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Research on Fairway Width Based on the Statistical Theory

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Abstract: The fairway with certain width is one of prerequisite for ship's safety navigation. Channel's width is closely linked to ship's safety navigation. It is essential to research channel's width. The relationship between fairway's width and marine accident is analyzed in the present study and mathematical model of fairway's width is also put forward based on statistical theory in this study. Analysis shows that the fairway's width mathematical model put forward in this study can provide good guide for fairway's maintenance.

Key words: Fairway's width, marine accident, probability, gaussian distribution, random variable

INTRODUCTION

According to the interrelated statistics data, about 10-15% maritime accidents are caused by fairway defects (Chen and Wang, 2004; Gan, 2001). The fairway defects include water depth, radius of curvature, channel width and so on. The fairway with certain width is one of prerequisite for ship's safety navigation (Wu and Zhan, 1999). Channel width usually includes the track width of navigable ship, the safety space between vessel and vessel, between vessel and shore (Qi, 1991; Yang and Ai, 2007). At present, fairway arrangement in China is carried out by mainly referring to Inland Navigation Standards in china. The channel width in straight one-way traffic area that is defined in the Standards is as follows (Shen *et al*., 2004; Liu *et al*., 2006):

$$B_T = (|L\times \text{Sin}\alpha| + |B\times \text{Cos}\alpha|) + 2D \qquad (1)$$

where, L is the length of the vessel; B is the width of the vessel; $D = (L\times \text{Sin}\alpha + B)/4$, it is the safe distance between the vessel and the shore. Inland Navigation Standards also points out that the navigable width in winding channel can be widened on the base of the straight channel width. Inland Navigation Standards in china puts forward the width of the straight channel and winding channel on the basis of the ship's dimension which is reasonable to some extent but there are also some deficiencies in respect to the definition of navigable channel width. The fairway's dimension determination methods mentioned in standards are only related with ship's length and width and are without considering ship's maneuvering characteristics, especially the effects of winds and currents on fairway layout (Zhuang, 2007; Liu and Lv, 2006). The wind and the current not only make ship deflect but also make ship adrift. As a matter of fact, there are many factors affected channel's navigation safety, these factors include operating personnel's capacity, ship's machine condition and navigation environment etc (Liu and Lv, 2006). So, it is not reasonable to define fairway's dimension only depending on ship's length or its width. As early as 1960s, to the ship-to-ship effects and ship-shore effects, Japanese scholar put forward the ship field theory (Dai *et al*., 2009), the theory regarded that in order to safe navigate, ship need a certain field conditions, the field generally can be oval-shaped, the size of the field is concerned with scales of the ship, speed and environmental condition. When the ship is sailing at normal speed, its field is generally preferable to 6 times of the ship length along ship's length direction and 1.6 times of the ship's length along ship's width direction. Since ship's safety domain model has been proposed, many experts used it to research fairway's dimension. However, the concept of ship's safety domain model also only takes into account ship's dimension, such as ship's length and ship's width and the consideration factor of this model is also too unitary. In order to ensure ship safety navigation in fairway, all kinds of factors which affects ship's safety are worthy of consideration when determining fairway's dimension.

It is a worthy of discuss issue how to consider all kinds of affecting factors to determine fairway's dimension. Statistical theory can solve the problem preferably. Statistical theory can use plenty of statistical data to establish relationship between accident probability and fairway dimension. From the point of view of reducing traffic accidents, reasonable fairway dimension can be determined by using the relationship between traffic accident and fairway dimension. The purposes of the present work, therefore, are to put forward the method of determining fairway's width based on the statistical theory.

RELATIONSHIP BETWEEN TRAFFIC ACCICENT AND FAIRWAY WIDTH

A large number of statistical results show that traffic accidents are closely related with fairway width. Figure 1, in which K stands for traffic accident probability and B stands for fairway width, demonstrates that traffic accidents reduce with the increasing of the channel width. But even so, fairway width cannot be too wide, because if it is too wide, channel resources will be wasted. It is very important to reasonably design channel width according to navigation requirements.

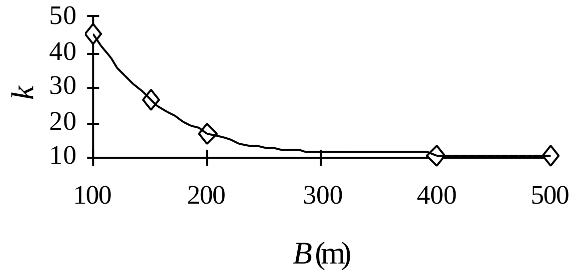

Fig. 1: Relationship between traffic accident and channel width

FAIRWAY WIDTH MODEL

Two-way navigation channel is shown in Fig. 2.

From Fig. 2, the following equation can be obtained:

$$B = d+c_1+c_2+B_1+B_2 \tag{2}$$

where, B is channel width, c1 is the safety space between left sailing ship and shore, c2 is the safety space between right sailing ship and shore, d is safety space between ships; B1 is left sailing ship's track width; B_2 is right sailing ship's track width. Every parameter in Eq. 2 will be introduced in the following contents.

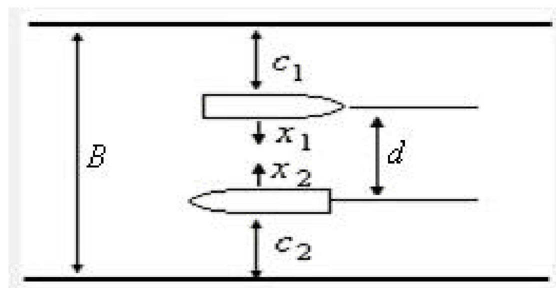

Fig. 2: Two-way navigation channels

Safety space between ships: If x_1 is left sailing ship's random probability distance of deviating away channel navigation zone axis, x_2 is right sailing ship's random probability distance of deviating away the channel navigation zone axis, then the probability under which the two ship can safe navigate and cannot collide with each other can be expressed as $P(x_1+x_2<d)$. Statistical theory has shown that most of events complied with Gaussian distribution, thus the safety space between ships can also be regarded as complying with Gaussian distribution and the $P(x_1+x_2<d)$ can be determined by the following equation:

$$P(x_1 + x_2 < d) = \frac{1}{\sqrt{2\pi}\sigma_t}\int_{-\infty}^{d} e^{\frac{-x^2}{2\sigma_t^2}}dx \tag{3}$$

where σ_t is two ship's summation mean-square deviation of deviating away fairway navigation zone axis. Because the behavior of left or right sailing ship deviating away channel navigation zone axis can be regarded as two independence random variables, x_1 and x_2 also comply with the Gaussian distribution, according to Normal superposition principle, the following equation can be obtained:

$$\sigma_t = \sqrt{\sigma_{x1}^2 + \sigma_{x2}^2} \tag{4}$$

where σ_{x1} is left sailing ship's mean-square deviation of deviating away fairway navigation zone axis, σ_{x2} is right sailing ship's mean-square deviation of deviating away fairway navigation zone axis. Eq. 3 can be rewritten as the following:

$$P(x_1 + x_2 < d) = \frac{1}{\sqrt{2\pi}}\left(\int_0^{\infty} e^{\frac{-u^2}{2}}du + \int_0^{d/\sigma_x} e^{-\frac{u^2}{2}}du\right) \tag{5}$$

Due to:

$$\frac{1}{\sqrt{2\pi}}\int_0^{\infty} e^{\frac{-u^2}{2}}du = \frac{1}{2} \tag{6}$$

Eq.(5) can be rewritten as the following:

$$P(x_1+x_2<d) = 0.5+M\ (d/F_t) \tag{7}$$

If the probability of ship deviating away channel navigation zone axis and happening collision accident is P_1, then P_1 can be expressed as the following:

$$P_1 = -P(x_1+x_2<d) = 0.5+M\ (d/F_t) \tag{8}$$

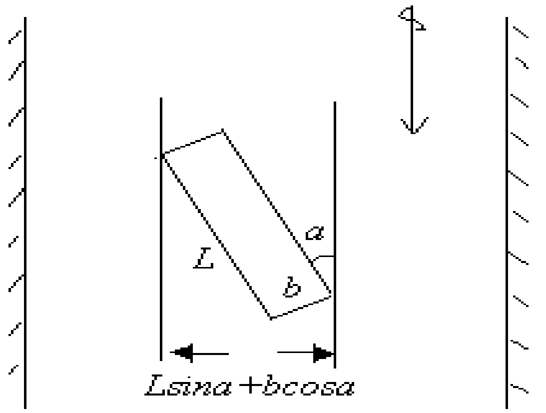

Fig. 3: Ship's track width

Uniting Eq. 8 and 4, d can be obtained:

$$d = \sqrt{\sigma_{x1}^2 + \sigma_{x2}^2}\Phi^{-1}(0.5 - P_1) \quad (9)$$

Safety space between ship and shore (c1 or c2): If the probability of ship left sailing out of the fairway boundary is P_2, so the summation probability of the ship's both sides sailing out of the fairway boundary is $2P_2$. Under the premise of complying with the Gaussian distribution, $2P_2$ can be expressed as the following:

$$2P_2 = 1 - \frac{1}{\sqrt{2\pi}\sigma_{x1}}\int_{-c_1}^{c_1} e^{-\frac{u^2}{2\sigma_{x1}^2}} du \quad (10)$$

Equation 10 can be rewritten as the following:

$$2P_2 = 1 - \int_0^{\frac{c_1}{\sigma_{x1}}} e^{\frac{-u^2}{2}} du = 1 - 2\Phi\left(\frac{c_1}{\sigma_{x1}}\right) \quad (11)$$

The following equation can be derived from Eq. 11:

$$c_1 = F_{x1}M^{-1}(0.5\text{-}P_2) \quad (12)$$

Similarly, the safety space between right sailing ship and shore c_2 can be obtained:

$$c_2 = F_{x2}M^{-1}(0.5\text{-}P_2) \quad (13)$$

If σ_{x1} and σ_{x2} can be obtained by statistics data, c_1, c_2 and d can also be determined by using Eq. 13, 14 and 9 respectively and the channel width B is also completely determined. The σ_{x1} and σ_{x2} are closely related with navigation environment, professional quality of seaman and machine condition and so on.

Table 1: Data of representative ship

Representative ship	Ship length (m)	Ship width (m)	Molded depth (m)	σ_x (m)
Barge1	291	65.0	4.2	48.7
Barge2	199	48.6	5.0	36.5
Barge3	180	40.0	3.5	30.2
Sea ship	106	19.7	10.0	14.7
River ship	65	11.0	5.3	8.3

Table 2: Computation results of channel width

Right sailing ship	Left sailing ship	c_1(m)	c_2(m)	d(m)	B(m)
Barge 1	Barge 2	112	84	156	399.7
Barge 1	Barge 3	112	69	148	370.7
Barge 1	Sea ship	112	34	132	309.4
Barge 1	River ship	112	19	128	287.2
Barge 2	Barge 3	84	69	122	312.6
Barge 2	Sea ship	84	34	102	247.3
Barge 2	River ship	84	19	97	224.1
Barge 3	Sea ship	69	34	86	210.3
Barge 3	Sea ship	69	19	80	186.1
Sea ship	Sea Ship	34	19	44	104.8
Barge 1	Barge 1	112	112	409	684.8
Barge 2	Barge 2	84	84	306	517.6
Barge 3	Barge 3	69	69	252	421.6
Sea ship	Sea ship	34	34	124	203.0
River ship	Sea Ship	19	19	69	111.6

Ship's track width: Ship's track width is determined by ship's length and its width. Figure 3, where L is ship's length, b is ship's width and $\alpha(°)$ is ship's leeway angle, illuminates ship's track width. From Fig. 3, B_1 and B_2 can be expressed as Eq. 14 and 15, respectively:

$$B_1 = |L_1 \sin a| + |b_1 \cos a| \quad (14)$$

$$B_2 = |L_2 \sin a| + |b_2 \cos a| \quad (15)$$

where, L_1 is the length of left sailing ship, b_1 is the width of left sailing ship, L_2 is the length of right sailing ship, b_2 is the width of right sailing ship.

APPLICATION OF FAIRWAY WIDTH MODEL

There are many data provided by some VTS in Table 1 which are about representative ships' particulars in a inland channel. In Table 1, σ_x is mean square of ship deviation away navigation zone axis. The data in Table 1 are obtained based on many years' observation for some fairway.

The data in Table 2 are calculation results by using Eq. 2. Methods of calculation parameters utilized in Table 2 are as follows: P_1 and P_2 are probability given value in advance, they are fixed at P_1 = 0.5% and P_2 = 1% respectively and the channel control department hopes to control the probability of happening collision accident between upstream ship and downstream ship within 0.5% and the channel control department hopes to control the probability of ship sailing away fairway zone axes within 1%. Results of many years observation showed that ships leeway angle a in this channel was in the scope of 10-25°. From the view of navigation safety, a is made a maximum value of 25° in calculating channel width.

From the calculation results in Table 2, it can be learned that in order to control fairway traffic accident probability in a specified target range, the two-way navigation fairway's width had better exceed 684.8 m. Channel regulatory department can dredge and can maintain the channel width according to the standard of 684.8 m. Therefore, the Eq. 2 is a good guidance for fairway maintaining.

CONCLUSION

The fairway with a certain width is a prerequisite for ship's safety navigation. Channel width is closely related with traffic accident. A mathematical model of the channel width is established by using the basic principles of statistical theory in this study. The application example of Eq. 2 shows that the mathematical model established in the study about fairway width is a preferable guidance for fairway maintenance and fairway dredging.

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