se operateri dodatno ne opterećuju zadacima.

U ovome radu korištena je metoda analize pri navođenju empirijskih formula za izračun dodatnog zagažaja, koje su također obrađene i s metodom komparacije. Upotrebljena je metoda deskripcije prilikom predstavljanja mogućeg djelovanja sustava za predviđanje dodatnog zagažaja i dubine ispod kobilice broda u sklopu VTS službe.

INTRODUCTION

With the development of technology in today's era, one can almost say that there are no limits in the construction of ships for different purposes. Ships are being built in dimensions that were not imaginable in only a few decades ago. Ports and terminals around the world are often in difficulty to follow the trend of building larger ships, and because of their limitations, especially in depth and width of waterways and berths, they cannot accommodate large ships. To lessen this problem, ports with their approaches are being dredged and rearranged and often receive ships with a very small under keel clearance (UKC). During the navigation in restricted waterways, ships are at risk of grounding due to small UKC and the squat effect. This effect can be calculated and predicted, but in practice it is often omitted or miscalculated.

With the VTS (Vessel Traffic Service) development in coastal states, the level of safety at sea is increasing. The combination of electronic charts, radar, automatic identification system (AIS), cameras and other systems and sensors, offers VTS the possibility to monitor and partially control maritime traffic from the land. One of the new directions in data processing and organizational support development in VTS service is predicting dangerous situations at sea and warning traffic participants before the onset of such critical situations.

The aim of this paper is to present and discuss methods for squat calculation and under keel clearance of the vessel in real time using the existing systems in VTS service, where AIS is a primary source of ship data. With such integration it could be possible to predict the occurrence of the squat effect, minimum allowed under keel clearance and appearance of grounding danger. VTS service should be able to predict the above mentioned situations automatically, independent of communication with the ship, with no extra burden tasks to the operators.

In this paper, the analysis method is used in indicating the empirical formulas for squat calculation, which are elaborated by the comparison method. The descriptive method is used in presenting the possible operation for predicting the squat effect and critical under keel clearance of the ship within the VTS service.

2. METODE IZRAČUNA DODATNOG ZAGAŽAJA BRODA

Dodatni zagažaj (engl. squat) može se definirati kao razlika urona broda u mirovanju i broda koji se kreće kroz vodu. Kretanjem broda dolazi do ubrzanog strujanja vode uz bok i ispod kobilice, što uzrokuje promjene hidrodinamičkog tlaka vode oko trupa broda te konačno pojavu dodatnog urona. U plovidbi na otvorenom moru dodatni zagažaj poprima vrlo male vrijednosti te se može zanemariti, za razliku od plovidbe u plitkim vodama ili kanalima u kojima je slobodno protjecanje vode ispod trupa ograničeno, te dodatni zagažaj može poprimiti znatne vrijednosti, u nekim slučajevima i do dva metra. Najveća opasnost pri takvoj pojavi u plitkim vodama je nasukanje broda, što može dovesti do niza drugih izvanrednih okolnosti poput oštećenja i proboja trupa, oštećenja tereta, onečišćenja mora te ljudskih žrtava[1].

Pojavljivanje dodatnog zagažaja, odnosno ulazak u plitke vode ili kanale u kojima se stvaraju uvjeti pogodni za taj efekt može se djelomice prepoznati po određenim općeprihvaćenim znacima u pomorstvu, kao što su povećanje valova na pramcu, otežano kormilarenje, smanjenje okretaja vijka, smanjenje brzine, promjena gaza, vibriranje cijeloga broda, pojavljivanje zamuljene vode u brazdi broda i dr.

Iako je problem dodatnog zagažaja poznat već nekoliko desetljeća, zbog mnogih faktora, među kojima se posebno ističu različite linije trupa brodova i bitno različite konfiguracije morskog dna diljem svjetskih mora, danas još nije izvedena općenita metoda proračuna dodatnog zagažaja koja se može pouzdano primijeniti u svim slučajevima, odnosno na svim vrstama brodova u svim područjima plovidbe. Do danas je izvedeno mnogo različitih testiranja na brodovima, modelima brodova, računalima i u raznim laboratorijima.

Posljednjih desetak godina na brodovima se testiranja najčešće provode analizirajući podatke iz GPS uređaja (Global positioning system) po-

[1] Na opasnost od dodatnog zagažaja može uputiti i sljedeća lista poznatijih nasukanja uslijed tog efekta u posljednjih 10 godina: *Riverdance*, Ro-Ro brod, Blackpool, 2008., *LT Cortesia,* brod za prijevoz kontejnera, Dover, 2008., *Emsland,* brod za generalni teret, Montrose, 2006., *Desh Rakshak,* tanker, Melbourne, 2006., *Kentucky Highway,* Ro-Ro brod, Parana River, 2005., *Eastern Honour,* tanker, Marsden Point, New Zealand, 2003., *Don Raul,* brod za rasute terete, Pulluche Canal, 2001. [10]

2. SQUAT CALCULATION METHODS

Squat can be defined as the ship's vertical drop in the water as it moves through the water. While underway ship induces an accelerated flow of water along the hull and below the keel, causing a change in hydrodynamic pressure around the hull of the ship and, finally, the appearance of additional vertical drop. During navigation in the open unrestricted waters, squat takes a very small value and can be ignored, but in navigation in shallow waters or canals, where the free flow of water beneath the hull is limited, squat can take considerable value, in some cases up to two meters. The biggest danger with the squat phenomenon in shallow waters is stranding of the ship, which can lead to a number of other emergencies such as damage and breach of the hull, cargo damage, pollution and injuries[1].

The appearance of squat and entering shallow waters or canals, where conditions favorable for the squat effect are created, may be recognized, in part, by certain generally accepted signs in the seafaring. These signs are wave increase in the bow, steering difficulties, propeller rotation reduction, speed reduction, change in draft, ship vibrating, appearing muddy water in the ship's wake, etc.

Although the squat problem has been known for several decades due to various factors, among which different hull lines and substantially different configurations of the seabed across the seas are emphasized, a general method for squat calculation that can be reliably applied in all cases i.e. on all ship types in all areas of navigation, has not been developed. Until now, many different tests have been carried out on ships, models, computers, and in different laboratories.

Over the past ten years, tests on ships have been conducted mostly by analyzing data from GPS devices mounted onto the ship's bow, stern and amidships, precisely measuring the

[1] At the risk of squat danger can indicate the following list of known groundings due to this effect in the last 10 years: *Riverdance*, Ro-Ro ship, Blackpool, 2008.; *LT Cortesia*, container ship, Dover, 2008.; *Emsland*, general cargo, Montrose, 2006; *Desh Rakshak*, tanker, Melbourne, 2006.; *Kentucky Highway*, Ro-Ro ship, Parana River, 2005.; *Eastern Honour*, tanker, Marsden Point, New Zealand, 2003.; *Don Raul,* bulk carrier, Pulluche Canal, 2001. [10] Listen Read phonetically

stavljenih na pramac, sredinu i krmu broda, koji precizno mjere vertikalni pomak dijelova broda prilikom kretanja [3, 8, 6]. Korištena je i SHIPS (Shore independent precise squat observation) metoda mjerenja [5] koja uz testirani brod uključuje prateću referentnu brodicu. S obzirom na veličinu, dodatni zagažaj male brodice, na kojoj se nalazi GPS uređaj kao referentna nula promatranom brodu, može se zanemariti. Tom metodom mjeri se razlika visina GPS uređaja na promatranom brodu i referentne brodice, prilikom stajanja te kretanja kroz plitke vode.

Od mnogobrojnih testiranja na računalima i modelima, mogu se izdvojiti mjerenja u simulatorima poput ERDC STS simulatora (Engineer research and development center Ship/Tow simulator) koristeći *Fortram* program [2] te CFD (Computational fluid dynamics) metoda koristeći *Fluent* program [7].

Između mnogih istraživača i autora koji su dali svoje prijedloge metoda za izračunavanje dodatnog zagažaja, postoje i suglasja koja su dokazana raznim fizikalnim zakonima i testiranjima, a ona su:

- dodatni zagažaj se povećava približno proporcionalno s kvadratom brzine broda, međutim obično je potrebna brzina veća od 6 čv da nastupi taj efekt, odnosno pri manjim brzinama je zanemariv;
- dodatni zagažaj se javlja i na otvorenom moru, a uzrok je strujanje vode uslijed kretanja broda;
- dodatni zagažaj bitno se povećava u područjima ograničenog prostora uokolo broda, poput uskih kanala ili plitkih voda;
- dodatni zagažaj djeluje na trim broda: za brodove s velikim koeficijentom punoće deplasmana (koeficijent punoće deplasmana – Cb > 0,7) poput VLCC-ULCC tankera, specifičan je dodatni zagažaj pramcem, posebice u slučaju ako je brod početno pretežan. Za uske brodove finih linija poput putničkih ili kontejnerskih brodova (Cb < 0,7), specifičan je dodatni zagažaj krmom, posebice pri velikim brzinama i u slučaju ako je brod početno zatežan [9, 4];
- tvrda morska dna (kamen) pretežno uzrokuju veći dodatni zagažaj kod brodova nego meka dna (mulj, pijesak) iste dubine;
- blisko prestizanje i mimoilaženje brodova u vodama ograničene širine pretežno uzrokuju

vertical move of the ship's parts during navigation.[3][8][6] The SHIPS (Shore Independent Precise Squat Observation) measuring method, which includes a small escort craft along the tested ship, has also been used [5]. The squat of the escort craft is known due to separate calibration measurements. The difference between the tested ship and the escort craft in GPS devices height is measured in static and dynamic (underway) conditions using this method.

Some measurements, such as ERDC STS simulator (Engineer Research and Development Center Ship/Tow Simulator) using *Fortram* program [2], and CFD (Computational Fluid Dynamics) method using *Fluent* software [7], can be singled out of a number of tests on computers and models.

Among many researchers and authors, who have given their approach to squat calculation methods, there are compliances sustained by the various laws of physics and testing. They are listed as follows:

- squat increases approximately proportionally to the square of the ship's speed. However, it usually requires a speed of six knots or higher for this effect to appear [10],
- squat occurs in open waters as well, and it is caused by the water flow while the ship is underway,
- squat significantly increases in waters with limited space around the ship's hull, such as narrow channels, shallow waters or canals,
- squat affects the trim: bow squat is specific for ships with a large block coefficient (C_b>0.7), such as VLCC-ULCC tankers, especially if the vessel is initially trimmed by the bow. Stern squat is specific for ships with fine lines, such as passenger or container ships (C_b<0.7), especially at high speeds or if the ship is initially trimmed by the stern.[9][4]
- rigid sea beds (rocks) mainly cause higher squat than soft sea beds (mud, sand) of the same depth,
- close overtaking or passing of two or more ships in constrained waters mainly cause higher squat than unobstructed sailing on the same route,
- turning during underway in rivers or canals in most cases leads to drift and increase of the squat effect.

veći dodatni zagažaj nego prilikom neometane plovidbe istim putem;

- prilikom zakretanja u rijekama i kanalima, u većini slučajeva dolazi do efekta zanošenja i povećanja dodatnog zagažaja.

Zbog raznolikosti u ograničenjima plovnih putova po širini i dubini, određene su tri osnovne vrste plovnih putova: plitke vode neograničene širine, plitke vode ograničene širine i kanali. Za izračune dodatnog zagažaja ograničenost plovnog puta, u odnosu na veličinu broda, najtočnije opisuje vrijednost odnosa površina presjeka broda i plovnog puta koja se označuje s blok faktorom S [9, 4].

Na pojavu i vrijednost dodatnog zagažaja utječu mnogi brodski i vanjski faktori. Od brodskih faktora najznačajniji su forma broda, brzina kretanja i početni trim. Od vanjskih faktora koji se odnose na plovni put najznačajniji su širina puta ili kanala, zavojitost, odnos širine broda i puta, odnos gaza broda i dubine puta, blizina obale, konfiguracija i vrsta dna te promet drugih plovila. Vanjski faktori koji se odnose na oceanološke utjecaje su valovi, vjetar i morske struje.

Jedan od važnijih brodskih faktora je bezdimenzionalni koeficijent punoće deplasmana broda C_b, kojim se opisuje brodska forma, a označava dio volumena koju zauzima podvodni dio trupa broda u bloku istih dimenzija.

Simboli koji se koriste u izrazima za proračune dodatnog zagažaja jesu:

Karakteristike i mjere za brod

Lpp – duljina broda između okomica (m)
B – širina broda (m)
T – gaz broda (m)
v – brzina broda (m/s), v_k (u čvorovima)
∇ – volumen podvodnog dijela broda (m^3)
C_b – koeficijent punoće deplasm. ($=\dfrac{\nabla}{LppBT}$)
s – dodatni zagažaj (m)
s_{max} – maksimalni dodatni zagažaj (m)
sM – srednji dodatni zagažaj (m)
sB – dodatni zagažaj na pramcu (m)
AS – podvodna površina na glavnom rebru (≈BT) (m^2)
AWP – površina broda na vodenoj liniji (m^2)
CWP – koeficijent površine broda na vodenoj liniji (=AWP/LppB)
θ – kut trima (m/m, °)

Due to a diversity of waterway restrictions in breadth and depth, three basic types of waterways used for squat analysis are determined: unrestricted shallow water, restricted channel and canal. For squat calculations, the restriction of the waterway in relation to ship's size most accurately describes the ratio between the value of cross-sectional area of the ship and the waterway, marked with the blockage factor S. [9][4]

Many ship and external factors influence the appearance and value of the squat effect. Among the ship factors, the most important are ship's form, speed and initial trim. Among external factors related to the waterway, the most significant are width, characteristics of the bends, the width ratio between ship and waterway cross-sectional area, the ratio between ship's draft and depth, distance to the bank, configuration and type of the seabed and traffic. External factors related to the oceanographic impact are waves, winds and currents.

One of the most important ship factors is the dimensionless block coefficient C_b, which describes the ship's form by indicating a volume occupied by the submerged ship's hull in the block of the same size.

Symbols used in formulas for squat calculation are:

Ship characteristics:

Lpp – ship length between perpendiculars (m);
B – ship beam (m);
T – ship draft (m);
v – ship speed through water (m/s), v_k (knots);
∇ – ship volume of displacement (m^3);
C_b – ship block coefficient ($=\dfrac{\nabla}{LppBT}$);
s – squat (m);
s_{max} – maximum squat(m);
s_M – amidships/average squat (m);
s_B – bow squat (m);
A_S – ship's underwater amidships cross section (≈BT) (m^2);
A_{WP} – ship waterplane area (m^2);
C_{WP} – ship waterplane coefficient (=A_{WP}/LppB);
θ – trim angle (m/m, °).

Karakteristike i mjere za plovni put

W – širina puta ili kanala na dnu (m)
W_{eff} – širina puta na površini vode (m)
h – dubina vode (m)
A_C – površina presjeka plovnog puta (m²)
ΔA_C – smanjenje A_C zbog depresije vodenog raza (m²)
S – blok faktor (=A_S /A_C)
S_1 – ispravljeni blok faktor (=(A_S /A_{Ch})/K_1) (Huuska)
S_2 – faktor povratnog strujanja vode uzrokovano brodom (=S/(1-S)) (Barrass)
F_{nh} – *Froud*-ov broj dubine tj. brodski otpor kretnju kroz plitke vode ($=\frac{v}{\sqrt{gh}}$)

Empirijske formule za izračun dodatnog zagažaja

Prve teorijske pristupe rješavanju problema dodatnog zagažaja učinio je Tuck (1966) čiji su se radovi temeljili na brodovima finih linija. Tako je Tuck predložio formule za izračun srednjeg dodatnog zagažaja te kuta trima, za plovne putove neograničene širine, u kojima je upotrijebio koeficijente C_Z i C_θ kao funkcije karakteristika brodskog trupa:

$$s_M = C_Z \frac{\nabla}{Lpp^2} \frac{F_{nh}^{\ 2}}{\sqrt{1-F_{nh}^{\ 2}}}, \qquad (1)$$

$$\theta = C_\theta \frac{\nabla}{Lpp^2} \frac{F_{nh}^{\ 2}}{\sqrt{1-F_{nh}^{\ 2}}} . \qquad (2)$$

Nakon Tucka, Hooft (1974) je izveo nekoliko formula u kojima je predlagao vrijednosti koeficijenata C_Z i C_θ za brodove različitih brodskih formi te je predstavio konačni izvod za dodatni zagažaj na pramcu sa zajedničkim koeficijentom vrijednosti u rasponu od 1,9 do 2,03 koji glasi:

$$S_b = (1.9...2.03) \frac{\nabla}{Lpp^2} \frac{F_{nh}^{\ 2}}{\sqrt{1-F_{nh}^{\ 2}}} . \qquad (3)$$

Hooftova formula je jedna od ukupno šest formula (Barrass II, Huuska, Eryuzlu, Eryuzlu i Hausser, ICORELS, Hooft) koje su uspoređivane prilikom CFD-e testiranja u programu *Fluent* (uzorak: brod za prijevoz kontejnera s Cb = 0,65). Tada je Hooftova formula jedina davala gotovo iste rezultate kao i prosječna vri-

Waterway characteristic:

W – channel width, measured at bottom (m);
W_{eff} – effective width of waterway (m);
h – water depth (m);
A_C – cross section area of canal (m²);
S – blockage factor (=A_S /A_C);
S_1 – corrected blockage factor (=(A_S /A_{Ch})/K_1) (Huuska);
S_2 – velocity return factor (=S/(1-S)) (Barrass);
F_{nh} – *Froude* number, i.e. ship's resistance to movement through shallow water ($=\frac{v}{\sqrt{gh}}$).

Empirical formulas for squat calculation:

The first theoretical approach to squat problem was made by Tuck (1966), whose experiments were based on fine lined ships. Tuck proposed the formula for calculating the average squat and trim angles for the shallow water waterways of unlimited width, using C_Z and C_θ coefficients as functions of the hull characteristics [9]:

$$s_M = C_Z \frac{\nabla}{Lpp^2} \frac{F_{nh}^{\ 2}}{\sqrt{1-F_{nh}^{\ 2}}}, \qquad (1)$$

$$\theta = C_\theta \frac{\nabla}{Lpp^2} \frac{F_{nh}^{\ 2}}{\sqrt{1-F_{nh}^{\ 2}}} . \qquad (2)$$

After Tuck, Hooft (1974) presented several formulas proposing values for C_Z and C_θ coefficients for ships of various forms, after which he presented the final formula for the bow squat with a common coefficient ranging from 1.9 to 2.03 :

$$S_b = (1.9...2.03) \frac{\nabla}{Lpp^2} \frac{F_{nh}^{\ 2}}{\sqrt{1-F_{nh}^{\ 2}}} . \qquad (3)$$

Hooft's formula is one of the six formulas (Barrass II, Huuska, Eryuzlu, Eryuzlu and Hausser, ICORELS, Hooft) evaluated during the CFD testing in the *Fluent* program (sample: container ship with C_b = 0.65). Only Hooft's formula gave almost the same results as the average value of all tested formulas together.[7] Except for Hooft's formula, the authors of the CFD tests sorted out Eryuzlu et al and Barrass II methods that gave good and most consistent results.

jednost svih testiranih formula zajedno [7]. Autori CFD-e testiranja su, osim Hooftove formule, izdvojili Barrass II i Eryuzlu i dr. metode koje su davale dobre i većinom sukladne rezultate.

Huuska (1976) se nakon mnogobrojnog testiranja nadovezuje na Hoofta te zaključuje da koeficijent 2,4 daje bolje rezultate na putevima neograničene širine. Formuli još dodaje blok faktor za kanale K_S kojim omogućuje računanje dodatnog zagažaja i na putovima ograničene širine te kanalima:

$$S_b = 2.4 \frac{\nabla}{Lpp^2} \frac{F_{nh}^{\ 2}}{\sqrt{1-F_{nh}^{\ 2}}} K_s \ . \qquad (4)$$

Prilikom računanja blok faktor za kanale poprima sljedeće vrijednosti: $K_S = 7{,}45S_1 + 0{,}76$, za slučaj kada je ispravljeni blok faktor $S_1 > 0{,}03$, te vrijednost $K_S = 1$ za slučaj kada je $S_1 \leq 0{,}03$ [9].

Huuskova formula je davala najtočnije rezultate u usporedbi s mjerenim vrijednostima dodatnog zagažaja prilikom testiranja panamax brodova za rasute terete u Panamskom kanalu. Dodatni zagažaj je mjeren vertikalnim pomakom četiri DGPS uređaja (Differential global positioning system) postavljenih na oba krila mosta, sredini broda te na pramcu [6]. Međutim, prilikom testiranja i mjerenja dodatnog zagažaja na prilaznom putu luci Charleston, čiji je uzorak bio 12 brodova (kontejnerski, Ro-Ro i brodovi za rasuti teret) Huuskova metoda je davala najviša rješenja, tj. najopasniji scenarij dodatnog zagažaja u usporedbi s drugim testiranim empirijskim formulama (Barrass II i Romisch). Na nekim dijelovima puta izračunate vrijednosti Huuskovom metodom iznosile su gotovo dvostruko više od mjerene [3].

ICORELS (International commission for the reception of large ships, 1980) formula je nastala na temelju Hooftove, s koeficijentom 2,4. preuzetim od Huuska, a predložena je za izračun pramčanog dodatnog zagažaja brodova konvencionalnih linija. Neki autori predlažu početni koeficijent između 1,75 i 2,4 za brodove pune linije, odnosno s visokim koeficijentom punoće deplasmana.

$$S_b = 2.4 \frac{\nabla}{Lpp^2} \frac{F_{nh}^{\ 2}}{\sqrt{1-F_{nh}^{\ 2}}} \ . \qquad (5)$$

after numerous tests, Huuska (1976) concludes that the coefficient of 2.4 gives better results in the waterway of unlimited width. Huuska adds a correction factor K_S to the Hooft's formula, which enables calculation of the squat in the restricted channels and canals:

$$S_b = 2.4 \frac{\nabla}{Lpp^2} \frac{F_{nh}^{\ 2}}{\sqrt{1-F_{nh}^{\ 2}}} K_s \ . \qquad (4)$$

The correction factor takes the following values: $K_S=7.45S_1+0.76$, when the corrected blockage factor is $S_1>0.03$, and $K_S=1$ when $S_1 \leq 0.03$.[9] Huuska's formula gives the most accurate results in comparison with measured values during squat testing on Panamax bulk carriers in the Panama Canal. The Ship's squat was measured by vertical motion of four DGPS devices (Differential Global Positioning System) fitted to both bridge wings, amidships and bow.[6] However, in squat testing and measurement on the approaches to the port of Charleston, where 12 ships were involved (container ship, Ro-Ro ships and bulk carriers), Huuska's method gave the highest results i.e. the most dangerous scenario of squat effect compared with results of other empirical formulas (Barrass II and Römisch). In some parts of the waterway, the results calculated by Huuska's method gave values almost double to the measured ones.[3]

The ICORELS (International Commission for the Reception of Large Ships, 1980) formula was created on the basis of Hooft's formula, with a coefficient of 2.4 taken from Huuska. It is proposed for calculating the bow squat for conventional form ships. Some authors suggest the value of initial coefficient between 1.75 and 2.4 for full form ships with a high block coefficient.[9] ICORELS formula goes as presented:

$$S_b = 2.4 \frac{\nabla}{Lpp^2} \frac{F_{nh}^{\ 2}}{\sqrt{1-F_{nh}^{\ 2}}} \ . \qquad (5)$$

This is one of the empirical formulas recommended by PIANC (Permanent Association of Navigation Congresses) for general squat calculations. However, it should not be used if the *Froude* number $F_{nh} > 0.7$.[9] ICORELS proved to be a good approximate formula in comparison with the measured values during testing with SHIPS method, where three bulk carriers participated (217x23 m, 215x32.2 m and

Ujedno ovo je jedna od empirijskih formula koje preporuča PIANC (Permanent Association of Navigation Congresses) za opće izračune, međutim ne bi se smjela koristiti ukoliko je Froudov broj $F_{nh} > 0{,}7$ [9]. ICORELS se pokazala kao dobra aproksimativna formula u usporedbi s izmjerenim vrijednostima pri testiranju metodom SHIPS u kojoj su sudjelovala tri broda za rasuti teret (217 x 23 m, 215 x 32,2 m te 185 x 32,3 m). Izračunati dodatni zagažaj je pokazivao do 10 cm veće vrijednosti od mjerenog. Događalo se navedeno jer se dodatni zagažaj računa iz jedne točke broda, na što utječu valovi i konfiguracija dna (manje nagle promjene dubine), a na koje u naravi brod djeluje kao svojevrsni filtar, zbog svoje dužine i širine, čime kompenzira manje promjene [5].

Millward (1990) je predstavio svoju formulu za izračun maksimalnog pramčanog dodatnog zagažaja za plovne putove neograničene širine. Izvodio je testove na modelima s koeficijentom punoće deplasmana u rasponu 0,44 < Cb < 0,83, te za taj uvjet vrijedi formula:

$$S_b = \left(61.7 C_b \frac{T}{Lpp} - 0.6\right)\frac{Lpp}{100}\frac{F_{nh}^{\;2}}{\sqrt{1-F_{nh}^{\;2}}} \; . \qquad (6)$$

Rezultati izračuna daju više vrijednosti dodatnog zagažaja u usporedbi s drugima te time spada u tzv. pesimistične metode. Time se u konačnici povećava faktor sigurnosti brodova jer se uzimanjem u obzir većih vrijednosti smanjuje opasnost od nasukanja [9].

Barrass je predstavio i izmijenio nekoliko svojih formula, od kojih je aktualna pojednostavljena formula Barrass II za dobivanje najveće vrijednosti dodatnog zagažaja:

$$S_{max} = \frac{C_b S_2^{\frac{2}{3}} V_k^{2.08}}{30} \; . \qquad (7)$$

I ova je jedna od formula koje preporuča PIANC za opće izračune, međutim formula vrijedi za uvjete unutar kojih su se izvodili testovi na brodovima i modelima, a to su: koeficijent punoće deplasmana u rasponu 0,5 < Cb < 0,9, vode neograničene i ograničene širine te kanali s odnosom dubine i gaza 1,1 < h/T< 1,5, te Froudov broj $F_{nh} < 0{,}7$. Za putove neograničene širine postoji uvijet za minimalnu širinu plovnog puta $W_{eff} \geq 8B$ [9, 2]. Prilikom istraživanja SHIPS metodom, u usporedbi s mjerenim 185x32.3 m). The Calculated squat showed up to 10 cm higher values than the measured ones. This difference appeared because the squat is calculated from one ship's point, influenced by the wave height and seabed configuration (small abrupt changes in depth), but normally the ship acts as a filter, due to its length and width which compensates for such minor changes.[5]

Millward (1990) presented another formula for calculating the maximum bow squat for waterways of unrestricted width. He performed tests on ship models with the block coefficient in range $0.44<C_b<0.83$, and for this condition the formula states:

$$S_b = \left(61.7 C_b \frac{T}{Lpp} - 0.6\right)\frac{Lpp}{100}\frac{F_{nh}^{\;2}}{\sqrt{1-F_{nh}^{\;2}}} \; . \qquad (6)$$

Generally, the calculation results provide higher squat values compared to others and thus belong to the so-called pessimistic methods. Ultimately this increases ship's safety, because if a higher value is taken into account the risk of grounding is reduced.[9]

Barrass introduced and updated several formulas, Barrass II being the current simplified formula used to obtain the maximum squat value:

$$S_{max} = \frac{C_b S_2^{\frac{2}{3}} V_k^{2.08}}{30} \; . \qquad (7)$$

This is one of the formulas recommended by PIANC for general calculations. The formula is valid for the conditions under which tests were performed on ships and ship models, and they are: block coefficient in range $0.5<C_b<0.9$, unrestricted waters, restricted channels and canals with the depth/draft ratio 1.1<h/T<1.5, and *Froude* number $F_{nh}<0.7$. For the unrestricted waterways there is a requirement for a minimum effective width $W_{eff} \geq 8B$.[9][2] In experiments with SHIPS method, in comparison with the measured values BarrassII formula was also used (general cargo ship 115.23x20.2 m). The results of squat calculations proved to be in good correlation with measured ones, with small discrepancies, although the h/T ratio along the tested waterway was slightly higher than 1.5.[5]

vrijednostima koristila se i Barrassova formula testiranjem broda za generalni teret (115,23 x 20,2 m). Rezultati izračuna su se pokazali u dobroj korelaciji s mjerenim, uključivši manja odstupanja, iako je odnos dubine i gaza h/T na testiranom plovnom putu bio nešto veći od 1,5 [5].

Postoje i pojednostavljeni izrazi Barrassove formule za neograničeni plovni put s odnosom dubine i gaza u rasponu 1,1 < h/T < 1,4 :

$$S_{\max} = \frac{C_b V_k^2}{100} \quad . \tag{8}$$

te za ograničeni plovni put na kojem je blok faktor u rasponu 0,100 < S < 0,265:

$$S_{\max} = \frac{C_b V_k^2}{50} \quad . \tag{9}$$

Eryuzlu i Hausser (1978) su izvodili testiranja s tankerima u nakrcanom stanju u vodama neograničene širine, u rasponu 1,08 ≤ h/T ≤2,75, te dali prijedlog za izračun dodatnog zagažaja na pramcu:

$$S_b = 0.113\left(\frac{T}{h}\right)^{0.27} BF_{nh}^{1.8} \quad . \tag{10}$$

Eryuzlu (1994.) je izvodio testiranja na modelima brodova za generalni i rasuti teret s vlastitim pogonom. Karakteristike eksperimenata su sljedeće: C_b ≥ 0,8, 6,7 ≤ L/B ≤ 6,8, 2,4 ≤ B/T ≤ 2,9, 1,1 ≤ h/T ≤ 2,5. Predložena formula može se koristiti u vodama neograničene i ograničene širine te kanalima:

$$S_b = 0.298\frac{h^2}{T}\left(\frac{V}{\sqrt{gT}}\right)^{2.289}\left(\frac{h}{T}\right)^{-2.972} K_b \quad . \tag{11}$$

Formula uključuje blok faktor za kanale K_b koji se mijenja sukladno uvjetima:

$$\frac{W}{B} < 9.61 \Rightarrow K_b = \frac{3.1}{\sqrt{\frac{W}{B}}}\text{; te } \frac{W}{B} \geq 9.61 \Rightarrow K_b = 1. \tag{12}$$

Općenito, ova metoda je preporučena za brodove punijih linija te valja računati na to da se dobivaju rezultati nižih vrijednosti u odnosu na druge formule [9].

There are also simplified expressions for Barrass formula for unrestricted waterway with a depth/draft ratio in range of 1.1<h/T<1.4:

$$S_{\max} = \frac{C_b V_k^2}{100} \quad . \tag{8}$$

And for a restricted waterway with a blockage factor in range of 0.100<S<0.265:

$$S_{\max} = \frac{C_b V_k^2}{50} \quad . \tag{9}$$

Eryuzlu and Hausser (1978) performed tests with laden tankers in unrestricted waterways with depth/draft range 1.08≤h/T≤2.75, and gave a proposal to calculate the bow squat:

$$S_b = 0.113\left(\frac{T}{h}\right)^{0.27} BF_{nh}^{1.8} \quad . \tag{10}$$

Eryuzlu (1994) carried out tests on general cargo and bulk carrier ship models with their own propulsion. Characteristics of the experiments are as follows: C_b≥0.8, 6.7≤L/B≤6.8, 2.4≤B/T≤2.9, 1.1≤h/T≤2.5. The proposed formula can be used in the unrestricted waterways, channels and canals:

$$S_b = 0.298\frac{h^2}{T}\left(\frac{V}{\sqrt{gT}}\right)^{2.289}\left(\frac{h}{T}\right)^{-2.972} K_b \quad . \tag{11}$$

The formula includes a correction factor for channel width K_b that changes in the following conditions:

$$\frac{W}{B} < 9.61 \Rightarrow K_b = \frac{3.1}{\sqrt{\frac{W}{B}}}\text{; te } \frac{W}{B} \geq 9.61 \Rightarrow K_b = 1. \tag{12}$$

Generally, this method is recommended for full form ships and it should be noted that the results have lower values when compared to other formulas.[9]

After numerous tests on ship models, Römisch (1989) developed a formula that is valid for all waterway types within the conditions 1.19≤h/T≤2.25, and reads as follows:

$$S_b = C_V C_F K_{\Delta T} T. \tag{13}$$

This formula is based on determining the critical ship velocity V_{cr}, which depends on the type of waterway where the vessel is sailing. A

Römisch (1989) je razvio svoju formulu nakon mnogobrojnih testiranja na modelima koja vrijedi za sve plovne putove unutar granica 1,19 ≤ h/T ≤ 2,25, a glasi:

$$S_b = C_V C_F K_{\Delta T} T. \tag{13}$$

Ova formula se temelji na određivanju kritične brzine broda V_{cr} koja ovisi o tipu plovnog puta u kojem se brod kreće, a iz koje se dobiva faktor ispravka brodske brzine C_V. Faktorom C_F Römisch označava ispravak za brodski oblik.[2] Römisch jedini daje mogućnost da se empirijskom formulom izračuna i dodatni zagažaj na krmi broda, za čiji izračun se koristi ista navedena formula u kojoj faktor C_F poprima vrijednost 1 [9, 2]. Prilikom testiranja i mjerenja dodatnog zagažaja na prilazu luke Charleston, u kojoj je Huuskova metoda davala najviše vrijednosti i time poprilično odstupala, rezultati Römischove formule su davali najtočnije, odnosno najsličnije vrijednosti u usporedbi s izmjerenim vrijednostima, podjednako na pramcu i krmi testiranih brodova [3].

Noorbin (1986) je razvio svoju formulu koja se temelji na Tuckorovom i Taylorovom izračunu dodatnog zagažaja. Formulom se računa pramčani dodatni zagažaj u vodama neograničene širine, a uvijet je Froudov broj $F_{nh} < 0,4$ [2]:

$$S_b = \frac{C_b}{15}\left(\frac{1}{Lpp/B}\right)\left(\frac{1}{h/T}\right)V_K^2 \ . \tag{14}$$

U konačnici, *The Overseas Coastal Area Development Institute of Japan* (2002) je u sklopu novog standarda plovnih putova u Japanu predstavio formulu za izračun pramčanog dodatnog zagažaja kako slijedi [2]:

$$S_b = \left[\left(0.7 + 1.5\frac{1}{h/T}\right)\left(\frac{C_b}{Lpp/B}\right) + 15\frac{1}{h/T}\left(\frac{C_b}{Lpp/B}\right)^3\right]\frac{V_S^2}{g}\ , \tag{15}$$

V_s označava servisnu brzinu broda.

Od ovih navedenih metoda PIANC izdvaja tri: *ICORELS*, *Barras II* te *Eryuzlu* koje su najprihvaćenije i koje su preporučene za opće izra-

[2] Za potpni uvid u cjelovitost i izvod formule i faktora preporuča se [PIANC, str 79]

correction factor for ship speed C_v is determined from the critical ship velocity. Factor C_F is a correction factor for ship shape[2]. Only Römisch formula gives the possibility to empirically calculate the stern squat, for calculation of which is used the same expression, in which factor C_F assumes a value of 1.[9][2] During the squat testing and measuring on the approach to Charleston harbor, where the Huuska's method gave the highest values and thus differed considerably, the results of Römisch formula gave the most accurate i.e. the most similar values when compared with the measured ones, both at the bow and stern of tested vessels.[3]

Noorbin (1986) developed his formula based on the calculations of Tuck and Taylor. Formula is used for bow squat calculation in the unrestricted waterways, with a *Froude* number condition $F_{nh}<0.4$ [2]:

$$S_b = \frac{C_b}{15}\left(\frac{1}{Lpp/B}\right)\left(\frac{1}{h/T}\right)V_K^2 \ . \tag{14}$$

Ultimately, *The Overseas Coastal Area Development Institute of Japan* (2002), as a part of a new standard for waterways in Japan, presented a formula to calculate bow squat, as follows [2]:

$$S_b = \left[\left(0.7 + 1.5\frac{1}{h/T}\right)\left(\frac{C_b}{Lpp/B}\right) + 15\frac{1}{h/T}\left(\frac{C_b}{Lpp/B}\right)^3\right]\frac{V_S^2}{g}\ , \tag{15}$$

V_s denotes ship service speed.

From the above mentioned methods PIANC distinguishes three: *ICORELS, Barras II* and *Eryuzlu*. These three are most accepted and recommended for general calculations if any squat test measurements on different ship types for a specified waterway are not performed.[9] For the correct selection and use of any of the above mentioned methods, it is essential to know their limitations in different conditions.

[2] For complete insight into the formula and factors it is recommended Permanent International Association of Navigation Congresses (PIANC), *Approach channels, a guide for design*, Supplement to Bulletin no 95, Brussels, 1997.p. 79.

čune ukoliko se nisu provodila testna mjerenja dodatnog zagažaja na različitim brodovima za određeni plovni put i time odredila najpogodnija metoda [9]. Za ispravni odabir i korištenje metoda na pojedinom brodu u različitim uvjetima potrebno je poznavati ograničenja svake metode te imati određeno iskustvo.

3. PREDVIĐANJE DODATNOG ZAGAŽAJA BRODA NA TEMELJU AIS PODATAKA

AIS podaci s brodova zaprimljeni u VTS centrima, osim za identifikaciju i nadzor plovidbe, pravilnom obradom mogu se korsititi u mnoge druge svrhe poput širokih analiza pomorskog prometa i predviđanja opasnih situacija na moru. Takvim obradama[3] AIS podataka unapređuje se svakodnevni rad VTS službi te se povećava opća sigurnost na moru.

Predviđanje dodatnog zagažaja koristeći AIS podatke pripadalo bi skupini mrežnih metoda obrađivanja podataka u stvarnom vremenu (*online analysis*)[4]. *Online* analizama se neprekidno prati stanje i kretanje brodova na plovidbenom području odgovornosti, a jedan od ciljeva je da VTS služba bude u stanju predvidjeti potencijalno vrlo opasne situacije te na vrijeme upozoriti ugroženi brod ili brodove radi sprječavanja pomorske nezgode.

Online analizom dodatnog zagažaja želi se postići aktivan nadzor i predviđanje tog efekta na brodovima od strane obalnih službi s osnovnim ciljem sprječavanja nasukanja. Metoda može djelovati na način da se upotrebom računalnih algoritama, poznatih empirijskih formula za dodatni zagažaj, zadanih kriterija, vektorskih elektroničkih karata te AIS podataka brodova izračunava trenutna i buduća vrijednost brodskog dodatnog zagažaja te dubine ispod kobilice.

Svaki brod odašilje niz podataka putem AIS sustava, a dijele se u tri kategorije: statički, dinamički te podaci o putovanju i teretu. Statički

[3] Takve obrade AIS podataka mogu biti: analiza gustoće pomorskog prometa; analiza opasnosti od sudara ili udara (*near miss analysis*); analiza prolaska linijom (*passage line analysis*); zapis brodskog puta; izdvajanje u posebnom području; nadzor sidrene pozicije i dr.

[4] Druga vrsta su izvanmrežne ili tzv. *offline* analize koje se koriste za obradu arhiviranih AIS podataka brodova za odabrano prošlo razdoblje, a najčešće za izradu različitih dnevnih, mjesečnih i godišnjih statističkih izvješća.

3. PREDICTING SQUAT USING AIS DATA

The ship's data, received in VTS service via AIS, can be used for many purposes other than identification and traffic surveillance, such as broad analysis of maritime traffic and prediction of dangerous situations at sea. Such AIS data processes improve daily work of VTS centre and increase safety at sea in general[3].

Squat prediction using AIS data belongs to a group of online analyses[4] which deals with data in real time. Online analyses are used for constant situation and vessels' movement surveillance in the jurisdiction area. One of the goals in this approach is to make VTS service able to anticipate potentially dangerous situations and to warn the endangered ship or ships in time to prevent a marine accident.

By implementing real time analysis of ship squat, it is intended to monitor and predict squat by VTS services, the primary goal being the prevention of grounding. The method can be performed by integrating computer algorithms, well-known squat empirical formulas, a set of criteria, vector electronic charts and AIS ship data, calculating the current and future squat value and respective under keel clearance.

Ships equipped with AIS system transmit a series of data, which are divided into three categories: static, dynamic, and information about voyage and cargo. Static data are entered when installing the device and do not change during normal ship operation. They include basic information such as the ship's name, call sign, type, dimensions, etc. Dynamic or navigational data, such as speed, rate of turn or course, are variable in time and are automatically updated from other ship's equipment. Finally, voyage and cargo data are manually entered by the responsible officer before and during the voyage, and includes draft, navigation status, dangerous cargo categories, time and port of arrival, etc.

[3] AIS data can be used for an analysis of maritime traffic density, collision or impact hazard (Near miss analysis), passage line statistic; history tracks, separation scheme control, anchor position supervision, etc.

[4] The second type are offline analysis, used for the processing of archived AIS ship data for the selected past time period, used mostly for the production of various daily, monthly and annual statistical reports.

podaci se upisuju pri instalaciji uređaja i ne mijenjaju se tijekom normalne eksploatacije broda, a obuhvaćaju osnovne podatke poput imena, pozivnog znaka, vrste, dimenzija broda i sl. Dinamički ili navigacijski podaci su promjenjivi u vremenu, poput brzine, kutne brzine i kursa, te se automatski osvježavaju iz brodskih senzora i uređaja. Na koncu, podaci o putovanju i teretu se ručno unose od strane odgovornog časnika prije i tijekom plovidbe, a obuhvaćaju gaz broda, navigacijski status, vrstu opasnog tereta, vrijeme, luku dolaska i dr.

Načelno, za potrebe izračuna dodatnog zagažaja empirijskim formulama, neophodni brodski podaci su:

	Dio AIS poruke:
Lpp – duljina broda između okomica (m)	NE
B – širina broda (m)	DA
T – gaz broda (m)	DA
v – brzina broda (čv)	DA
C_b – koeficijent punoće deplasmana	NE

Lpp nije dio AIS poruke i teško je očekivati da VTS služba bez direktne komunikacije s časnikom broda može doći do toga podatka.[5] Međutim, kao aproksimacija za Lpp neki autori su se koristili podatkom duljine preko svega (LOA – Length over all) koji jest dio AIS poruke, te uspješno provodili mjerenja za dodatni zagažaj s obzirom na relativno male razlike u tim podacima [6]. Postoji još metoda za aproksimaciju Lpp-a, poput korištenja tablica tipičnih brodskih dimenzija koje je objavio PIANC [9] ili uvođenjem koeficijenta za umnožak s LOA za približno izrčunavanje Lpp-a. Nadalje, širina broda je dio statičkih podataka, gaz broda je dio ručno upisivanih podataka o putovanju, a brzina broda je dio dinamičkih podataka AIS poruke. Koeficijent punoće deplasmana je moguće relativno dobro i brzo računalno aproksimirati na temelju tablica tipičnih brodskih dimenzija koje je objavio PIANC [9]. U tablicama se koeficijent punoće dobiva unosom podataka o vrsti broda, LOA, B i T, koji su dostupni putem AIS poruke. Na temelju navedenog VTS služba može relativno jednostavno izdvojiti i dobiti sve neophodne brodske podatke za izračun dodatnog zagažaja.

[5] Lpp kao podatak brodske dimenzije nije dostupan niti u poznatijim svjetskim bazama brodova *Equasis* (European Commission) [12] te *ITU particulars of ship stations* (International Telecommunication Union) [11].

Generally, the necessary ship data for squat calculation with empirical formulas are:

	Part of AIS message:
Lpp – length between perpendiculars (m);	NO
B – ship width (m);	YES
T – ship draft (m);	YES
v – ship speed (kts);	YES
C_b – block coefficient.	NO

Lpp is not a part of the AIS messages and it is unlikely that VTS operators can get this information without direct communication with the ship's officer[5]. However, some authors have used the length over all (LOA) as a proxy for Lpp and successfully carried out squat measurements and calculations, given the relatively small differences in these data.[6] LOA is a part of the AIS messages. Also, there is a method for Lpp approximation, for example, using the Typical Ship Dimensions table published by PIANC [9] or by introducing a coefficient with LOA for approximate calculation of Lpp. Furthermore, ship width is part of the AIS static data, ship draft is part of the inserted voyage data, and ship speed is part of the automatically updated dynamic data.

Block coefficient can be reasonably well approximated using the Typical Ship Dimensions table published by PIANC.[9] Using these tables the block coefficient is obtained by a type of vessel, LOA, B and T data, which are all available through the AIS message. Based on the above mentioned, VTS service can relatively easily obtain all the necessary ship data for the squat calculation.

VTS receives the necessary waterway data within the VTS jurisdiction, such as depth, underwater cross section and width from the relevant hydrographic institutes and vector electronic charts which include vector data of the seabed and depths (International Hydrographic Organization – IHO, standard S-57). With the help of computers, depth information can be corrected for tide oscillations in real-time. If additional equipment is available, like oceanographic buoys, salinity and wave heights can be taken into account as well.

Given that squat is dangerous for ships only in certain circumstances, there is no need to

[5] Lpp is not available in any well-known global database of ships like *Equasis* (European Commission) [12] and *ITU particulars of ship stations* (International Telecommunication Union).[11]

Neophodne podatke o plovnom putu, tj. području nadležnosti VTS službe, poput dubine, poprečnog podvodnog presjeka, širine kanala i sl. obalna služba dobiva od nadležnih hidrografskih instituta i vektorskih elektroničkih karata koje uključuju vektorske podatke morskog dna i dubine (International Hydrographic Organization – IHO, standard S-57). Podatak o dubini mora moguće je u realnom vremenu relativno jednostavno računalno ispravljati za visinu morskih mijena te se računalno mogu koristiti i podaci o salinitetu mora ukoliko postoji potrebna oprema na raspolaganju poput oceanografskih plutača.

S obzirom da je dodatni zagažaj svojstven i opasan brodovima samo u određenim uvjetima, nema potrebe računati ga za sve brodove u svim navigacijskim područjima te bespotrebno opterećivati i trošiti računalne resurse. Stoga je potrebno uvesti preduvjete kao okidače za početak računanja, praćenja i predviđanja dodatnog zagažaja i UKC-a.

Osnovni preduvjeti za računanje dodatnog zagažaja najmanje moraju biti granične veličine brzine te odnosa dubine mora i gaza broda. Razlog tome je što dodatni zagažaj prvenstveno nastaje kretanjem broda, a raste približno proporcionalno kvadratom brzine broda. Odnos gaza i dubine označava područje plitkih voda, a time i opasnih s obzirom na gaz.

Stoga se može sljedećim izrazom naznačiti da funkcija računanja (R) dodatnog zagažaja pojedinog broda započinje zadovoljavanjem sljedećih uvjeta:

$$R = \{ 1 ; v_p > v_g \wedge (h/T)_p < (h/T)_g , \qquad (16)$$

gdje je:

v_p i v_g promatrana i granična brzina broda, $(h/T)_p$ i $(h/T)_g$ promatrani i granični odnos dubine mora i gaza broda.

Promatrane vrijednosti se dobivaju iz AIS podataka promatranih brodova te se osvježavaju prilikom svake zaprimljene AIS poruke. Granične vrijednosti određuje i postavlja VTS služba.

Barrass kao jedan od poznatijih autora formula za izračunavanje dodatnog zagažaja navodi da za pojavu tog efekta brod mora načelno imati brzinu veću od 6 čv [10]. Na testiranjima nekih autora vidljivo je da se dodatni zagažaj javlja i pri manjim brzinama [3, 5, 7, 8], ali pri-

calculate it for all vessels in all areas of navigation and thus unnecessarily spend and slow down computer system resources. It is therefore necessary to introduce conditions which would automatically start the calculation, tracking and prediction of squat and UKC values.

Ship speed and depth/draft ratio should be the basic starting conditions for squat calculation. The reason for that is the fact that squat is primarily caused by the movement of the ship through water, and grows approximately proportional to the square of ship speed. Depth/draft ratio indicates an area of shallow water, and therefore danger regarding to ship draft.

Therefore, the following expression may indicate that the function of squat computation (R) for each ship begins by satisfying basic conditions:

$$R = \{ 1 ; v_p > v_g \wedge (h/T)_p < (h/T)_g , \qquad (16)$$

where v_p represents the observed ship speed, v_g is ship speed limit value, $(h/T)_p$ is the observed ship depth/draft ratio, and $(h/T)_g$ is ship depth/draft ratio limit value.

The observed values are derived from ships AIS data, and are updated with each received AIS message. Limiting values are determined by VTS service.

As a known squat researcher, Barrass states that a ship must have a speed greater than 6 knots [10] for the occurrence of this effect. Observing test reports of some authors, it is evident that squat appears at lower speeds as well [3][5][7][8], but it takes a very small value which in most cases can be ignored. However, given that the goal of VTS service is to predict a danger of grounding by squat effect, it is necessary to begin ship tracking earlier at lower speeds, than from the speed when the possibility of this effect is evident. Therefore, the speed limit v_g can be set to 3-5 knots. Speeds less than 5 knots are generally classified as maneuvering speeds within the port area.

Shallow water cannot be defined only by depth because drafts of various ships differ considerably. For this reason, shallow water has to be defined by the depth/draft ratio (h/T). PIANC states that shallow water is considered when depth/draft ratio is $h/T \leq 1.5$. A maximum value of h/T during squat empirical formula testing by various authors ranges from 2.25 to tom poprima vrlo male vrijednosti pa se u nekim slučajevima može i zanemariti. Međutim, iz razloga što je cilj VTS službi predvidjeti opasnost od nasukanja dodatnim zagažajem, potrebno je početi pratiti brod i ranije od mogućnosti nastanka tog efekta u plitkim vodama, stoga se granična brzina može odrediti na 3-5 čv. Brzine manje od 5 čv su načelno manevarske unutar lučkih područja.

Plitke vode se ne mogu definirati samo po dubini jer se gazovi različitih brodova bitno razlikuju. Iz tog se razloga plitko more definira odnosom dubine mora i trenutnog gaza broda h/T. PIANC navodi da se plitkim morem smatra kada je odnos dubine i gaza h/T ≤ 1,5, a najveća vrijednost h/T prilikom testiranja empirijskih formula raznih autora iznosi od 2,25 do 2,75 [9]. Kao i u prethodnom slučaju, cilj VTS službe je unaprijed predvidjeti opasnu situaciju, stoga granična vrijednost h/T mora biti veća od 1,5., pa je preporučljiva vrijednost 2,5 uzimajući u obzir granične vrijednosti empirijskih formula.

Nakon zadovoljavanja osnovnih kriterija, VTS služba mora nadalje pratiti brod te računalnom podrškom predvidjeti moguću kritičnu situaciju u plitkim vodama. Da bi to bilo moguće potrebno je odrediti kriterije računanja minimalne dubine ispod kobilice UKC-a, obvezno računajući i uzimajući u obzir dodatni zagažaj. U slučaju prekoračenja graničnih. tj. dozvoljenih vrijednosti minimalnog UKC-a potrebno je osigurati funkciju javljanja alarma (P) VTS operateru (Slika 1). Navedeno se može izraziti na sljedeći način:

$$UKC_p = h_p - T\,, \tag{17}$$

$$P = \{\ 1\ ;\ UKC_p - S_{max} \leq UKC_g\,, \tag{18}$$

gdje je:

UKC_p – dubina ispod kobilice promatranog broda
h_p – dubina mora na poziciji promatranog broda
T – gaz broda (AIS)
S_{max} – računati najveći dodatni zagažaj promatranog broda
UKC_g – granična vrijednost dubine ispod kobilice.

UKC_p je moguće jednostavno pratiti oduzimanjem prijavljenog gaza broda iz AIS poruke od dubine mora trenutne pozicije broda iz vek-

2.75.[9] As in the previous case, the goal of VTS service is to predict dangerous situation, thus the limiting value of h/T must be greater than 1.5. The recommended $(h/T)_g$ value is 2.5 taking into account the published tests with empirical formulas.

After meeting the basic criteria, VTS service has to continue to monitor the ship, and predict the possible critical situation in shallow waters with the help of computers. To make this possible it is necessary to determine the criteria for calculating the minimum under keel clearance – UKC, taking into account the squat effect (Figure 1). In the case of exceeding the limit values, i.e. the value of minimum allowable UKC, it is required to ensure the alarm function (P) for the VTS operator. This can be expressed as follows:

$$UKC_p = h_p - T\,, \tag{17}$$

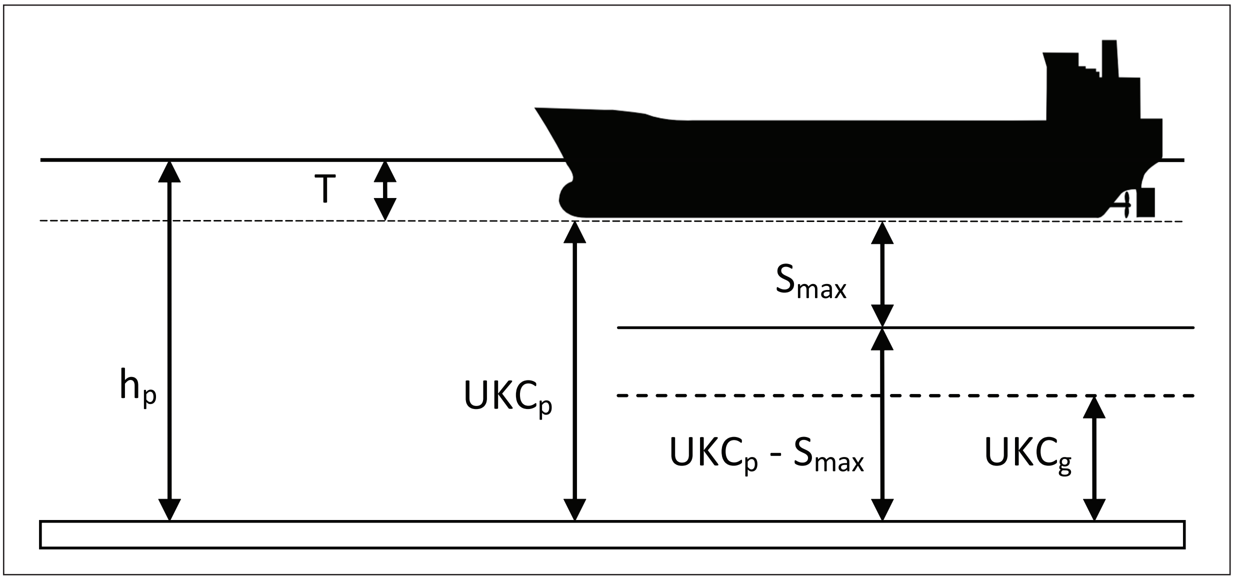
$$P = \{\ 1\ ;\ UKC_p - S_{max} \leq UKC_g\,, \tag{18}$$

Where UKC_p represents under keel clearance of observed ship, UKC_g is under keel clearance limit value (set by VTS), h_p is depth at the observed ship position (vector charts), T is ship draft (AIS), and S_{max} is maximum calculated squat of the observed ship.

UKC_p can be easily monitored by subtracting the reported ship draft from current depth of the ship's actual position extracted from the vector electronic chart. Without taking the squat effect into account, UKC_p actually represents the under keel clearance of the ship that is not underway. The shortcoming of this expression, and further squat prediction, is the credibility of the draft value, which depends on the accuracy and attention of the ship's duty officers, who enter and update this value manually into the ship's AIS.

The critical UKC alarm (P) is activated if the observed UKC_p reduced for the calculated squat value S_{max} is equal or smaller than the minimum allowable under keel clearance UKC_g[6]. Squat is obtained by calculation using real time ship data and a selected adequate empirical formula. Minimum allowable UKC_g is determined by VTS service operators. A number of factors can affect UKC_g determina-

[6] There are other factors that influence on the reduction of ship UKC, such as the effect of waves and ship list, which can be determined with different probabilistic methods and added to the above calculation.



Slika 1. Prikaz podvodnih veličina analize dodatnog zagažaja
***Figure 1** Display of subsea values for squat and UKC analysis.*

Izvor / ***Source***: autori / *authors*

torske elektroničke karte. UKC_p predstavlja dubinu ispod kobilice koju brod ima u mirovanju. Nedostatak ovog izraza, a i daljnjega računanja dodatnog zagažaja, je vjerodostojnost vrijednosti gaza, ovisna o točnosti i ažurnosti časnika plovidbne straže promatranog broda, koji tu vrijednost ručno upisuje u brodski AIS.

Alarm (P) kritičnog UKC-a u VTS službi određen je uvjetom prelaska graničnog UKC-a, koji se dobiva oduzimanjem računatog dodatnog zagažaja broda upotrebom odabrane empirijske formule od dubine ispod kobilice promatranog broda u mirovanju.[6] Granični UKC_g određuje VTS služba, na što može utjecati više faktora, od kojih je najznačajniji vrsta morskog dna. U pomorstvu je postalo uvriježeno da je UKC_g= 0,5 m za meka dna (mulj i pijesak) i UKC_g = 1,0 m za tvrda dna (kamen) [9, 1]. Javljanje alarma (P) upućuje VTS operatera da je promatrani brod prešao dozvoljenu graničnu vrijednost UKC-a te njegova dužnost mora biti hitno obavješťavanje časnika u straži o nastaloj situaciji te savjetovanje o daljnjim postupcima, poput smanjivanja brzine ili skretanja broda u vode veće dubine.

S obzirom da je putem AIS-a poznata trenutna pozicija, brzina, kutna brzina i kurs broda, moguće je donekle točno računalno simulirati,

[6] Postoje i drugi faktori koji utječu na smanjenje brodskog UKC-a, poput utjecaja valova i nagnuća broda, koji se mogu odrediti različitim probabilističkim metodama i pridodati navedenom izračunu.

tion, but mostly the type of seabed. In many states it has become accepted that minimum allowable UKC_g is 0.5 m for soft sea beds (mud and sand) and 1.0 m for hard sea beds (rocks). [9][1] Alarm activation (P) indicates to VTS operators that the observed ship exceeded the minimum allowable UKC. Therefore, their duty should be to promptly notify ship's officer of the watch about the situation and advise on further action, such as reducing ship speed or turning the ship towards deeper waters if possible.

Given that a current position, velocity, rate of turn and course of the ship are known from AIS, it is possible to simulate and predict the future ship position to a certain degree. Logically, the further in time the position is simulated, the less credible it is. By simulating the position n minutes in future, it is possible to predict the observed under keel clearance UKC_{pn} and depth h_{pn} for the ship's future position at the n-th minute. In the same way a maximum squat $S_{max\,n}$ can be calculated. This can be expressed as follows:

$$UKC_{pn} = h_n - T\,, \tag{19}$$

$$P_n = \{\, 1\,;\, UKC_{pn} - S_{max\,n} \le UKC_g\,, \tag{20}$$

Alarm activation (P_n) for the future critical UKC facilitates the VTS operator to predict a dangerous situation in time, and it gives more time to alert the officer of the watch before the tj. predvidjeti buduću poziciju broda. Logično, što se dalje u budućnost simulira pozicija broda, to je točnost manje vjerodostojna. Simulirajući stanje promatranog broda u budućnost za n minuta, moguće je i računanje dubine ispod kobilice UKC_{pn} te dubine mora h_n na budućoj poziciji n-te minute. Na jednak način, simuliranim stanjem broda moguće je računati i maksimalni dodatni zagažaj (S_{maxn}) za n minuta. Izraz se može prikazati na sljedeći način:

$$UKC_{pn} = h_n - T, \quad (19)$$

$$P_n = \{ 1 ; UKC_{pn} - S_{max\,n} \le UKC_g , \quad (20)$$

Javljanjem alarma (P_n) budućeg kritičnog UKC-a u VTS službi olakšava VTS operateru na vrijeme predvidjeti opasnu situaciju, te upozoriti časnika u straži broda o situaciji i prije nego nastupi opasnost, tj. prelazak granične vrijednosti UKC-a. Primjerice, predviđanje buduće pozicije broda može biti određeno za $n = 2$, 4 i 6 minuta (Slika 2). Nedostatak simulacije budućeg stanja broda je predviđanje skretanja broda, što se donekle može predvidjeti računanjem kutne brzine, međutim iako dio AIS poruke, taj podatak često nije dostupan.

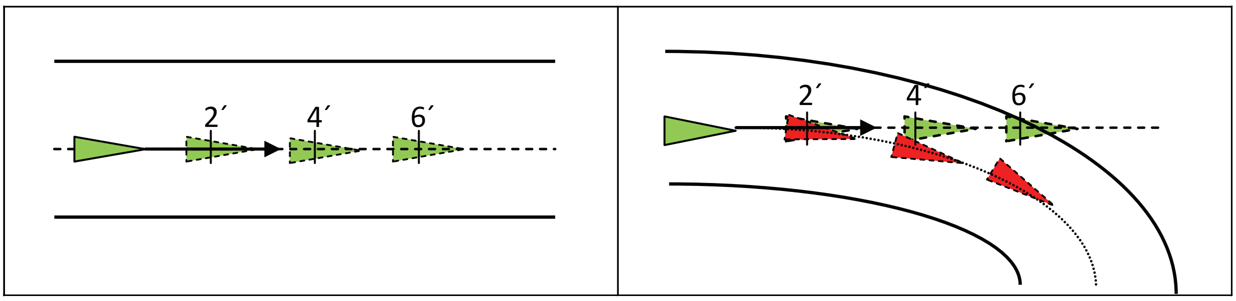
Bitno je naglasiti da je cilj uvođenja alarma kritičnog smanjenja dubine ispod kobilice broda skrenuti pozornost VTS operateru na potencijalnu opasnost od nasukanja ukoliko se poveća brzina broda ili dalje smanji dubina mora. Operater je dužan takvu spoznaju potvrditi i upozoriti časnika ili zapovjednika toga broda davajući savjet ili uputstva. Međutim, takav postupak nikako ne umanjuje odgovornost časnika ili zapovjednika za sigurnost broda tijekom plovidbe.

danger occurs. For example, predicting the ship future position may be determined for n=2, 4 and 6 minutes (Figure 2). The lack of simulations of the ship's future state is the poor possibility to predict the ship's turn, which can be partly predicted using the ship's rate of turn. However, although part of the AIS data, rate of turn is often not available.

It is important to emphasize that the aim of introducing the UKC critical alarm is to draw attention of the VTS operator in case of potential grounding danger, if the ship's speed is increased or depth is further reduced. The operator is required to confirm this finding and to warn the master or duty officer on board giving advice or instructions. However, such action does not diminish the officer's and master's responsibility for the ship's safety during the voyage.

CONCLUSION

Given that there is no universal method for squat calculation for all types of ships and fairways, tests are performed on ships for different purposes and in restricted waterways. The aim of such tests and measurements is to determine which squat empirical formulas suit which ship types in specific waterways or port approaches. After determining the appropriate method, the development of computer-based squat calculation and prediction offers the coastal state or VTS service advanced monitoring and greater degree of safety during navigation of the ship within the jurisdiction area. Predicting squat, and thus the actual under keel clearance, VTS may predict the risk of grounding independent-



Slika 2. Prikaz simuliranja AIS pozicija broda pri pravocrtnom kretanju broda i prilikom skretanja broda
Figure 2 *Preview of ship's AIS position simulation in a linear movement in a waterway and with possible error due to ships turn.*

Izvor / ***Source***: autori / *authors*

ZAKLJUČAK

S obzirom da ne postoji univerzalna metoda izračuna dodatnog zagažaja za svaki brod i svaki plovni put, provode se mjerenja tog efekta na brodovima različite namjene na ograničenim plovnim putovima i prilazima luka. Cilj takvih mjerenja je ustanoviti koja od empirijskih formula dodatnog zagažaja najviše odgovara različitim brodovima na određenom dijelu puta. Nakon utvrđivanja odgovarajuće metode, razvoj računalne podrške za izračun i predviđanje dodatnog zagažaja broda omogućuje obalnoj državi, odnosno VTS službi veći stupanj nadzora sigurne plovidbe svakoga broda zasebno. Predviđanjem dodatnog zagažaja, a time i vrijednost dubine ispod kobilice broda, obalna služba može neovisno o brodskim časnicima predvidjeti nastanak opasnosti od nasukanja, čime se umanjuje rizik od većih šteta, onečišćenja i ozljeda.

Daljnji rad i istraživanja u pogledu izračuna i predviđanja dodatnog zagažaja u VTS službi trebaju načelno ići u tri smjera. Jedan od smjerova je razvoj programske podrške za integraciju potrebnih podataka iz sustava vektorskih elektroničkih karata te AIS-a i određenih empirijskih metoda za određivanje dodatnog zagažaja. Programska podrška mora biti u mogućnosti računati i prikazati trenutna i buduća (simulirana) stanja brodova tijekom prolaska odabranim ograničenim plovnim putom. Drugi smjer daljnjeg rada jest umanjiti i ukloniti problem vjerodostojnosti i nedostupnosti brodskih AIS podataka. Zbog povremene neispravnosti brodskih uređaja te neažurnosti ili neodgovornosti brodskih časnika AIS podaci nerijetko nisu točni ili nisu upisani. Neki od važnijih podataka, poput brzine i kursa broda VTS može dobiti integracijom radara i vektorskih elektroničkih karata. Bitno je naglasiti da postoje mnogi drugi faktori, osim dodatnog zagažaja, koji utječu na smanjenje dubine ispod kobilice, a to su: kretanje brodova pod utjecajem valova, morske mijene, nagnuće broda, promjena u salinitetu mora i dr. Neki od navedenih faktora mogu se pratiti senzorima na meteorološkim i oceanografskim plutačama te dobiti komunikacijom s brodom. Treći smjer daljnjeg rada trebao bi ići prema integraciji predviđanja svih faktora koji povećavaju maksimalni uron broda i pridonose povećanju rizika od nasukanja.

ly of the ship's officers, and reduces the risk of major damage, pollution or injury.

Further work and research in terms of squat calculation and prediction in VTS services should proceed in three directions. First, it is software development to integrate the necessary data from the vector electronic charts and AIS with selected empirical methods for squat and UKC calculation. The software must be able to calculate and display the current and future (simulated) conditions of the ship during passage in specific restricted waterways.

The second direction is to reduce and eliminate the problem of credibility and lack of ship AIS data. Due to occasional malfunctioning of ship's equipment and inefficiency or irresponsibility of ship's officers, AIS data are often inaccurate or not updated. VTS can obtain some of the important data, such as ship's speed and course, by integrating radar with vector electronic charts.

It should be noted that there are many other factors, apart from squat, which affect the reduction of under keel clearance, and they are: ship movements under the influence of waves, tides, ship's inclination, changes in salinity and others. Some of these factors can be monitored by meteorological and oceanographic buoy sensors and received by communication with the ship's officers. The third direction should proceed toward the integration of all factor predictions which influence the reduction of the ship's under keel clearance, thus contributing to increased risk of grounding.

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