Design standard for fairway in next generation

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ABSTRACT

The depth, width and alignment of fairway that are main port water facilities should be designed considering the various elements including particulars of design ships, weather and sea conditions around fairway and method of ship-handling. However not only the existing Japanese design standard for fairway and also those of other countries do not take into consideration of such kind of elements and no design standard is made by quantitative analysis. In this circumstance the new design standard [Approach Channels, A Guide for Design] depending on classified various elements and quantitative analysis was proposed in 1997 by PIANC and IAPH. But it was proved that calculated values according to this standard were unfounded and had some problems to output the discontinuous value by small difference of calculation condition because the each value for each element was simply added. And also it is hard to apply this standard to the design of port water facilities in Japan because this [A Guide for Design] is the design standard for long channels in European port. The proposal of more reasonable Japanese standard will be expected by applying the study result of naval architecture and navigation and by the cooperation of ship operators to use fairway, naval architects to built ships and civil engineers to dredge fairway.

The concept of a fairway in "Design standard for fairway in next generation" is defined as passage (or approach channel) and traffic lane designated by light buoys as navigable water for safe navigation. In "Design standard for fairway in next generation" depth, width and alignment are picked up among many design elements of a fairway. Design method for those elements is shown based on design ships and navigational environments.

This standard shows the method of design for each dimension depending on characteristic on design ship and weather and sea condition. On the other hand, in case of existing fairway, it is possible to decide the size of ship and navigation criteria by opposite analysis.

1. Introduction

The main point of this study is to clarify the each element of depth, width and alignment (bend) of the fairway design in viewpoint of ship's manoeuvrability and also is to develop the practical standard under the criteria of operational condition. This means the new standard can apply not only for fairway design but also apply the study of acceptable ship for existing fairway depending on navigational environments. The result of study is shown below.

2. Contents of the study

2.1 Depth of fairway

When the dimension of design ship, navigational environments such as weather and sea condition and ship speed is specified, the necessary depth of fairway can be calculated by the following formula. In actual operation, tide, accuracy of depth of water, others (air pressure, bottom nature, obstruction in water, density of seawater and etc.) should be taken into consideration if necessary.

$$D = d + D1 + \mathrm{Max}\,(D2, D3) + D4$$

d : Maximum draft in still water under operational weather and sea condition

D1: Squat (bow sink during underway)

D2: Bow sink due to heaving and pitching motion (Additional element in case of $\lambda > 0.45Lpp$)

D3: Bilge keel sink due to heaving and rolling motion (Additional element in case of TR=TE)

D4: Allowance of depth

λ : Length of wave including swell, Lpp: Length between perpendiculars of design ship

TR: Natural rolling period of design ship, TE: Meeting period of design ship and design wave

(1) D1 is calculated as follows.

$$D1 = \left(0.7 + 1.5\frac{d}{D}\right)\cdot\left(\frac{Cb}{L\,pp/B}\right)\cdot\frac{U^2}{g} + 15\cdot\frac{d}{D}\cdot\left(\frac{Cb}{L\,pp/B}\right)^3\cdot\frac{U^2}{g}$$

D : Depth of fairway, Lpp: Length between perpendiculars of design ship

B: Breadth of design ship, Cb : Block coefficient of design ship

U: Ship speed (m/s), g: Acceleration of gravity ($9.8 m/s^2$)

(2) Maximum of D2 and maximum of D3 do not occur at the same time. Therefore larger value of D2 or D3 shall be selected.

D2: Bow sink due to heaving and pitching (In case of $\lambda > 0.45Lpp$)

D3: Bilge sink due to heaving and pitching(In case of $\lambda > 0.45Lpp$)

D2 in case of $\lambda > 0.45Lpp$ can be calculated by the value of D2/h0 taken from the Figure 2.1.

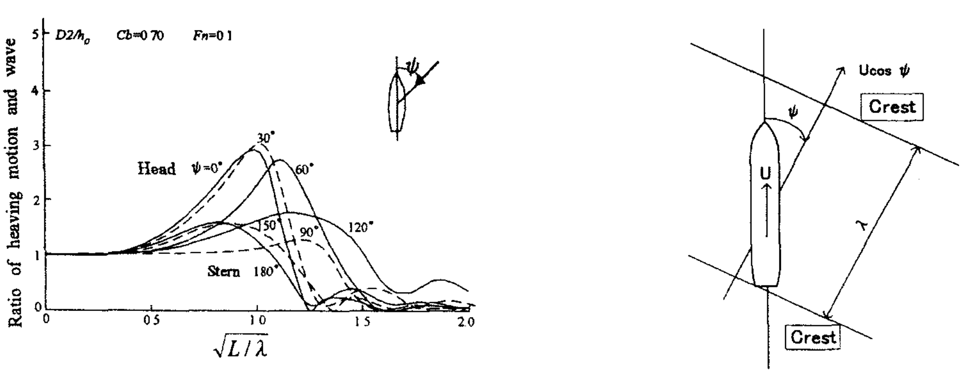


Figure 2.1 Ratio of heaving motion and wave amplitude

In case of TR and TE is nearly equal, D3 can be calculated by the following formula.

$$D3 = 0.7 \cdot \left(\frac{H_{1/3}}{2}\right) + \left(\frac{B}{2}\right) \cdot \sin\Theta$$

$\Theta = \mu \cdot \gamma \cdot \Phi$, $\mu \cdot \gamma = 7$, $\Phi = 360 \cdot (0.35 H_{1/3} / \lambda) \cdot \sin\phi$

$TR = 0.8B / (GM)^{0.5}$, $TE = \lambda / (\lambda / TW + V\cos\phi)$

GM=0.5～2.0・ (B / 25) is applied because real value of GM varies depending on ship condition.

GM: Distance between the center of gravity and metacentre, W: Wave period

$H_{1/3}$: Significant wave height, B: Breadth of design ship

Θ : Maximum rolling angle of design ship(degree), μ : Ratio of rolling induced by regular wave

γ : Effective wave slope coefficient, Φ: Maximum wave slope angle (degree)

ϕ : Encounter angle between ship's head and wave direction (degree)

(3) D4 is the allowable water for list of ship by large rudder angle to alter her course and can be calculated by the following formula.

$d \leqq 10m$: D4=0.5m, $d > 10m$: D4=0.05・d

2.2 Width of fairway

When the dimension of design ship and navigational environments such as weather and sea condition and navigation aids are specified, necessary width of fairway shown in Figure 2.2 can be calculated by the following formula.

(1) Fairway without ship meeting (One-way fairway)

W = Wb1 + Wm0 + Wb

(2) Fairway with ship meeting (Two-way fairway)

W = Wb1+Wm1 + Wc + Wm2 + Wb2

(3) Fairway with ship meeting and overtaking (Four-way fairway)

W = Wb1+Wm1-1+Wov1+Wm1-2 + Wc + Wm2-1+Wov2+Wm2-2 + Wb2

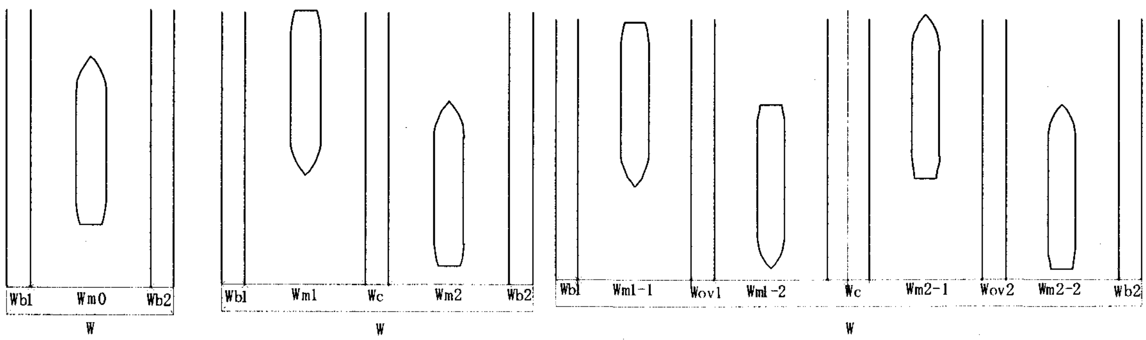


Figure 2.2 Type of fairway

1) Wmi (Basic manoeuvring lane) is composed of two elements mentioned below and can be calculated as maximum distance between center-line and side-line of fairway. Figure 2.3 and 2.4 show the idea of basic manoeuvring lane.

①Wm(β ,y): Manoeuvring lane against the effect of wind, current and ship yaw

②Wm(S): Manoeuvring lane for the detection of drift

Wmi=2Wm(S) + Wm(β ,y)

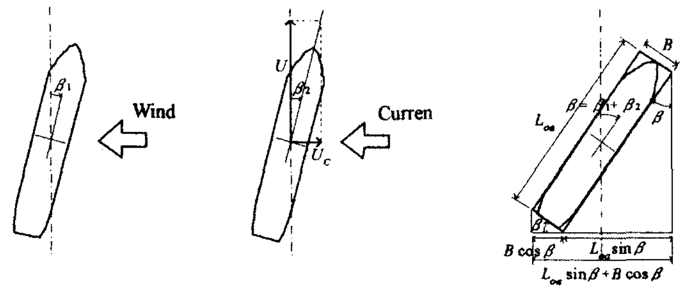


Figure 2.3 The drift angle due to wind and current

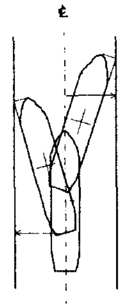


Figure 2.4 The drift sideway due to yaw

Basic manoeuvring lane against wind and current shall be calculated by total drift angle due to wind and current. Then, the drift sideway due to ship yaw is added to the above basic manoeuvring lane. Counter rudder angle shall be calculated depending on wind velocity under the limit of 15 degrees. In case that calculated angle is over 15 degrees, maximum wind velocity of the criteria for port entry should be reconsidered.

Ship motion equation relating rudder angle δ and drift angle β under constant wind is expressed as follows.

$$Y_\beta \cdot \beta + Y_\delta \cdot \delta + Cy \cdot \left(\frac{\rho_a}{\rho_w}\right) \cdot \left(\frac{Ay}{L \cdot d}\right) \cdot \left(\frac{Ua}{U}\right)^2 = 0$$

$$N_\beta \cdot \beta + N_\delta \cdot \delta + Cm \cdot \left(\frac{\rho_a}{\rho_w}\right) \cdot \left(\frac{Ay}{L \cdot d}\right) \cdot \left(\frac{Ua}{U}\right)^2 = 0$$

Rudder angle and drift angle are calculated by the following formula based on the above equation.

Rudder angle: $$\delta = -\left(\frac{\rho_a}{\rho_w}\right) \cdot \left(\frac{Ua}{U}\right)^2 \cdot \left(\frac{Ay}{L \cdot d}\right) \cdot \left(\frac{Cm \cdot Y'_\beta - Cy \cdot N'_\beta}{Y'_\beta N'_\delta - Y'_\delta N'_\beta}\right)$$

Drift angle: $$\beta = \left(\frac{\rho_a}{\rho_w}\right) \cdot \left(\frac{Ua}{U}\right)^2 \cdot \left(\frac{Ay}{L \cdot d}\right) \cdot \left(\frac{Cm \cdot Y'_\delta - Cy \cdot N'_\delta}{Y'_\beta \cdot N'_\delta - Y'_\delta \cdot N'_\beta}\right)$$

$Y'_\beta = Y_\beta/(0.5\rho w \cdot L \cdot d \cdot U^2)$, $N'_\beta = N_\beta/(0.5\rho w \cdot L^2 \cdot d \cdot U^2)$

$Y'_\delta = Y_\delta/(0.5\rho w \cdot L \cdot d \cdot U^2)$, $N'_\delta = N_\delta/(0.5\rho w \cdot L^2 \cdot d \cdot U^2) = -0.5\, Y'_\delta$

Y_β: Hydrodynamic derivative of lateral force acting on hull at drift angle of β

N_β: Hydrodynamic derivative of yaw moment acting on hull at drift angle of β

Y_δ: Hydrodynamic derivative of lateral force produced by rudder angle of δ

N_δ: Hydrodynamic derivative of yaw moment produced by rudder angle of δ

U: ship speed, Ua: Wind speed, ρw: Density of sea water, ρa: Density of air, Ay: Side windage area

Drift angle due to current effect can be calculated by the following formula depending on ship speed and cross current velocity.

$\beta 2 = \arctan (U c / U)$

β2 :Drift angle due to current effect, U c: Cross current velocity against center line of fairway

The manoeuvring lane against the effect of wind and current can be calculated by the following formula.

$W(\beta) = Loa \cdot \sin\beta + B \cdot \cos\beta \quad (\beta = \beta 1 + \beta 2) \quad \beta 1$: drift angle due to wind

The drift sideway due to ship yaw can be calculated by the following formula. In case that Ty and φ_0 of design ship are not defined, the value of Ty=12 seconds and φ_0 =4 degrees are used for the value of dangerous side.

$$W(y) = U \int_{t=0}^{t=Ty/4} \sin\varphi(t)dt = \frac{1}{4} U \cdot Ty \cdot \sin\varphi_0$$

Ty: Yawing period

φ_0 : Maximum yawing angle, $\varphi(t)$: Yaw at time of t $= \varphi_0 \cdot \sin(2\pi t / Ty)$

Maximum drift of one side due to wind, current and yaw can be calculated by the following formula.

$Wm(\beta, y) = W(\beta) + 2W(y) = Loa \cdot \sin\beta + B \cdot \cos\beta + 0.5U \cdot Ty \cdot \sin\phi_0$

Wm(S) (Manoeuvring lane for detection of drift) is the drift that makes ship handlers detect off course, and is defined regarding main methods used for ship handlers to detect the drift in fairway as follows.

a) Fixing position by observing light buoys on both sides of fairway

The lane for detection of drift can be calculated by the following formula. (unit of angle : degree)

$Wm(s) = Wm(\alpha) = LF \cdot \tan(\alpha max)$

$\theta = 2 \cdot \arctan\left(\frac{Wbuoy}{2LF}\right)$

$\alpha r = 0.00044 \cdot \theta^2 + 0.0002 \cdot \theta + 0.55343$

$\alpha max = 4\alpha r$

θ : Angle between ship and two buoys on both sides

Wbuoy: Clearance between two buoys forward

LF: Distance from the ship to light buoy forward

Wm(α): Basic lane for detection of drift

α r: Observation error of middle point

α max: Max observation error of center point (Maximum error that ship handlers of 99.8% can recognize the drift)

One way fairway: LF=7loa

Two-way fairway: LF = 3.5Loa

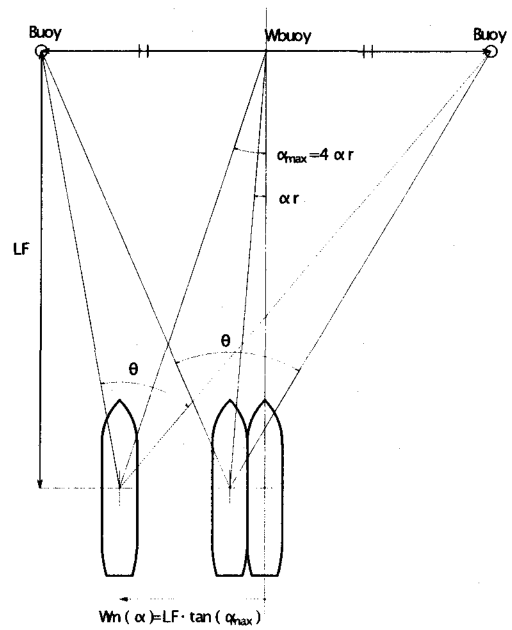


Figure 2.5 Idea for manoeuvring lane Wm(α)

b) Fixing position by observing leading post

$$Wm(s) = Wm(L) = 29.089 \cdot L_H \cdot (L_H / L_D - 1) \cdot 10^{-8}$$

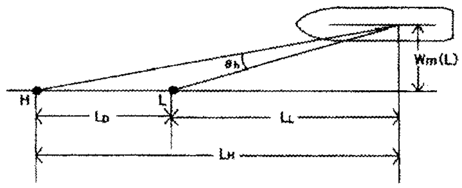
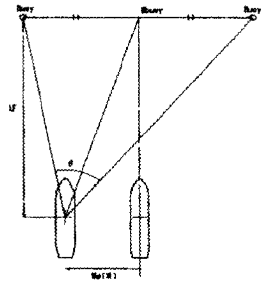


Figure 2.6 Idea for manoeuvring lane Wm(L)



c) Fixing position by RADAR

$$Wm(s) = Wm\ (R)\ = 0.0349 \cdot \frac{Wbuoy}{\sin\theta}$$

(θ is considered as 2 degrees)

Figure 2.7 Idea for manoeuvring lane Wm(R)

d) Fixing position by GPS

$Wm(s) = Wm(GPS)$ or $Wm(D\text{-}GPS)$

$Wm(GPS) = 0.5B + 30m$, $Wm(D\text{-}GPS) = 0.5B$

2) Wbi (Bank clearance) is the clearance is calculated as the distance from wall to absorb bank suction effect using the 5 degrees of rudder angle. Figure2.8 shows the idea of bank clearance.

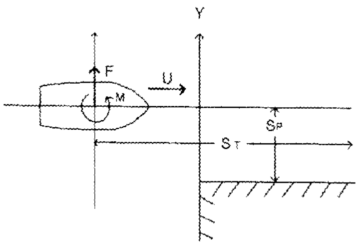


Figure 2.8 Idea for bank clearance

$$C_{Fb} = \frac{Fb}{0.5 \cdot \rho_w \cdot L \cdot d \cdot U^2}$$

$$C_{Mb} = \frac{Mb}{0.5 \cdot \rho_w \cdot L \cdot d \cdot U^2}$$

$$Wbi0 = Spb - 0.5B$$

Spb: Distance between center of ship and wall

F b: Lateral force acting on hull navigating along a wall

C_{Fb}: Dimensionless value of lateral force t acting on hull navigating along a wall

M b: Yaw moment acting on hull navigating along a wall

C_{Mb} : Dimensionless value of yaw moment acting on hull navigating along a wall

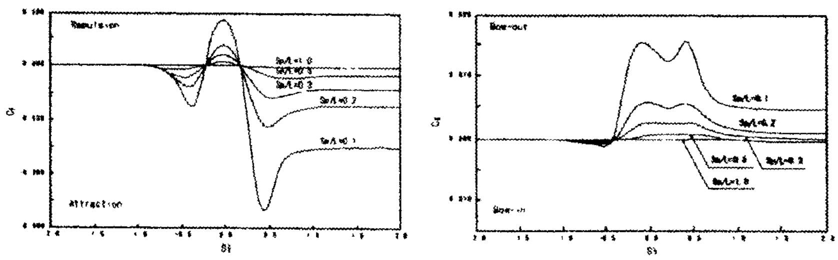


Figure 2.9 Lateral force and yaw moment acting on hull

At δ of counter rudder angle and β of drift angle, ship motion is shown by the following equation.

$$-C_{Fb}+Y'_{\beta}\cdot\beta+Y'_{\delta}\cdot\delta=0$$

$$-C_{Mb}+N'_{\beta}\cdot\beta+N'_{\delta}\cdot\delta=0$$

Counter rudder angle and drift angle are calculated by the following formula solving the above equation.

Bank clearance (Wbi) depending on the shape of cross section of fairway and the ratio of depth of fairway and outer water is calculated to apply correction coefficient (hf) based on straight bank wall.

$$\delta=\frac{C_{Mb}\cdot Y'_{\beta}-C_{Fb}\cdot N'_{\beta}}{Y'_{\beta}\cdot N'_{\delta}-Y'_{\delta}\cdot N'_{\beta}} \qquad hf=\exp\left(-2\cdot\frac{h1}{(1-h1)}\right)$$

$$\beta=-\frac{C_{Mb}\cdot Y'_{\delta}-C_{Fb}\cdot N'_{\delta}}{Y'_{\beta}\cdot N'_{\delta}-Y'_{\delta}\cdot N'_{\beta}}$$

$$Wbi=Wbi0\cdot hf$$

Wbi : Bank clearance in case of the designed cross-section geometry of fairway and depth /draft ratio

Wbi0: Bank clearance required allowable counter rudder of 5 degrees in case of steep wall.

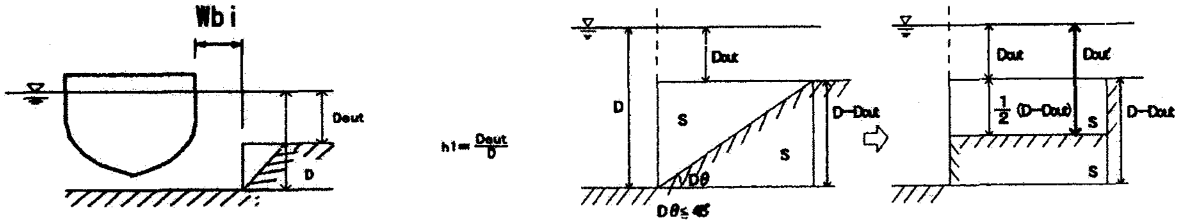


Figure 2.10 Idea for bank clearance depending on shape of wall

The effect of end of breakwater and jetty is different from the continuous bank effect and the duration of effect is brief. Therefore the counter rudder angle for the effect is limited to maximum 15 degrees. The clearance is calculated as the distance from end of breakwater and jetty to absorb the yaw moment using maximum 15 degrees of rudder angle. Wp is calculated by the following formula.

$$Wp=Spp-0.5B$$

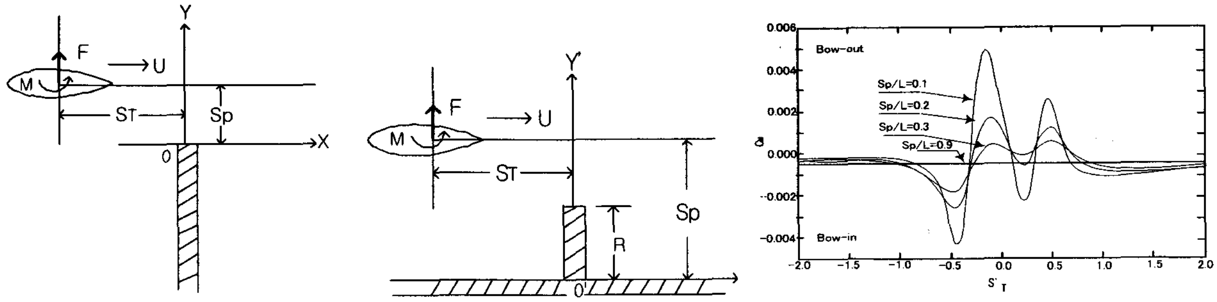


Figure 2.11 Yaw Moment acting on a ship navigating near end of break water [Shallow water D/d=1.2]

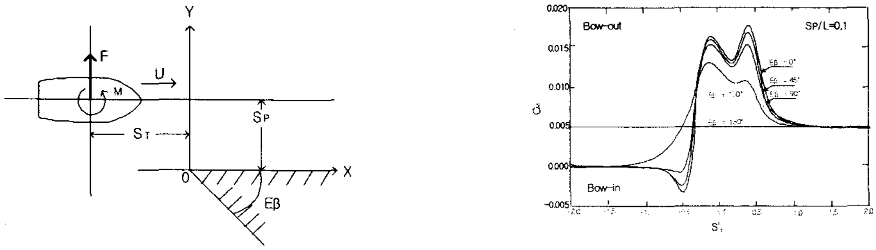


Figure 2.12 Yaw Moment acting on a hip navigating near end of breakwater [Shallow water D/d=1.2]

3) Wc (Width for passing distance) is the distance to absorb the effect of meeting ships with 15-degrees counter rudder.

$$C_{Fc}=\frac{Fc}{0.5\cdot\rho_w\cdot L\cdot d\cdot U^2}$$

$$C_{Mc}=\frac{Mc}{0.5\cdot\rho_w\cdot L^2\cdot d\cdot U^2}$$

$$-C_{Fc}+Y'_\beta\cdot\beta+Y'_\delta\cdot\delta=0$$

$$-C_{Mc}+N'_\beta\cdot\beta+N'_\delta\cdot\delta=0$$

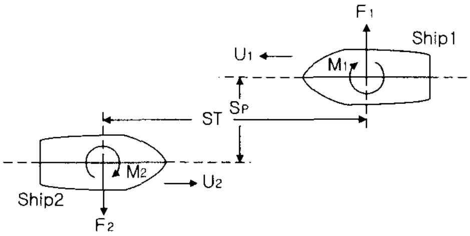


Figure 2.13 Idea for meeting

Counter rudder angle is calculated by the following formula based on the above equation.

$$\delta=\frac{C_{MC}}{N'_\delta}$$

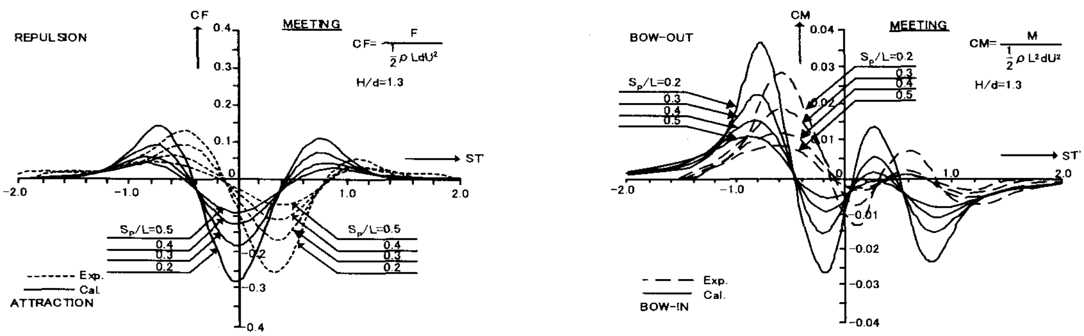


Figure 2.14 Lateral force and yaw moment acting on ship 1 in meeting

Wc is calculated by the following formula.

$$Wc=Spc-(0.5B+0.5B)=Spc-B$$

4) Wov (Width for overtaking) is the necessary distance to absorb the suction effect due to overtaking. Calculation method is basically same as meeting.

$$C_{Fovi}=\frac{Fovi}{0.5\cdot\rho_w\cdot Li\cdot di\cdot Ui^2}$$

$$C_{Movi}=\frac{Movi}{0.5\cdot\rho_w\cdot Li^2\cdot di\cdot Ui^2}$$

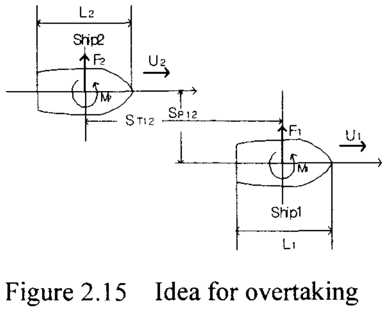


Figure 2.15 Idea for overtaking

Wov is calculated by the following formula.

$$Wov = Sp_{12} - (0.5B_1 + 0.5B_2)$$

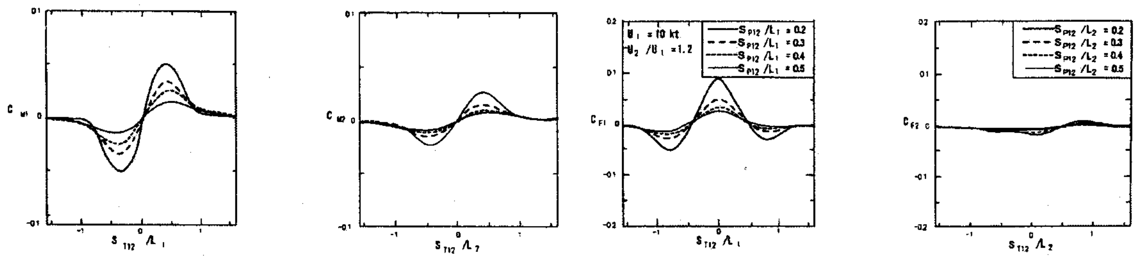


Figure 2.16 Lateral force and yaw moment acting on ship overtaken [Shallow water D/d=1.2]

2.3 Alignment (Bend)

The intersection angle of centerlines of fairway at bend ideally should not exceed 30 degrees.

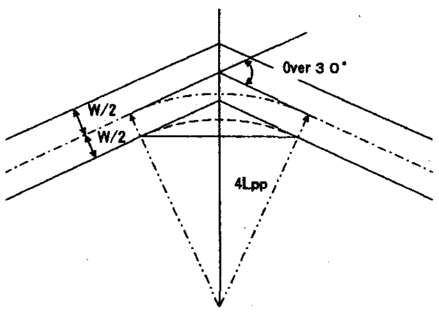


Figure 2.17 Inner corner of fairway with width of W

Kind of ship	K'
(1) Cargo ship	0.58
(2) Small cargo ship	0.47
(3) Container ship (Over Panamax type)	0.42
(4) Container ship (Panamax type)	0.52
(5) Large bulk carrier	0.52
(6) Bulk carrier (Panamax type)	0.49
(7) Small bulk carrier	0.62
(8) VLCC	0.62
(9) Small tanker	0.6
(12) LNG carrier	0.75
(13) Refrigerated cargo carrier	0.63
(14) Cruse ship (2 shafts 2 propellers)	0.66
(15)Ferry boat (2 shafts 1 propeller)	0.55

Table2.1 K' values [Shallow water D/d =1.2]

When cross angle of center line is larger than 30 degrees and navigational environments such as design ship and rudder angle are specified, a circular arc with the radius calculated depending on manoeuvrability index that indicates the ability of turning can be adopted. Also width of fairway should be wider than standard to widen inner corner. Other shapes of bend in addition to widening inner corner can be introduced considering installation of light buoys based on the study with mariners concerned. Especially when the cross angle of center line is large, the study of shape of curve is important because it is not always effective to widen the inner corner.

$$R = Lpp / (K' \cdot \delta) = U / (K \cdot \delta) \qquad [K' = K / (U / Lpp)]$$

R: Radius of turning circle of bend of waterway

K: Manoeuvrability index of turning, K': Dimensionless manoeuvrability index of turning

δ (radian):Rudder angle during underway at bend, U: Ship speed during underway at bend

K' values (except PCC) are obtained by the result of mathematical simulation under no wind condition at 20 degrees of rudder angle. In case of strong wind or in case of PCC with large deck structures, the further study to get K' value is necessary. K' values are calculated by the following formula.

$$K' = \left(\frac{180}{20\pi}\right) / \left(\frac{advance + transfer}{2L_{PP}}\right)$$

3. Conclusion

The new design standard for fairway has been developed. This standard can apply design of fairway for various types and sizes of ship, and navigational environments such as wind, wave, navigation aids. The depth, width and alignment (bend) of fairway can be calculated depending on ship size and navigational environments. Also the relation between max acceptable size of ship and navigational environments for existing fairway can be clarified by this standard. On calculation the new study results of naval architecture and navigation are introduced. Manoeuvring lane, bank clearance, width for passing and overtaking distance is taken into consideration for the width of fairway. Squat, bow sink, bilge keel sink, and allowance of depth are considered for the depth of fairway, and also manoeuvrability index of turning is considered for the alignment of fairway. It is expected that this standard will be effective for port facility designers and ship operators to use.

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