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Navigating Between Anchored Ships and Manoeuvering Difficulty

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When anchorages are arranged in a harbour, the manoeuvering difficulty of a ship navigating between anchored ships should be considered. However, until now, nobody has researched how to design the arrangement of anchorages from the viewpoint of manoeuvering difficulty. In this paper, the relationship between the arrangement of anchorages and manoeuvering difficulty is systematically analysed by applying the Environmental Stress Model to the problems of a ship navigating between anchored ships. Based on this analysis, a method of designing the arrangement of anchorages is considered that ensures manoeuvering difficulty is at an acceptable level for mariners. The distance needed between the anchored ships has been proposed to accord with the length of the navigating ship and the mean length of anchored ships.

KEY WORDS

1. Anchorage. 2. Harbour. 3. Design.

1. INTRODUCTION.

On entering harbour, a ship can be required to anchor at an anchoring point reserved for berth-waiting or offshore loading and unloading. If the harbour is crowded, the ship has to pass other ships at anchor to approach this point. While the ship is navigating in a harbour, the reduced water space due to anchored ships makes manoeuvering more difficult. This causes mariners to feel tension. So far, no quantitative research has been carried out to clarify the relationship between the arrangement of anchored ships and the manoeuvering difficulty of a passing ship.

The Environment Stress Model (Inoue *et al*., 1997) was proposed as a method to undertake a quantitative evaluation on how much stress a mariner experiences when navigable water is limited by objects such as wharf, breakwater, buoy, ship at anchor, fishing boat at work, or fixed shore net. This model is suitable for a quantitative evaluation of the burden on mariners caused by space limitations in a navigable water area, and indicates that burden with a stress value.

In this paper, the relationship between the arrangement of anchored ships and manoeuvering difficulty is systematically analysed by applying the Environment Stress Model to the problem of navigating between anchored ships. Throughout this analysis, a method of quantitatively fixing the design elements of anchorage arrangements is considered under the condition that manoeuvering difficulty remains within an allowable level for mariners.

2. DESIGN ELEMENTS OF ANCHORAGE AREA.

Figure 1 gives an example of an anchorage arrangement when a number of ships are anchored in a water area. Its design elements are:

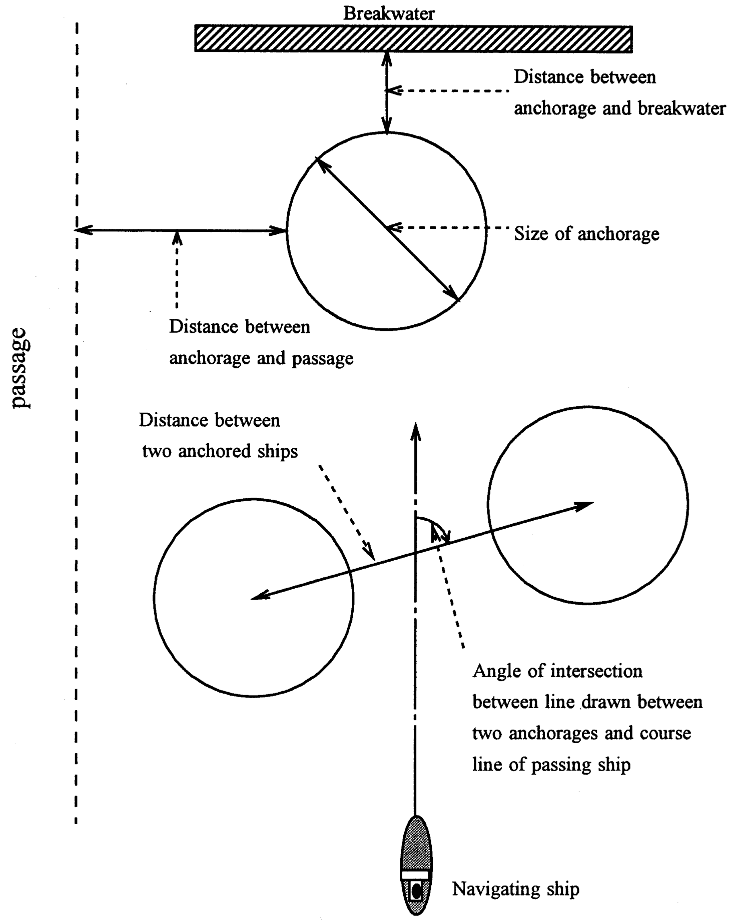

Figure 1. Design elements of an anchorage area.

(a) size of each anchorage,
(b) distance between two anchorage centres,
(c) angle of intersection between the line joining the centres with the course line of passing ship,
(d) distance from anchorage to a passage, and
(e) distance from anchorage to a breakwater.

Elements (a), (d) and (e) must be considered in terms of anchored ship motion and anchor dragging. These will be examined at another time. This study concerns elements (b) and (c) and seeks the optimum anchorage arrangement for stress-free navigation. First, the desirable relationship between two neighbouring anchorages for mariners needs to be clarified. Second, consideration is given to the way anchorages are arranged.

3. CONDITIONS OF CALCULATION.

3.1. *Parameters of a ship*. Ship length, whether a ship is navigating or at anchor, is classified into three types: 130 m, 200 m and 280 m, which are referred to as S, M and L. Gross tonnage is needed for the calculation of stress value using the Environment Stress Model. The regression formula is:

$$\log(\mathrm{GT}) = 3{\cdot}11 \times \log(\mathrm{Loa}) - 2{\cdot}85, \tag{1}$$

(coefficient of correlation: 0·996)

where:

GT = gross tonnage (tonnes),

Loa = length overall (metres).

This formula is derived from the correlation between length overall and deadweight tonnage of cargo ship, container ship or tanker, and from an expression of the relation that converts deadweight tonnage into gross tonnage, discussed in the Technical Standard of Port and Harbour Structures (Standards, 1989). Navigating ship speed is assumed to be constant at 6 knots and water area is open sea.

3.2. *Arrangement of anchored ships.*

3.2.1. *Case of two anchored ships.* The coordinates used for two anchored ships are shown in Figure 2. A mariner, when passing close to an obstacle, tries to maintain

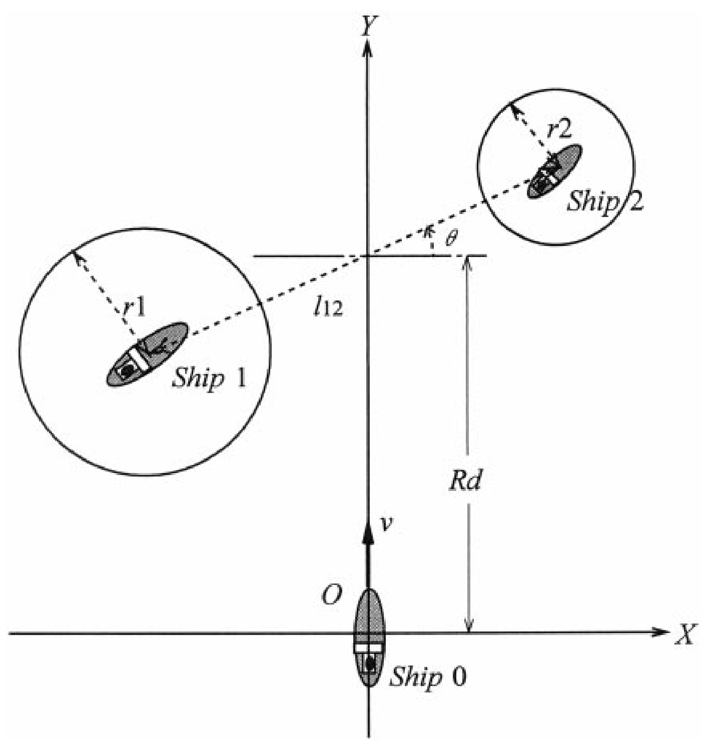

Figure 2. Coordinates of two anchored ships.

a certain distance from it. The regression formula to estimate the minimum distance needed to pass an obstacle at close range (Inoue, 1994) is:

$$\mathrm{db} = 0{\cdot}89 \times \mathrm{Ln}, \tag{2}$$

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where:

db = minimum distance needed to pass by an anchored ship at close range (m),

Ln = length overall of passing ship (m).

In the calculation of stress value, there is assumed to be a barrier around an anchored ship that would not cause a physical collision and whose radius is shown by:

$$r = 0{\cdot}89 \times Ln + 0{\cdot}5 \times La, \quad (3)$$

where:

r = radius of the barrier (m),

Ln = length overall of passing ship (m),

La = length overall of anchored ship (m).

The angle of a crossing course is shown as θ. It will be 0 degrees when a course line crosses at a right angle to a line drawn between two anchored ships, and positive (plus) in the counterclockwise direction. The distance between two anchored ships, or the centres of the two barriers surrounding each ship at anchor, is l.

3.2.2. *Case of three anchored ships*. Figure 3 shows the coordinates used for the case of three anchored ships. Its basic arrangement is an isosceles triangle whose base, a line between Ship 1 and Ship 2, is cut at right angles by a course line, and whose vertex, the position of Ship 3, is situated on the course line. The angles between the

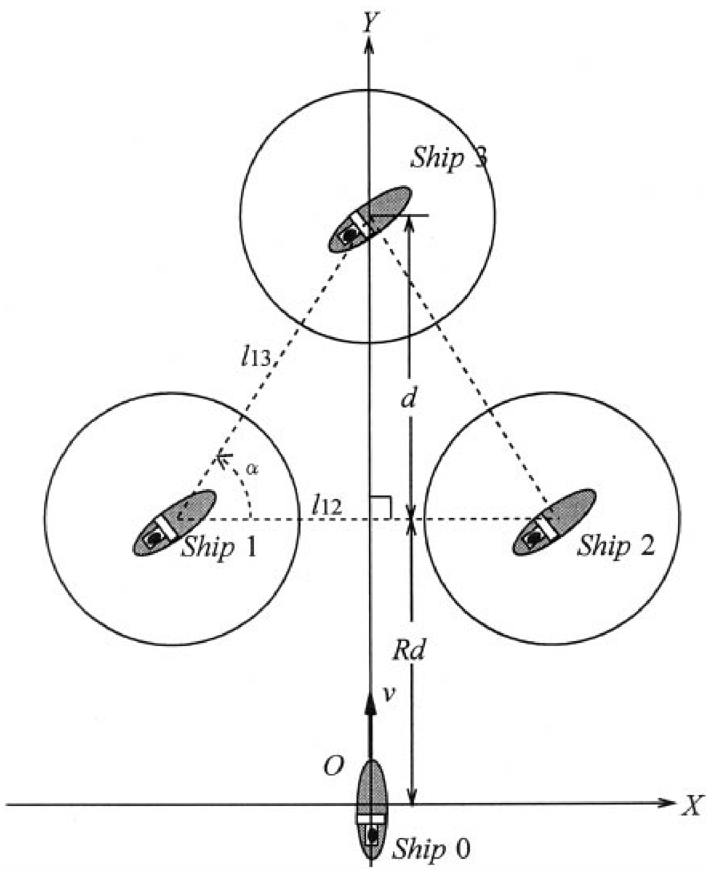

Figure 3. Coordinates of three anchored ships.

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base and the side from Ship 1 to Ship 3 or the other side from Ship 2 to Ship 3 are α. Perpendicular d is equal to the distance from the middle of the base to the ship anchored behind.

4. CONDITIONS OF MANOEUVERING DIFFICULTY AND QUANTITATIVE ANALYSIS OF DESIGN ELEMENTS OF ANCHORAGE ARRANGEMENTS.

4.1. *Navigation between two anchored ships.*

4.1.1. *Case of the same size.* When θ is 0 and Ship 0 passes the centre of the line between Ship 1 and Ship 2, the manoeuvering difficulty caused by the existence of two anchored ships was calculated with the Environment Stress Model as shown in Figure 4. For this calculation, each ship type is assumed to be 'M' (length 200 m).

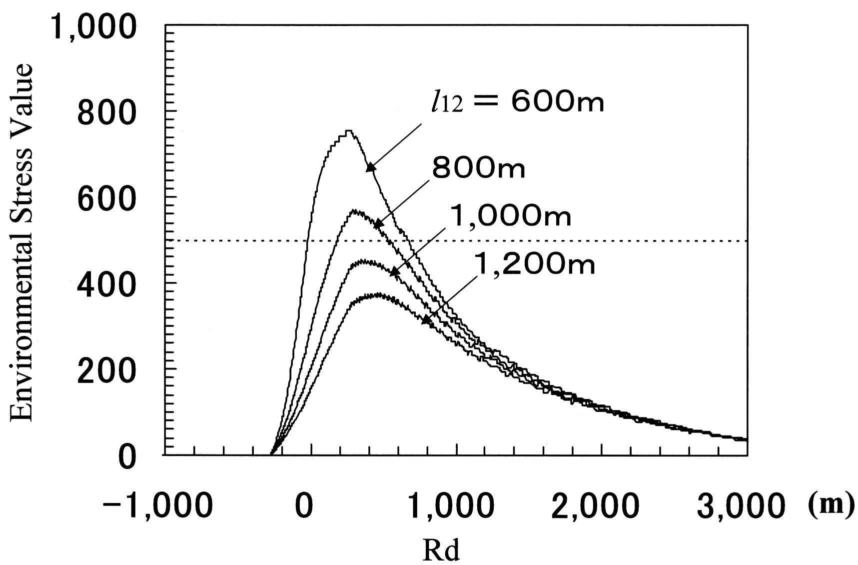

Figure 4. Change of stress value with two anchored ships.

Figure 4 shows that, as the distance between Ship 1 and Ship 2 is varied from 600 m to 800 m, to 1,000 m and to 1,200 m, the stress values change accordingly. This proves that as the distance between Ship 1 and Ship 2 increases, the peak stress value decreases, and that just before crossing the line drawn from Ship 1 to Ship 2 the stress values always arrive at the peak without any influence from the change of separation distances.

A stress value, an outcome measured with the Environment Stress Model, is a quantitative indication of the feeling of tension caused by the difficulty a mariner experiences when manoeuvering under an environmental condition that reduces available water area. Its numerical values correspond to the following criteria: a value of 500 or below signifies that the condition may be within an acceptable level for all mariners to operate; a value between over 500 and 750 means that 25% of mariners cannot operate safely; from over 750 to 900, 75% of mariners cannot operate safely; over 900, a condition of high stress, no-one can operate safely.

In terms of anchorage designs, it is desirable that the difficulty of passing other ships must be acceptable to all mariners. Therefore, the necessary design elements of

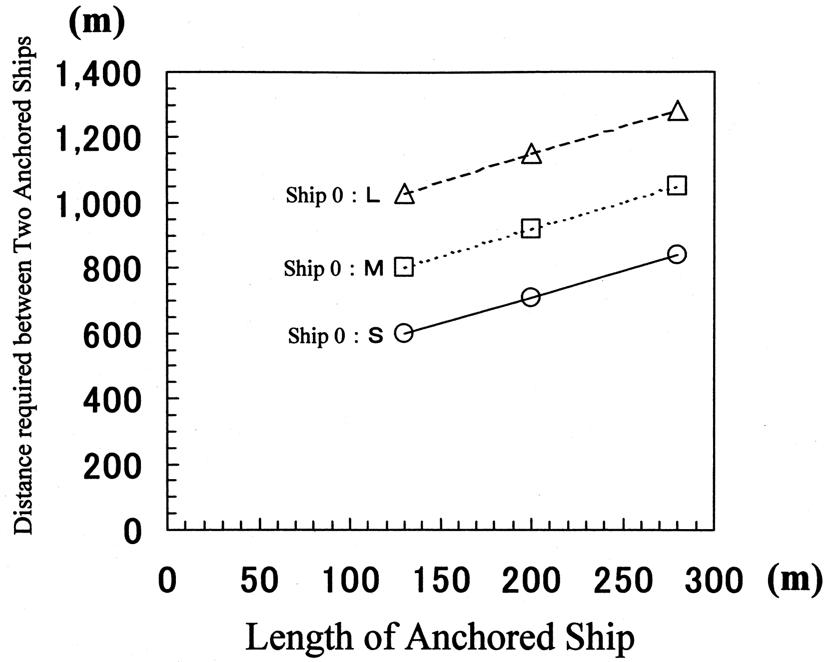

Figure 5. Distance required between two ships of the same size.

anchorages need to be considered on the basis of a maximum stress value of 500, which is regarded as the design standard for a burden that is 'negligible'. The required distance between Ship 1 and Ship 2 with the stress value of 500 is shown in Figure 4 by the graph line reaching the stress value of 500 as a peak, at the moment the ship crosses the line between Ship 1 and Ship 2.

Figure 5 plots passing vessel length, as a parameter, with anchored-ship lengths on the abscissa and distances between two anchored ships at the stress value of 500 on the ordinate, under the condition that the lengths of anchored ships are the same. For example, when two anchored ships are assumed to be S (130 m), the required distance will be 600 m for a passing ship S; 800 m for a passing ship M (200 m); and 1,000 m for a ship L (280 m). The longer the passing ship is, the greater the required distance. If a passing ship is S, size S anchored ships will require a distance of 600 m; size M will require 700 m; size L will require 800 m. This shows that the required distance between two anchored ships depends on the lengths both of passing and anchored ships. Multiple regression is applied to navigation between two anchored ships of the same length, with the lengths overall of passing ship and anchored ships regarded as explanation variables and with the distance required between two anchored ships considered as explained variables using the following formula:

$$l = 2{\cdot}91 \times \mathrm{Ln} + 1{\cdot}64 \times \mathrm{La} + 5{\cdot}0, \qquad (4)$$

(coefficient of multiple correlation: 0·9999)

where:

l: distance required between two anchored ships (m),

Ln: length overall of navigating ship (m),

La: length overall of anchored ship (m).

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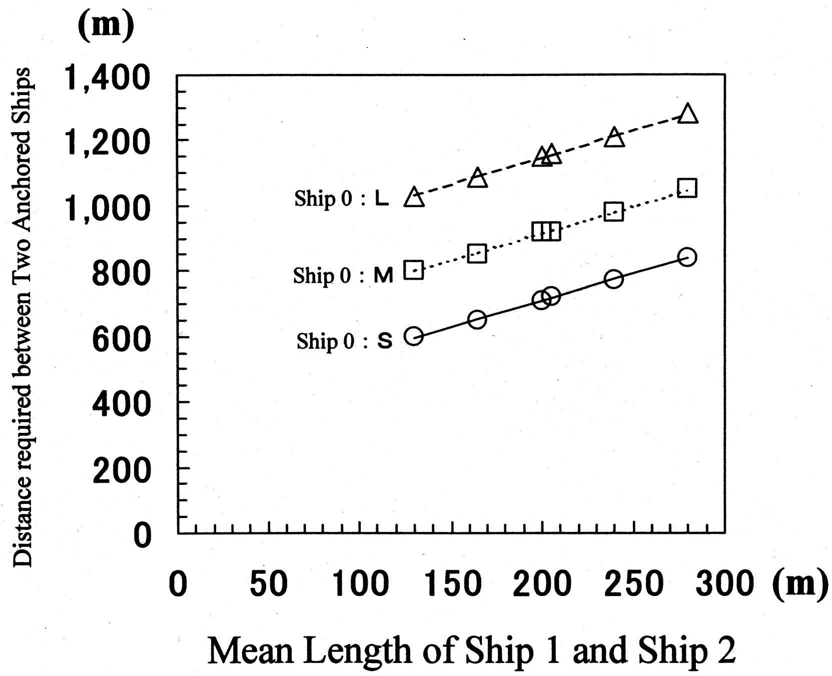

Figure 6. Distance required between two ships of different sizes.

This regression formula gives the distance required between two anchored ships of the same length when any size of ship passes between them.

4.1.2. *Case of different size*. When neighbouring ships at anchor are of the same size, it can be considered that a mariner is likely to choose a course line mid-way between the anchored ships. If one anchored ship is smaller than the other, the mariner may be willing to take a closer line to the smaller one rather than pass through the middle. It is possible that he might choose a course that mitigates the different levels of stress derived from each ship. Given the assumption that a passing ship might take a course that equalizes the bi-lateral stress values, each of which should be calculated as if one of the anchored ships is the only obstacle for a passing ship to avoid in her course line, this course line is shifted slightly from the centre to a position closer to the smaller ship. Although an actual course line is not examined in this study, if it lies within 50 m of both sides, the level of difficulty is not changed.

Figure 6 shows the calculation results for the required distances of all combinations of ship type (S, M and L) with a stress value of 500, when a ship passes between two anchored ships of different sizes. Marks ○, □ and △ in the figure refer to the length classes of passing vessels: ○ means S, and so on; the mean lengths of two anchored ships are on the abscissa. Multiple regression is applied here, with the lengths overall of passing ships and mean lengths of anchored ships as explanation variables and with the distance required between two anchored ships as explained variables, the following formula is obtained:

$$l = 2{\cdot}92 \times \mathrm{Ln} + 1{\cdot}64 \times \mathrm{Lam} + 0{\cdot}89, \qquad (5)$$

(coefficient of multiple correlation: 0·9999)

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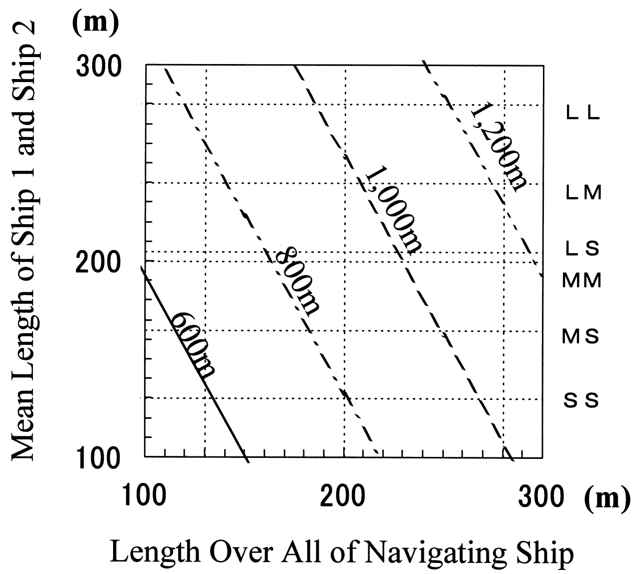

Figure 7. Distance required with two anchored ships.

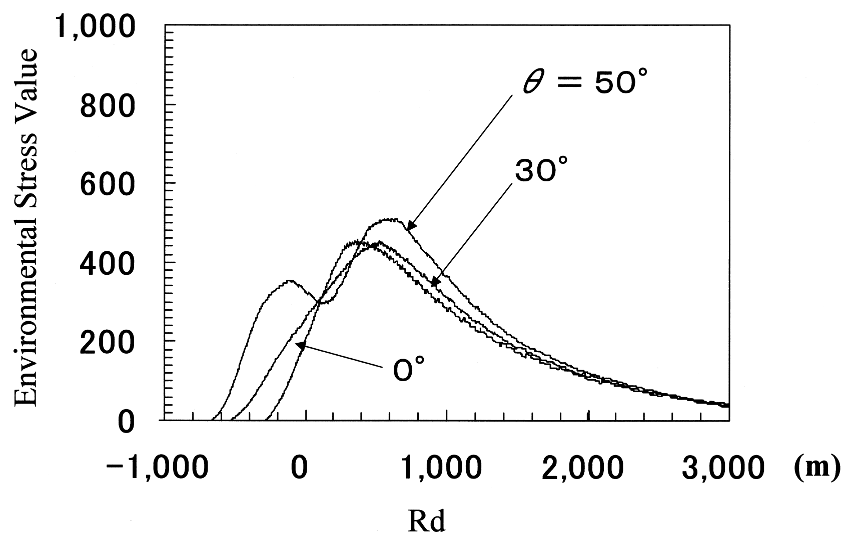

Figure 8. Influence of intersection angle with two anchored ships.

where:

l: distance required between two anchored ships (m),

Ln: length overall of navigating ship (m),

Lam: mean length of two anchored ships (m).

This regression formula gives the distance required for combinations of two anchored ships and passing ship of any size.

Figure 7 is a diagram of the results using Equation 5 for the lengths overall of a passing ship on the abscissa and with the mean length of anchored ships on the

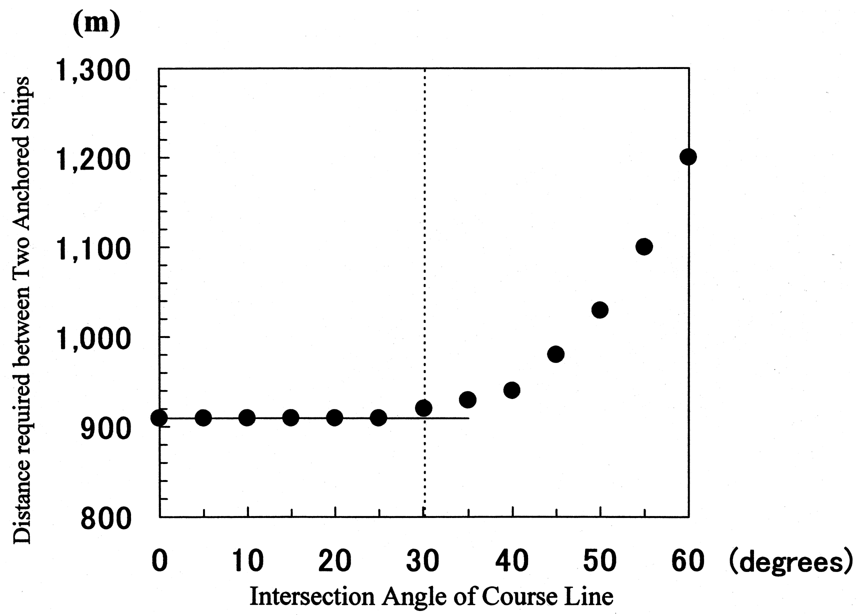

Figure 9. Change of distance required between two anchored ships.

ordinate. For example, this diagram shows that the combination of passing ship M with anchored ships L and S requires a distance of 900 m. This equation and Figure 7 are useful for calculating the distance necessary for every possible combination of passing ship and anchored ships for future design of anchorages.

4.1.3. *Intersection angle of course line.* Figure 8 shows the trends for stress change when the course line of a passing ship of type M crosses a line 1,000 m between anchored ships of the same type at the angle θ for the following values: 0°, 30°, and 50°. In the case of a ship passing at an angle of 0°, there is one stress peak, because in this arrangement the anchored ships may be regarded as one combined obstacle to be avoided by one passage. Up to an angle of 30° the trend is the same, and the stress peak has the same height. However, at an intersection angle of over 30°, there are two stress peaks, and the second peak is higher than the first.

Figure 9 is a dot graph showing distances having a stress peak at 500 when a ship passes at various angles. Up to an angle of about 30°, changing the intersection angle yields no significant results, but beyond 30° the distance required starts to increase sharply. Summarizing this, when two anchorages are arranged at an angle of $\pm 30°$ to the course line of approaching ships, it can be considered that these arrangements are the same in terms of arrangement design.

4.2. *Navigation among three anchored ships.*

4.2.1. *Case of the same size.* Figure 10 shows the results calculated using the Environment Stress Model for difficulties caused by three anchored ships, when the distance between Ship 1 and Ship 2 is assumed to be l_{12} = 1,200 m and distance d to the third ship is varied (see Figure 3). Ship 0 crosses the Ship 1–Ship 2 line at the centre, and all ships concerned are assumed to be of M type (length of 200 m).

A peak stress value appears at the moment Ship 0 reaches the line between Ship 1 and Ship 2; after passing the line the stress value line is lower, but as Ship 0

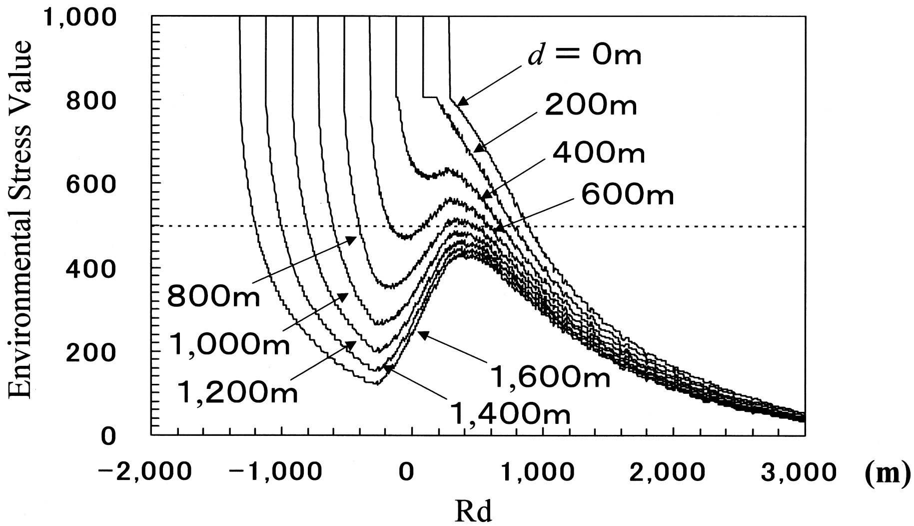

Figure 10. Change of stress value with three anchored ships.

approaches Ship 3, it increases again. An increase in distance d to Ship 3 corresponds to a decrease of the peak stress value. On the curved lines $d = 1{,}200$ m, 1,400 m and 1,600 m, the peaks tend to stay at a certain point. This means that increasing the distance to Ship 3 is not efficient for reducing the stress value; there is a limit beyond which any position of Ship 3 does not lower the stress value.

Therefore, positioning Ship 3 at a limit point must be taken into account as an anchorage arrangement condition. Based on this, distances l_{12} and d are calculated so that the stress value concerning this correlation for Ship 3 and Ships 1–2 indicates 500. The arrangement for three ships at anchor is decided in this way. Distance l_{12} between ships of the same size in a three-ships arrangement was calculated as a trial, and the result proved that the distance must be 1·3 times greater than the distance required between two ships of the same size. From the calculation carried out for the relationship of distance d to the third ship to the distance between two anchored ships, the angle formed by the base and the side was about 60°. Therefore, it is possible to assume that the arrangement of three ships that would not cause a mariner to feel stress is an equilateral triangle shape.

4.2.2. *Case of different sizes*. Distance l_{12} required between two anchored ships and length d to the third ship was calculated for combinations of all ship type: S, M and L, as mentioned in previous section. Figure 11 is a proportional display of how much greater the distance required is for three ships at anchor, based on the distance needed in the two-ships arrangement case. This calculation involves the case in which all three ships are of the same in size. The distance from the passing ship increases, but in general it remains around 1·3. From this observation, it can be said that the distance necessary to arrange three ships is given by multiplying the distance needed for two ship anchorages by 1·3 times.

Angle α decreases as the size of a passing ship or two anchored ships become bigger, while it increases as the third ship becomes larger. Multiple regression is applied here, with the lengths overall of Ship 0 and Ship 3 and the mean length of

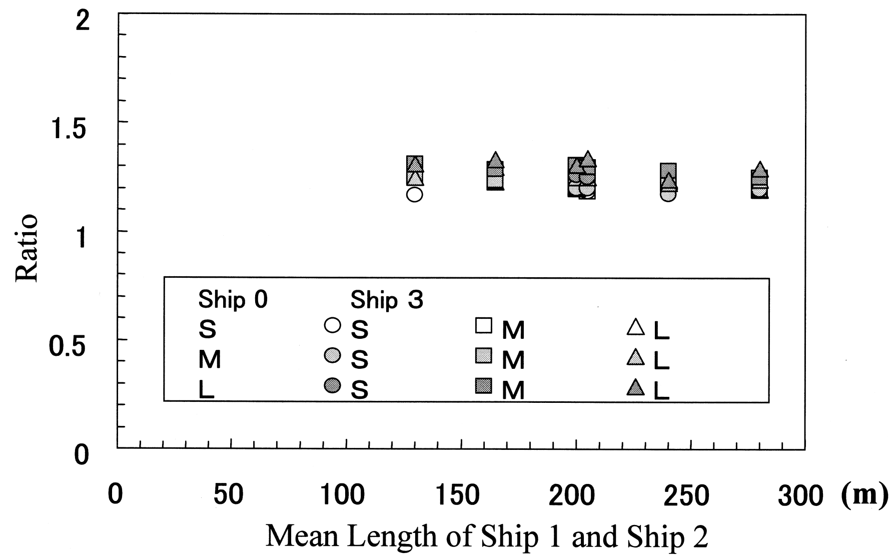

Figure 11. Distance required for three anchored ships based on distance needed for two anchored ships.

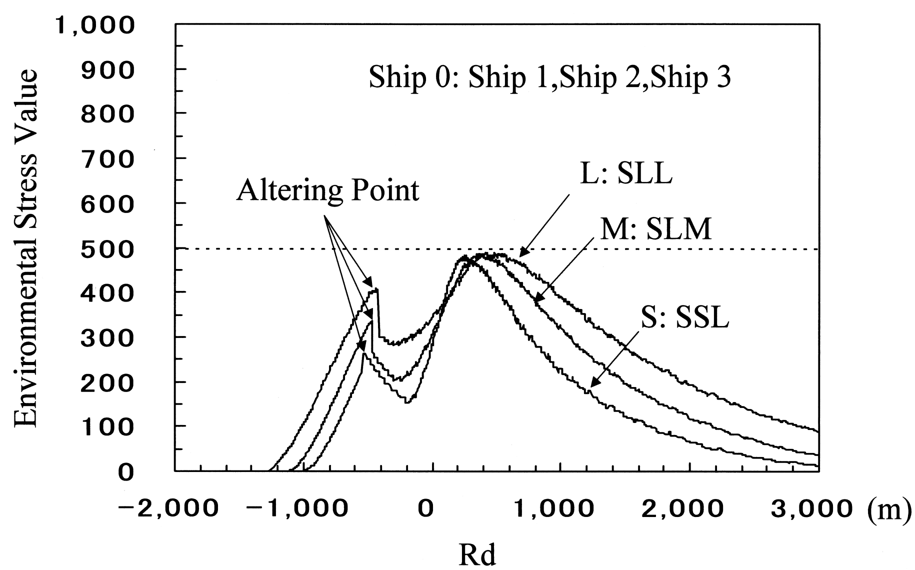

Figure 12. Change of stress value for navigating with turning at metacentre point.

Ship 1 and Ship 2 in front as explanation variables and with angle α as the explained variable, the following formula is obtained:

$$\alpha = -0{\cdot}050 \times \mathrm{Ln} + 0{\cdot}015 \times \mathrm{La}_3 - 0{\cdot}034 \times \mathrm{Lam} + 78{\cdot}679, \quad (6)$$

(coefficient of multiple correlation: 0·950)

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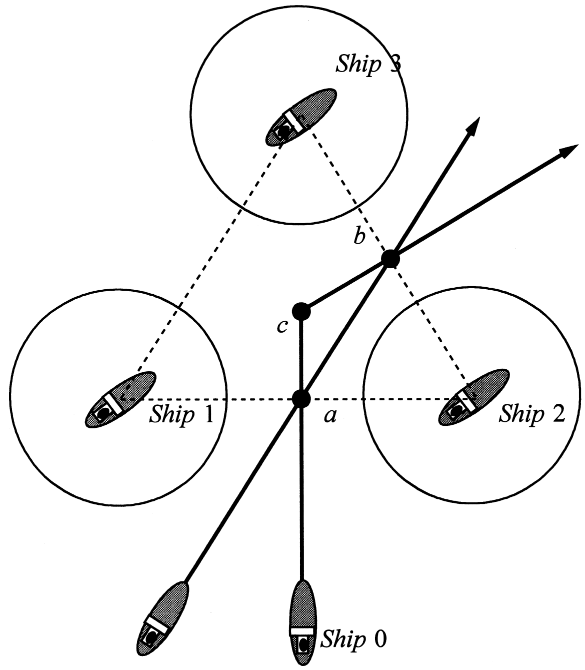

Figure 13. Setting course line among three anchored ships.

where:

α = angle between the base and the sides,

Ln = length overall of navigating ship (m),

La_3 = length overall of Ship 3 (m),

Lam = mean length of two anchored ships in front (m).

This regression formula gives angle α to form a triangular anchorage arrangement for any combination of any anchored ship type, and this numerical value and distance l_{12} between two anchored ships can be used to decide the anchorage arrangement.

4.2.3. *Trial calculation of manoeuvering difficulty when navigating through three anchored ships.* When navigating through three anchored ships, the course needs to be changed at a certain point after passing the two anchored ships in front. In this case, it is sufficient to place the point where the stress value for Ship 3 is not over 500. Provided that the course line crosses the lines between at right angles, geometrically, the course changing point will be the metacentre.

Figure 12 shows how the stress value changes as a ship on the course line turns at this metacentre to pass through three anchored ships. Of the model cases in Figure 12, combination of L (Ship 0); SLL (Ships 1, 2, 3) is the most difficult case of manoeuvering, combination S; SSL is, by contrast, the least difficult case, and the last combination M; SLM is one of the average cases. In all cases, the stress value peaks come when a ship is about to cross the line between Ship 1 and Ship 2, and Ship 0 approaches Ship 3 with the second peak, but a course change stops the stress value rising. Before the course change Ship 3 causes difficulty, and after the change Ship 3 and Ship 2 become a new combined obstacle to pass, so the difficulty increases again but to an allowable level for mariners. Navigating on a course line that crosses at right

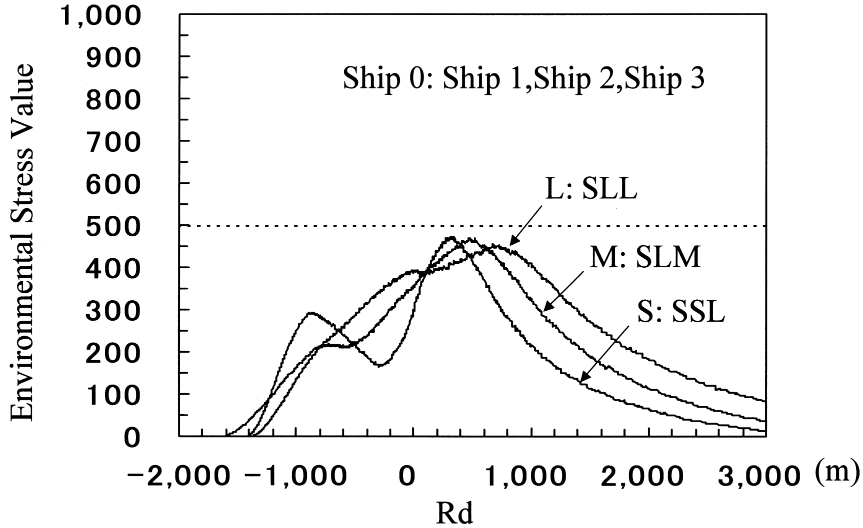

Figure 14. Change of stress value for navigating on a line connecting bisection points.

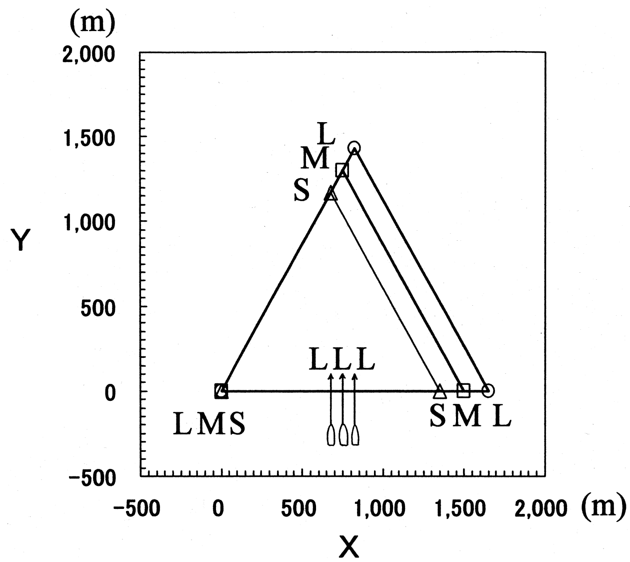

Figure 15. Examples of anchored ship arrangements. (Navigating ship is of type 'L'. Anchored ships are of the same size.)

angles the line between two anchored ships and turns at the metacentre does not seem to place an extra burden on a mariner, and this proves that the idea for designing anchorages proposed in this study is sound in terms of anchorage dimensions and arrangement.

Another course line can also be imagined. Marks a and b in Figure 13 are points bisecting the lines between two anchored ships. Figure 14 shows stress value changes when a ship navigates in a straight line passing points a and b. As in Figure 12, the results displayed here are limited to the most difficult, the mean and the least difficult

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cases. In all three cases, their stress-peaks are under 500. The deviation of $\pm 15°$ from the line passing a and b, after a ship has passed point a, has a stress value under 500. Consequently, the proposed concept for designing anchorages permits errors in the range of $\pm 15°$ when a ship navigates on the line passing the bisection points a and b between the anchored ships.

4.3. *Speed of passing ship*. The earlier part of this study assumed that a passing ship navigates at a speed of 6 knots. In practice, ships navigate at a speed of more than 6 knots. The correlation between speed and the stress value was examined; while a speed over 6 knots increases the stress value to a higher level and induces it earlier, there is no significant difference of peak stress values between the two-ships case and the three-ships case.

5. AN EXAMPLE OF ANCHORAGE ARRANGEMENT DESIGN.

While accentuating distance l_{12} between anchored ships and angle α, which are regarded as the principal elements of the design of anchorage arrangements, this study makes a quantitative examination in terms of manoeuvering difficulty. The results show that the design arrangements for a combination of passing ship of type L with anchored ships of the same type is an equilateral triangle, and that when anchored ships are smaller, it is also an equilateral triangle with shorter sides (see Figure 15), but that when anchored ships are of different sizes and the passing ship is type L, the arrangement is an isosceles triangle with angle α, calculated by the regression formula of Equation 6, as shown in Figure 16. These figures display the conditions required to maximize or minimize the areas of triangles. Based on variations of ship sizes: L (280 m), M (200 m) and S (130 m), the lengths of each side of the triangle are generally from 1,300 m to 1,500 m.

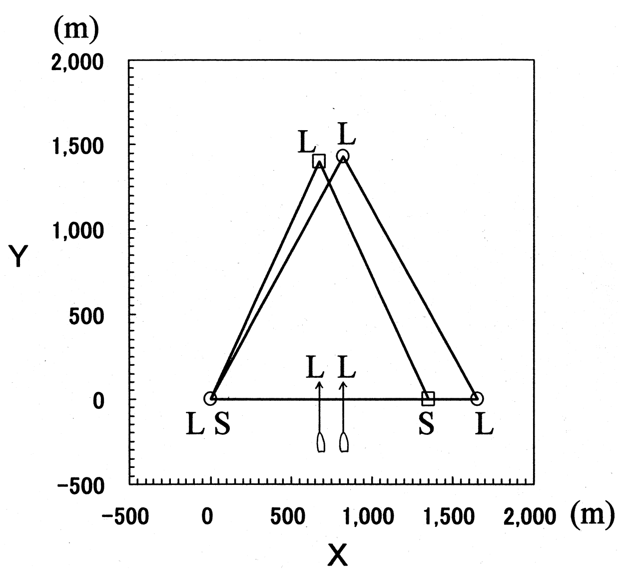

Figure 16. Examples of anchored ship arrangements. (Navigating ship is of type 'L'. Anchored ships are of different sizes.)

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Comparing this to the numerical values from 700 m to 1,000 m, which most harbours actually provide as the distance between anchored ships, the normal anchorage arrangement is expected to put more stress on mariners when manoeuvering in a harbour area.

6. CONCLUSION. This study, which uses the Environment Stress Model involving a systematic analysis of manoeuvering difficulty in a passage through anchored ships, has obtained the following results:

(a) Based on the length overall of the passing ship and the mean lengths of anchored ships, the regression formula at Equation 4 gives the distance between two anchored ships. This can be used to design an anchorage arrangement suitable for two ships that does not impose an unacceptable level of stress on the crew of a passing ship, as shown at Figure 2.
(b) To obtain the distance required between three anchored ships, the numerical value given by the regression formula at Equation 4 should be multiplied by 1·3; the three-ship arrangement is normally an equilateral triangle, and when it must be changed to an isosceles, angle α can be calculated by the regression formula at Equation 6.
(c) In terms of manoeuvering difficulty, when a course line passes through two ship anchorage arrangements at an intersection angle of less than $\pm 30°$, it can be considered to be equal to a straight course line for design purposes.

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