Evaluation Method of Ship-handling Difficulty for Navigation in Restricted and Congested Waterways

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This paper develops a quantitative model for evaluating the difficulty of ship-handling caused by a restricted manoeuvring area or by traffic congestion or by a combination of both. It includes acceptance criteria based on the mariner's perception of safety. An attempt is made to evaluate the model by applying it to the specific environmental conditions of major ports in Japan. The model can provide information on the degree of ship-handling difficulty and so enable better design of infrastructure for waterways.

KEY WORDS

1. Human Factors. 2. Simulation. 3. Safety.

1. INTRODUCTION. In a navigation system, which consists of linked relationships in a 'ship-human-environment', the human factor plays a significant role in triggering accidents. However, more important factors that affect the possibility of accidents occurring are the environmental conditions that determine the level of ship-handling difficulty.

A very small, careless mistake in the ship-handling process may cause an accident when the topographical and traffic environments impose difficulties on the mariner. The greater the level of difficulty, the higher the probability of an accident. The risk of an accident thus relates strongly to the level of difficulty forced on the mariner by the environment in which ship-handling is executed.

When reviewing policies for ensuring the safety of navigation in topographically restricted waters or in waterways congested with ships, it is important to evaluate the level of difficulty that the mariner may encounter while executing the ship-handling process under a given environment.

In this paper, a quantitative model is proposed for evaluating the difficulty of ship-handling caused by a restricted manoeuvring area or by traffic congestion. In the model, stress values are introduced as difficulty-indices, and these values are calculated on the basis of the residual time before the danger becomes a reality. The model also clarifies the acceptance criteria of the stress based on the mariner's perception of safety.

An attempt is made to evaluate ship-handling difficulty by applying the model to typical situations in waterways and specific environmental conditions of major ports in Japan. The model can provide information on the degree of ship-handling difficulty in waterways and allow us to design a better infrastructure for waterways.

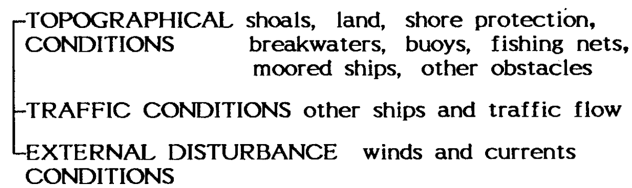

Figure 1. Elements of environmental conditions.

2. THE ENVIRONMENTAL STRESS MODEL

2.1. *Environmental Conditions*. As shown in Figure 1, the elements of the environmental conditions that can be taken into account in the model are as follows:

(i) Topographical conditions such as land, shoals, shore protection, breakwaters, buoys, fishing nets, moored ships and other fixed or floating obstacles.
(ii) Traffic conditions such as the density of other ships and traffic flow.
(iii) External disturbances such as winds and currents.

2.2. *Model Structure*. The proposed model, which expresses in quantitative terms the degree of stress imposed by topographical and traffic environments on the mariner, is called the Environmental Stress Model (ES-model). The ES-model is composed of the following three parts:

(i) Evaluation of ship-handling difficulty arising from restrictions to the water area available for manoeuvring. A quantitative index expressing the degree of stress forced on the mariner by topographical restrictions (ES_L value) is calculated on the basis of the time to collision (TTC) with any obstacles.
(ii) Evaluation of ship-handling difficulty arising from restrictions on the freedom to make collision-avoidance manoeuvres. A quantitative index expressing the degree of stress forced on the mariner by traffic congestion (ES_S value) is calculated on the basis of the time to collision (TTC) with other ships.
(iii) Aggregate evaluation of ship-handling difficulty forced by both the topographical and traffic environments, in which the stress value (ES_A value) is derived by superimposing the value ES_L and the value ES_S.

In the respective calculations of the value ES_L and the value ES_S, a common index was used and the same algorithm was introduced to perform simultaneous aggregate evaluations of ship-handling difficulty as experienced in encounters with other ships in narrow waterways.

2.3. *Calculation of Stress Values*. When, as in ocean sailing, there are no restrictions to the water area available for manoeuvring and there is sufficient TTC, regardless of the direction in which the ship proceeds, no stress is imposed on the mariner and he feels no difficulty in ship-handling. In narrow waterways, the water area available for manoeuvring is restricted, and there is little TTC regardless of the ship's direction; therefore, the topographical environment causes the mariner considerable stress and creates difficulty in ship-handling. When other ships are present in the vicinity, and there is a danger of collision with other ships according to the direction of sailing, the mariner is put under additional stress. The stress becomes particularly great when there is little TTC, regardless of the direction of the ship.

Based on this concept, the value ES_L and the value ES_S are calculated under the common procedure shown below:

1. Consider the ship's course in the range of 180°.

Table 1. Stress Ranking and Acceptance Criteria

SJ:	MARINERS' JUDGEMENT	ES value $\Sigma(SJ)_i$	STRESS RANKING	ACCEPTANCE CRITERIA
0	Extremely safe	[0]	NEGLIGIBLE	ACCEPTABLE
1	Fairly safe			
2	Somewhat safe			
3	Neither safe or dangerous	[500]	MARGINAL	
4	Somewhat dangerous	[750]	CRITICAL	UNACCEPTABLE
5	Fairly dangerous	[900]	CATASTROPHIC	
6	Extremely dangerous	[1000]		

2. Calculate the TTC for each one degree graduation in the range of $\pm 90°$ centred on the present course.
3. Convert the TTC into the mariner's perception of safety for each one degree.

The conversion formula shown at (1) are given by regression equations found through ship-handling simulator experiments (31-subjects) and a questionnaire (573-answers).[1]

$$SJ_L, SJ_S = \alpha \cdot TTC + \beta \tag{1}$$

Where SJ_L is the subjective judgement of mariners in relation to TTC with obstacles and SJ_S is the subjective judgement of mariners in relation to TTC with ships. The scales of subjective judgement consist of numeric values with seven steps from 0 (extremely safe) to 6 (extremely dangerous). α and β are coefficients determined by the size of own ship (in case of SJ_S value) or by the combination of the size of own ship and the target ship (in case of SJ_S value).

The values SJ_L, SJ_S within the range of courses $\pm 90°$ are summed to find the stress values as follows:

$$ES_L = \Sigma (SJ_L)_i \tag{2}$$
$$i = -90 \sim +90$$

$$ES_S = \Sigma (SJ_S)_i \tag{3}$$
$$i = -90 \sim +90$$

2.4. *Classification of Stress Values*. If there is no danger in any direction, the SJ value of 0 extends over 180°, so $0 \times 180 = 0$ is assigned as the minimum stress value. If there is immediate danger, regardless of the ship's direction, the SJ value of 6 extends over 180°, so $6 \times 180 \approx 1000$ is assigned as the maximum stress value. The stress ranking is set up by classifying the range of stress values as 0 to 1000 as shown in Table 1. The rank of stress can be classified according to the extent to which a dangerous situation causes a particular level of SJ value in the range of $\pm 90°$ around the present ship's course. In the model, a situation giving the same SJ value, regardless of direction, was taken as the standard situation. The relationship between each stress ranking and the acceptable level was found through the ship-handling simulator experiments and the questionnaire.[1] The ES model, therefore, allows us to judge how great the stress value will be when it is no longer acceptable and to point out the disadvantages of the topographical and traffic situation in a waterway.

2.5. *Calibration of The Model Output*. To verify the outputs of the ES-model, calibration was attempted using a ship handling simulator. In trials, several scenarios in which the ship encountered other ships in a curved, narrow waterway were prepared. ES_A values were calculated from the results of trials, and pulse of heart beats of the mariner subjected to the simulation trial was taken at the same time. The correlation between the stress values derived from the ES-model and the indices of physical stress obtained from the spectral analysis of the change of heart beats is shown in Figure 2. Because the index of physical stress increases as the ES_A value increases (in the 'unacceptable' area to a value of more than 750), the validity of the model is demonstrated.

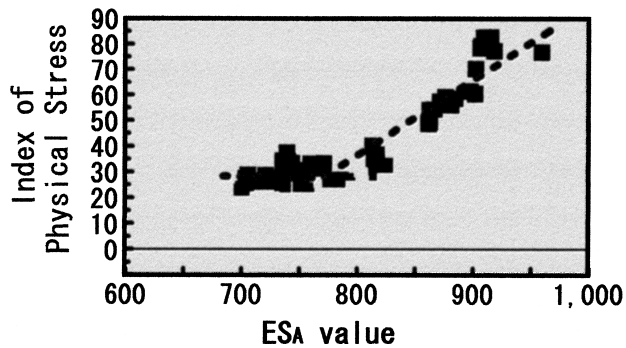

Figure 2. Calibration of model output.

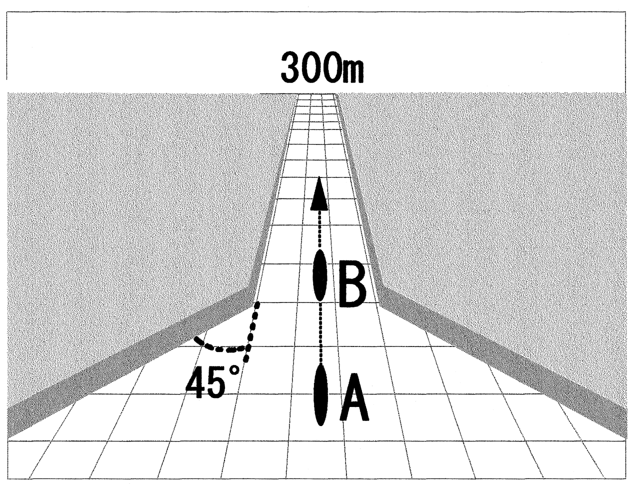

Figure 3(a). Narrow waterway.

3. EXAMPLES OF TYPICAL OUTPUTS FROM THE ES-MODEL.

3.1. *ES_L Values in a Narrow Waterway*. Figure 3(c) shows the calculated results of stress values imposed on a mariner who manoeuvres a ship with a length of 100 m at ship speed (V) of 10 kts and 5 kts in a narrow waterway with width of 300 m as shown in Figure 3(a). Figure 3(b) shows TTC values corresponding to virtual courses at

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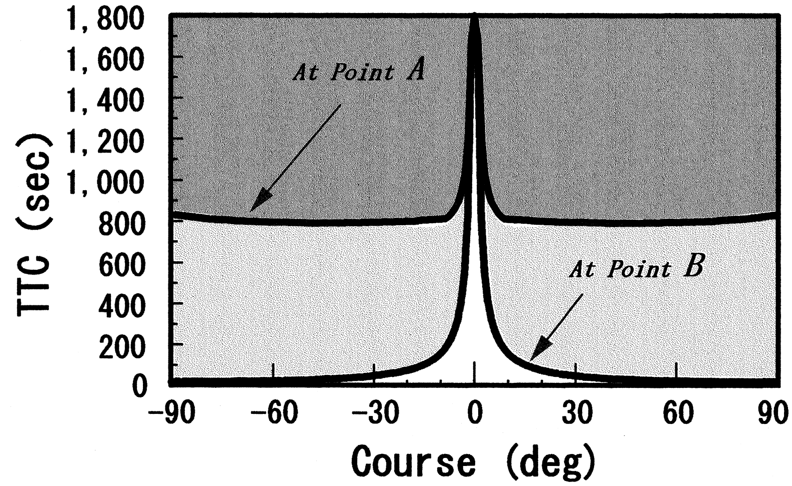

Figure 3(b). TTC values.

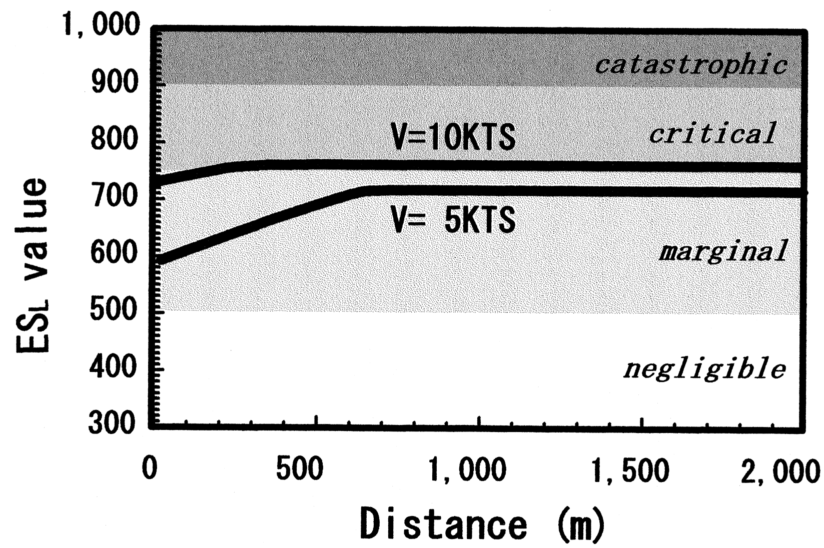

Figure 3(c). ES_L in narrow waterway.

every 1° in the range of ±90° from the original course of the ship. The meshed area in the figure increases as the width of the waterway decreases.

In the model, TTC values represented by the vertical axis are converted into psychological values SJ_L by the conversion formula (1); then the value ES_L is derived by integrating SJ_L values within the meshed area. Figure 3(c) shows ES_L values obtained by the above conversion process. The narrower the passage and the faster the ship speed, the higher the stress imposed on the mariner. With a ship speed of 10 kts, ES_L values come slightly above 750, which corresponds to 'critical' in the stress ranking. At a ship speed of 5 kts, the ES_L values are around 700, which corresponds to 'marginal' in the stress ranking.

3.2. *ES_L Values at Breakwater Entrance*. Figure 4 shows the calculated stress values when a ship with a length of 100 m passes through the entrance of a

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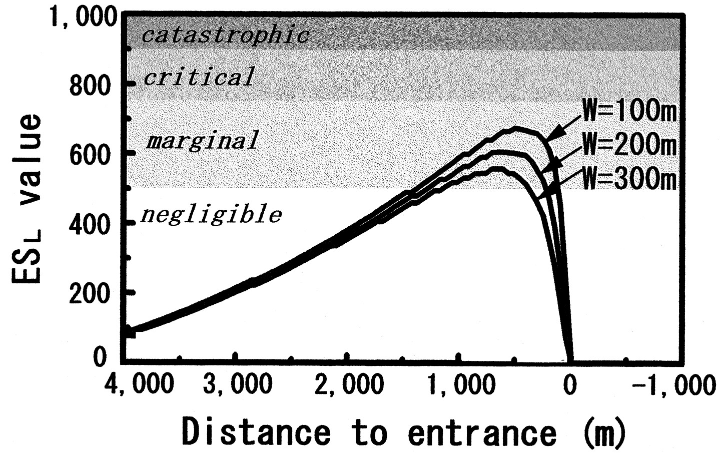

Figure 4. ES_L at breakwater entrance.

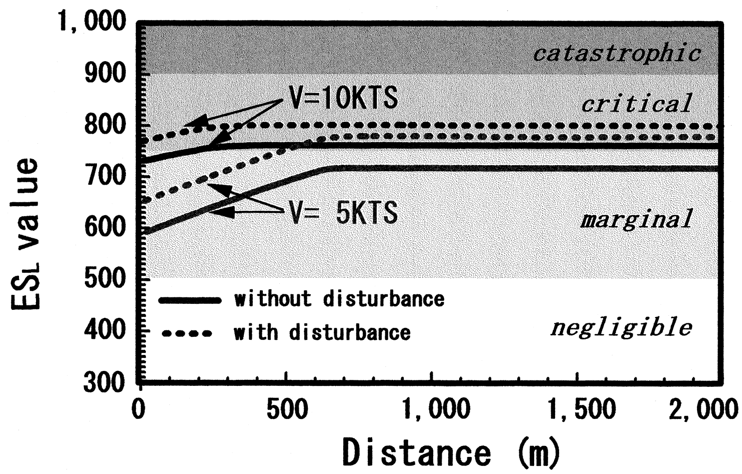

Figure 5. ES_L under external disturbances.

breakwater. Calculation was carried out for three cases assuming the ship passes through an entrance with a width (W) of 100 m, 200 m and 300 m respectively at a ship speed of 10 kts. It can be said that the calculated ES_L values closely represent the mental tension on the mariner when the ship passes the breakwater entrance.

3.3. *ES_L Values under External Disturbances*. The effects on the stress values when the ship drifts under the influence of external disturbances such as wind or current can be reflected in the calculation as follows:

1. Prepare a composite vector from the vectors of ship speed and external drift force at every 1° virtual course.
2. Calculate TTC from composite vector.
3. Compare the TTC value based on a composite vector at every 1° virtual course with the TTC value calculated under conditions without external disturbances. Then take the smaller TTC value to derive the ES_L value.

This concept takes additional ship-handling difficulty due to external disturbances into consideration, in addition to that of topographical restrictions. Figure 5 shows the calculated stress values affected by external disturbances when a ship with a length of 100 m proceeds in the restricted waterway shown in Figure 3(a). Calculation was carried out on the assumption that the drift vector is 0·5 m/s abeam at ship speed (V) of 5 kts and 10 kts. Figure 5 also shows ES_L values without external disturbances. The effects of external disturbances on the stress value increases remarkably when the ship speed is slow.

3.4. ES_S Values in Typical Encounters. The calculated stress values in typical encounter situations, such as head-on (A), crossing (B), (C), (D), overtaking (E) and overtaken (F) are shown in Figure 6(a). In these cases, calculations were carried out on the assumption that two ships each with the length of 100 m and a speed 10 kts come into collision after 15 minutes. However, in the cases of overtaking (E) and overtaken (F), the assumptions were that two ships were sailing in the same direction with a 6 kts difference in speed and a lateral distance between tracks of 200 m, and the following ship would overtake after 15 minutes.

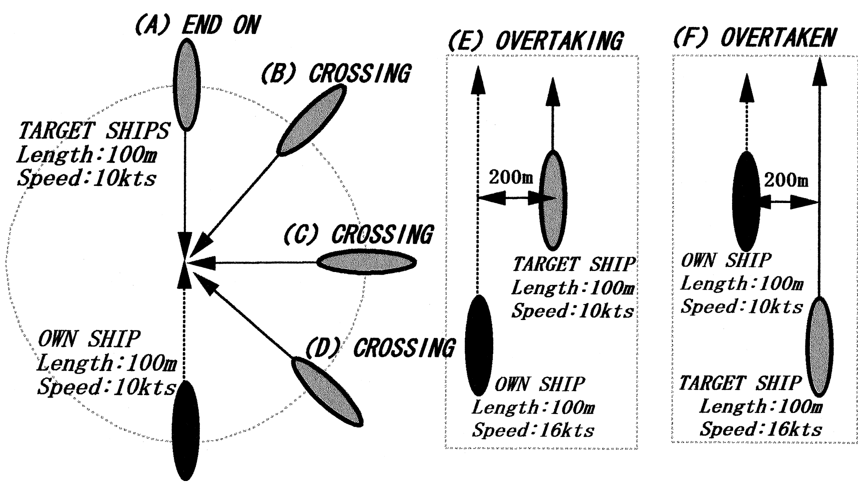

Figure 6(a). Encounter situations.

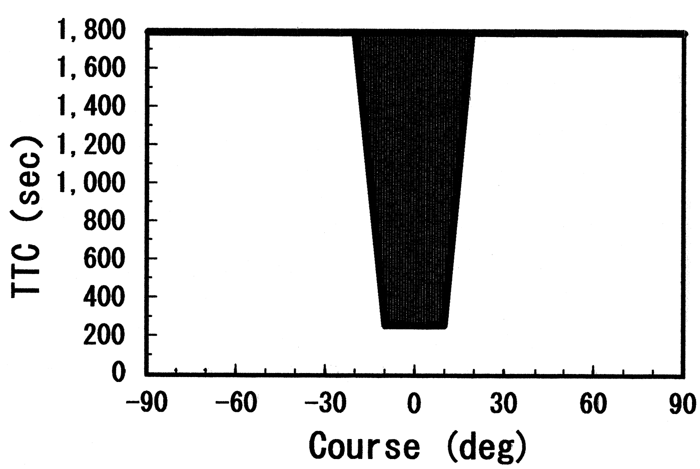

Figure 6(b). TTC values.

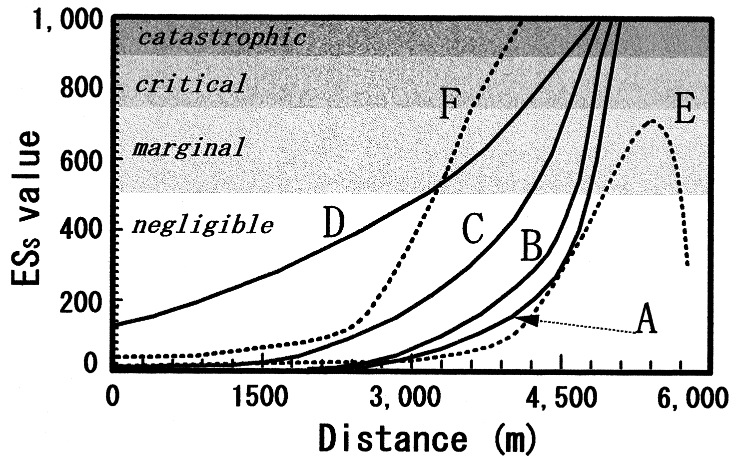

Figure 6(c). ES_S in typical encounters.

Figure 6(b) shows examples of TTC values calculated at every 1° in the range of ±90° from the original course for two ships meeting in the head-on situation of case (A). The larger the meshed area, the greater are the operational restrictions to take collision-avoidance action. In this example, TTC values represented by the vertical axis in Figure 6(b) are converted into psychological values SJ_S by the conversion formula (2), then the value ES_S is derived by integrating SJ_S values within the meshed area. Figure 6(c) shows the ES_S values in each encounter situation obtained by the above conversion process. The integrated value of time history data of ES_S in Figure 6(c) corresponds to the accumulated stress until the two ships come into collision or pass each other.

To compare the ship-handling difficulty in each encounter situation, Figure 7 shows accumulated stress values as a ratio compared to that of the head-on case (A)

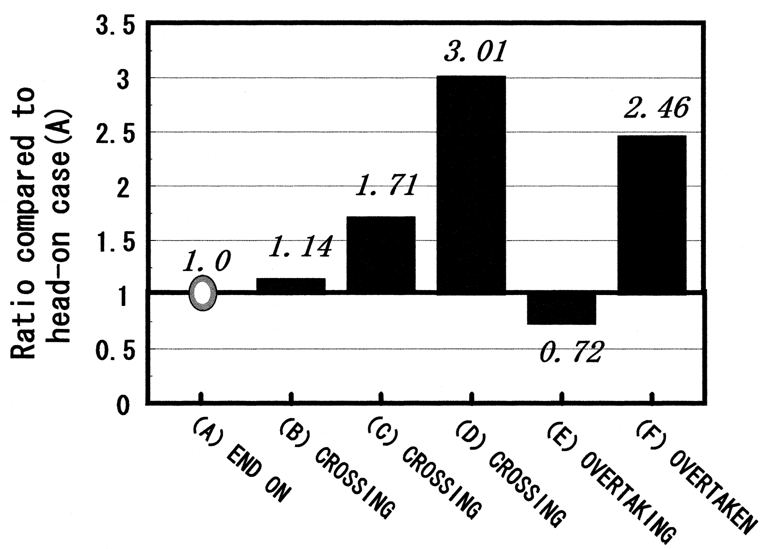

Figure 7. Comparison of shiphandling difficulty in each encounter situation.

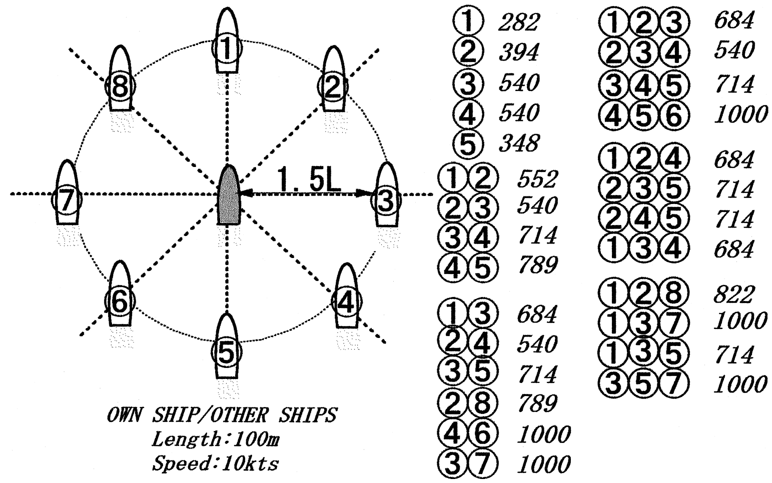

Figure 8. ES_S when surrounded by other ships.

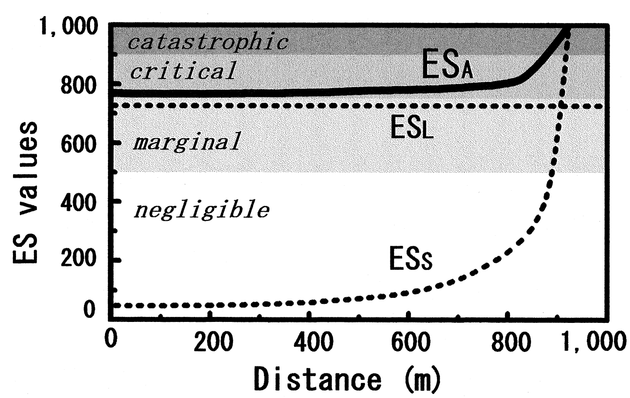

Figure 9. ES_A for encountering in a narrow waterway.

letting it be 1. The degree of ship-handling difficulty becomes greatest in the case of the ship being overtaken from the rear quarter, with stress values reaching three times that in a head-on situation. Stress grows larger when the other ship is overtaking with a narrow clearance, particularly when the difference in speed between the two ships is small.

3.5 *ES_S Values when Surrounded by Ships Sailing in the Same Direction*. When a ship is proceeding surrounded by other ships sailing with almost the same course and speed, the stress of the mariner on the ship increases as available space for manoeuvring is restricted. Figure 8 shows the calculated stress values when the ship is surrounded by other ships sailing in the same direction while keeping a 1·5L clearance (L = ship's length), on the assumption that the length of each ship is 100 m and ship speed is 10 kts. When other ships are located behind own ship and in close proximity, the stress values of the mariner on the own ship become greater. This is because the behaviour of the own ship would directly invite collision with following ships. By contrast, when the own ship navigates behind other ships, the stress imposed

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on the mariner may be small, because the own ship can take any action without possibility of collision with other ships.

3.6. *ES_A Values for Encountering Situations in a Narrow Waterway*. The degree of ship-handling difficulty that the mariner experiences when encountering other ships in a narrow waterway, can be derived by taking the larger value of either SJ_L or SJ_S calculated independently at every 1° virtual course. Figure 9 shows the calculated stress values when two ships each with a length of 100 m and at ship speed of 5 kts meet in a head-on situation in a straight narrow waterway with a width of 300 m. In Figure 9, the values for ES_L and ES_S are shown separately, in addition, ES_A is drawn with a thick solid line.

3.7. *Application to a Simulator Experiment*. Figure 10(a) shows a track chart of the results of ship-handling obtained from a simulator experiment carried out in Kobe University of Mercantile Marine. The own ship (450 GT, Training ship of *Kumm*) encounters a succession of other ships as it proceeds through a narrow waterway with a width of 500 m from the eastern waters of Port of Kobe to its mooring berth. The stress values (ES_L, ES_S and ES_A) imposed on the mariner during ship-handling executed under this scenario can be seen in Figure 10(b).

4. EVALUATION OF SHIP-HANDLING DIFFICULTY IN PORTS.

4.1. *Calculation Conditions*. Two major ports in Japan were selected as examples to carry out an evaluation of ship-handling difficulty of navigation in ports. One is port 'K' and the other is port 'O'; Figure 11 shows the topographies of these ports. Traffic density in both ports is quite high. In port 'K', about 65 ships were observed per hour during the early morning rush, and the traffic density in port 'O' was about twice this density during the same period. The data used for the evaluation are the outputs of simulator experiments completed on the ship-handling simulator of Kobe University of Mercantile Marine. A ship of 3000 GT was set for the own ship in these experiments.

The standard route to the berth is indicated in Figure 11. The distance from outside the port to the berth is about 9000 m in both ports, but the effects of external disturbances in the course to the berth are not counted in the scenarios for the simulator experiments. For traffic conditions inside the ports, the congested conditions due to incoming ships in the early morning rush hour were applied. Berthing simulations in ports 'K' and 'O' were carried out by six mariners. The mariners subjected to the simulator experiments were previously advised that they could alter course, change speed and take collision-avoidance action as necessary at their discretion in the process of the berthing operation.

4.2. *ES Values in the Ports*. The simulator experiments were conducted under the conditions shown above. The ES-model was applied to six mariners in each simulation. Figure 12 shows ES_L, ES_S and ES_A values calculated for ports 'K' and 'O'. ES_L values show increases just before the ship passes the breakwater entrance at both ports, at the point 5000 m at port 'K' and 6000 m at port 'O', because of topographical restrictions. No remarkable differences are seen in ES_L values between the six mariners. However, there are significant differences in ES_S values. It can be deduced that the individual skill and ability of a mariner may cause subsequent differences in collision-avoidance manoeuvre even under the same environmental conditions.

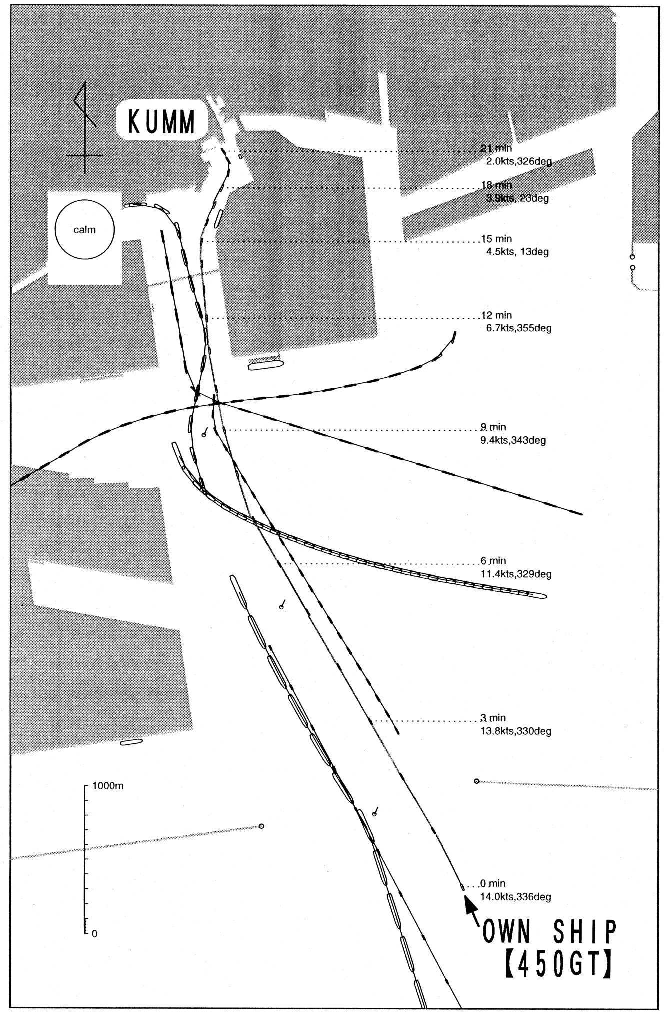

Figure 10(a). Track chart of simulator experiment result.

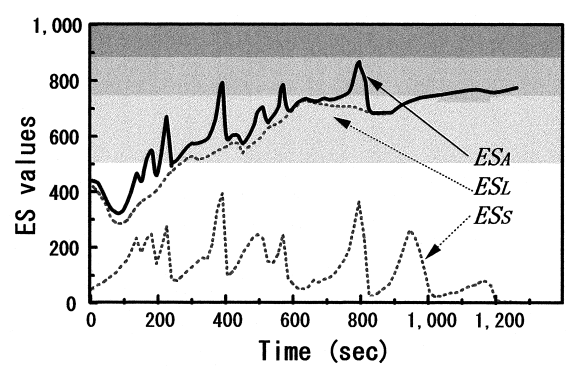

Figure 10(b). ES_L, ES_S and ES_A values.

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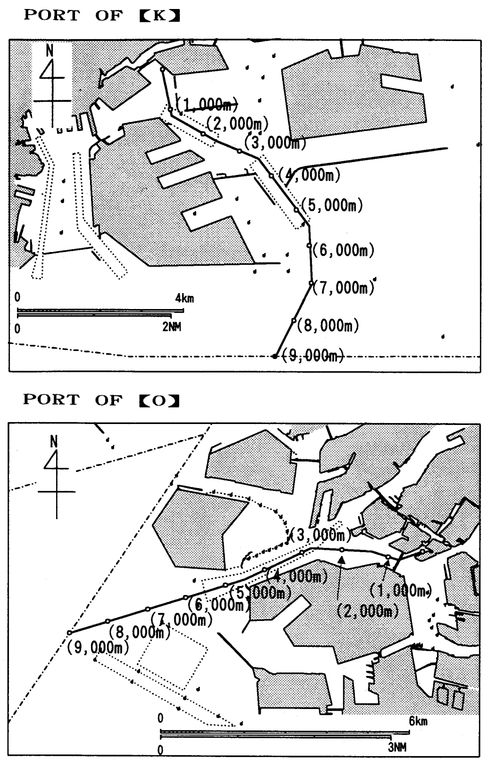

Figure 11. Topographies of two ports.

4.3. *Comparison of Ship-handling Difficulties for the Two Ports*. Encounters with other ships in a topographically restricted narrow waterway would impose great stress on a mariner. Consequently, ES_A values are significant when the degrees of stress imposed on a mariner in different ports with different environmental conditions are contrasted. Figure 13 shows the frequencies of stress classified into four ranks for each mariner based on calculated ES_A values. Although the stress that each mariner feels may vary depending upon differences of human factors such as individual skill and ability, it can be observed that the stress tends to be larger in port 'O'.

To illustrate this difference more clearly, the results were plotted by paying attention to the percentage of 'unacceptable ($ES_A \geqslant 750$)' and the percentage of 'negligible ($ES_A \leqslant 500$)' drawn from Figure 13 on Rating Table shown in Figure 14.

In Figure 14, the higher the percentage of 'unacceptable ($ES_A \geqslant 750$)', the greater the stress is on the mariner. And the lower the percentage of 'unacceptable ($ES_A \geqslant 750$)', the smaller is the stress on the mariner. However, it can be deduced that the higher the percentage of 'negligible ($ES_A \leqslant 500$)', the smaller is the stress even under the same 'unacceptable ($ES_A \geqslant 750$)' condition. This means that the degree of stress imposed on mariners under the given environmental conditions of these two ports can be judged from a combination of the percentages of 'unacceptable ($ES_A \geqslant 750$)' and 'negligible ($ES_A \leqslant 500$)'.

Using Figure 14, the degree of stress on mariners in the two ports can be compared. The reason why the evaluation results are not so good in Port 'O' is because that traffic congestion in addition to the topographical restrictions inside the port

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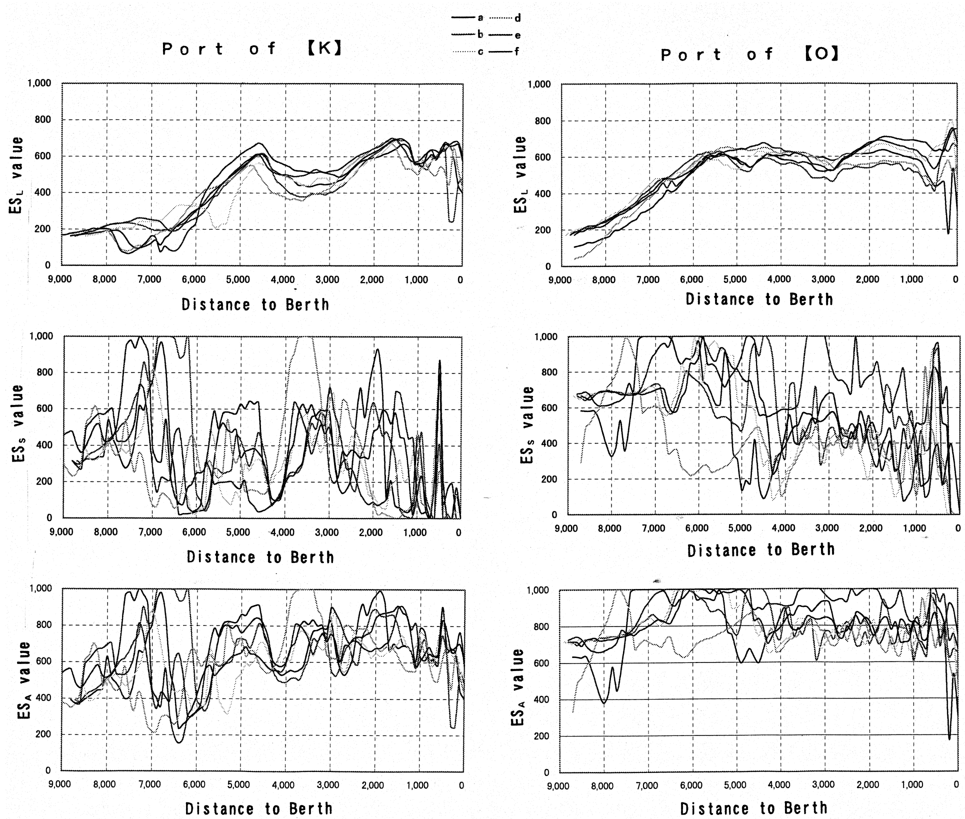

Figure 12. ES_L, ES_S and ES_A values for the 6 mariners.

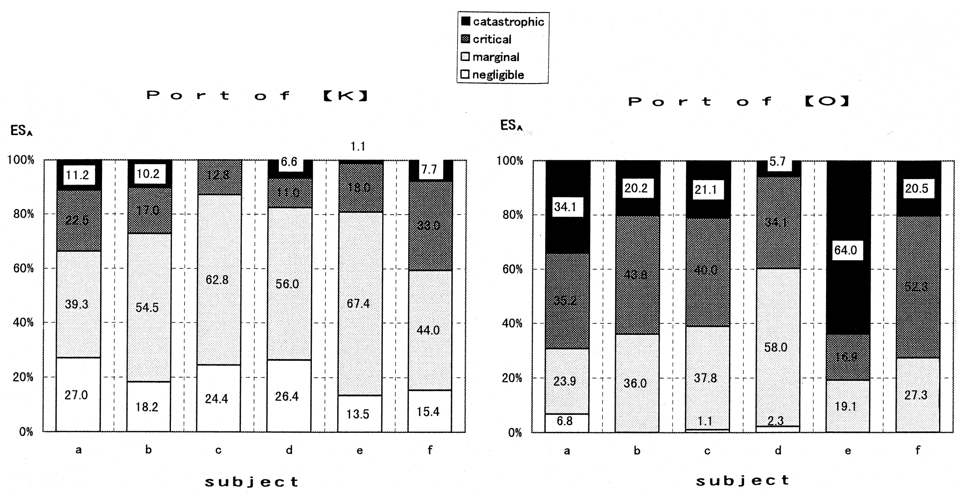

Figure 13. Percentage of each stress ranking.

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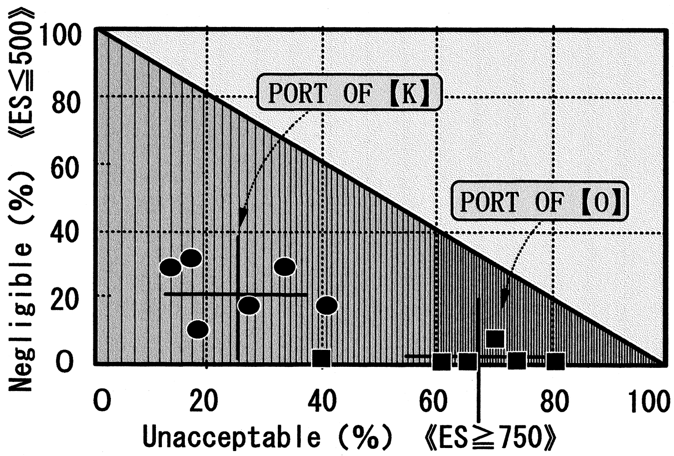

Figure 14. Comparison of shiphandling difficulty in Ports K and O.

contribute to the difficulty of ship-handling. Therefore, it is advisable for this port to take necessary safety measures to remove potential danger of accidents due to traffic congestion in the early morning rush hour.

5. CONCLUSION. As can be seen from the above examples, the ES-model is a practical method for evaluating the ship-handling difficulty of navigation in topographically restricted and congested waterways, and in ports and harbours. The strength of the model lays in its ability to evaluate simultaneously or individually the difficulties of ship-handling arising from topographical restrictions and encounters with other ships and because it includes acceptance criteria based on a mariner's perception of safety.

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