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Human Reliability in Grounding and Collision of Ships

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ABSTRACT

Conventional maritime regulations are a collection of measures established after the occurrence of casualties. Although the regulations are meaningful, not all of them are rational. In the light of these circumstances, IMO(International Maritime Organization) decided to introduce PSA(probabilistic safety assessment) in rule making process after about 2002, with the focus on FSA(Formal Safety Assessment). The FSA take into consideration human elements in addition to functional elements. Methods for probabilistic reliability analysis of complex functional systems considering human behavior are few in published number, especially in marine affair. This report investigates methods for introducing human elements in reliability analysis of grounding and collisions. Human behavior in casualties has been recorded in predictive form in maritime accidents inquiry records. These records should be expressed quantitatively if they are to be debated in the same arena as related structural reliability. In this report, human behavior is expressed by clausal logic equations, which is the basis of Prolog system.

INTRODUCTION

To make up FSA, persons concerned are now doing trial applications of PSA to some events and regulation items for this three years[1]. Recently, needs to introduce human elements into FSA have been emphasized [1], because the elements play important roles in casualties assessment.

The history of practical human engineering is quite old, extending back to 1930s. Various text books have been published on this subject, but most of these focus on human engineering as exemplified by ergonomics or man-machine interface. Human elements in marine field are long time work and multi-dimentional in nature, and are entwined with functional elements such as hull, machinery and navigation instruments, natural environment elements such as weather and topographic conditions at sea, and relationship with other ships. Generally, the standard practice for analyzing such events is to use FTA(Fault Tree Analysis) for occurrence probability of a casualty, and ETA(Event Tree Analysis) for studying the event of the disaster after a casualty[1]. RID(Regulatory Impact Diagram) is also used to reflect influences with sensitivity analysis. The probability data required for F,ETA of grounding and collisions have been summarized as reliability data sheets[2], based on documents of Japan Marine Accidents Inquiry Agency, Lloyd Casualty Returns and ClassNK Survey Reports. Human behavior in casualties have been recorded in predictive form. To express the human behavior records as quantitative probabilistic variables, clausal logic equation of Prolog system is used. The statistical distribution used in the analysis is normal distribution, which is stable and which does not vary with the operation. The human behavior is observed approximate to the normal distribution.

GROUNDING/COLLISION RELIABILITY DATA

Grounding/Collision casualties arise due to interaction of human behavior with functions, such as function of navigation equipment, and with natural environmental elements such as narrow channels and fogs. The causes therefore, are many and overlapping. Considering human elements only, casualties have arisen as a result of an overlapping of several human errors. An modified instance of collision that occurs is given below.

Collision between ship A and ship B: *Location:* Near the channel entrance between a island and a land

Behavior of ships A and B until the casualty: *Ship A:* After identifying a thick fog ahead, ship A deviated from its standard course toward port side to visually confirm buoys in the shoal ahead. Later, the ship changed course to starboard to return to its original course. Ship A confirmed Ship B cruising on the radar. Ship A was cruising at full speed. *Ship B:* Ship B was sailing through the fog on a course to port side, violating the rules of the route which requires a ship to alter course to starboard when approaching another ship head on so that they pass port-to-port. Ship B had confirmed ship A on its radar, but the judgment by radar identified the action taken by ship A to port side take out of channel course; this judgment did not coincide with the actual behavior of ship A. Ship B was cruising at full speed. It blasted fog whistle signals. *Collision;* The ships confirmed each other's existence visually when they approached each other, reduced the revolutions and operated the rudder immediately, but before the ships could respond to the rudder action, they collided. *Issues related to rules and regulations;* 1. An exempt from the rules and regulations status, "a ship that had detected another ship only on the radar or a ship that has heard a fog whistle signal ahead shall reduce its speed to the minimum required for maintaining its course—-,communicate with the other ship by radio—," but neither ship reduces speed nor communicated each other by radio. 2. The rules and regulations stipulate that ships alter course to starboard pass each other "port-to-port" when approaching each other. However, ship B did not alter course to starboard, while ship A barely altered its course to starboard. 3. Casualties occur frequently in the channel inquisition. Presently, independent courses have been established on either side of the island for ships sailing in opposing directions.

The number of cases of casualties, causes and damages have been summarized and published for each year. This data shows differences in the number of casualties and the proportion for each year. Statistical features of the data were studied for preparing reliability data sheets[2], and examples of these features are given in *Fig.1*.

Reliability Data Sheet related to Grounding/Collision			**Sheet No. 39**
Classification No. Item: (II) Probability of collision of a rank higher than obstacles to operation caused by dozing while on duty and not adhering to the navigation rules			
Probability value			
per Year-Ship		**Branching probability**	
/Year-ship	$0.35*10^{-3} \pm 0.045*10^{-3}$	**Branching prob.**	0.139
Ship type	All kinds	**84.1% reliability (zero probability)**	**mean ± σ** 0.139 ± 0.018 (0)
Population (type/quantity)	Same as in Sheet No. 10 Japan Inquiry Records	**Top events in Sheet No. 6**	Collisions that cause obstacle to navigation
Remarks (Values/details of events in other documents)			
The causes in Sheet No. 39 to 47 have led to collision of a rank higher than obstacle to navigation by not adhering to one of the rules of navigation in Sheet No. 33 to 38. The branching probability considers a collision worse than obstacle to navigation of Sheet No. 6, as the top event.			

Fig.1 Sample of Reliability Data Sheet

Grounding and collision account for 80% of oil spills, 30% of serious casualties and 40% of lives lost[2]. The distribution of number of cases of annual casualties for tankers was studied as a representative example. The number of cases of casualties that rarely occur, for instance, a casualty in which death of a soldier occurred as a result of being kicked by a horse, can be represented by the Poisson distribution. This has been verified by Bortokiewicz[3]. *Figure 2 and 3* show the distribution of the annual pollution casualties and annual lives lost, in case of tankers. The dotted line curve in the figure indicates discrete Poisson distribution, while the solid line curve indicates normal distribution. It is observed from the figures that the distribution of the number of cases can be represented by a normal distribution. The distribution of annual lives lost has a part that approaches the Poisson distribution, but overall it is a normal distribution. The part that does not approach the Poisson distribution, shows years when a large number of lives were lost in one casualty or years when the movement of cargo was sluggish and the operating rate was small. The Poisson distribution is considered to be effective when the operating environment is fixed. From the instances and others[2], he events associated with grounding and collisions were studied assuming normal distribution. The dispersion of estimated probability for each event was established, considering population parameters based on simulation using χ^2 estimation, random number generation and actual data differed for each year.

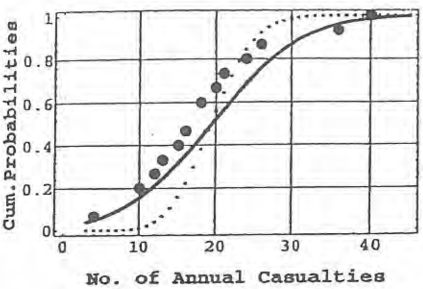

Fig.2 Distribution of Annual Oil Pollution of Tankers

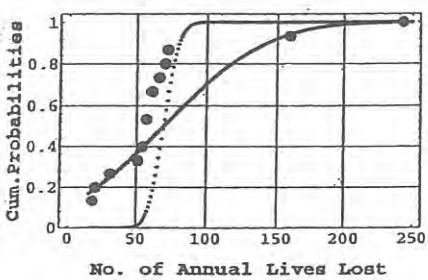

Fig.3 Distribution of Annual Lives Lost of Tankers

Documents of the Marine Accidents Inquiry Agency [4] shows that most casualties are associated with human factors. Shown below are the classification of main causes of grounding and collisions and the branching probability of causes.

Classification of Grounding Casualties

1. Ship's position unconfirmed 0.337 Course selection deficient 0.207 (total 0.554)
   1.1 (Detailed causes of 1) Dosing while on duty 0.188 Neglected checks due to accustomed habits and vessel aimlessly 0.108 Neglected radar check 0.052 Attention distracted by other ships 0.049 Did not considered the effect of wind and current 0.039 Inappropriate use of radar or Loran 0.022 Sailed on a risky course in spite of being aware of the danger 0.015 Decided course without making use of nautical charts 0.005 Others 0.067

2. Hydrographic surveys inadequate 0.183 3. Guidance on services such as watchkeeping inadequate 0.136
4. Considerations for weather and sea conditions inadequate 0.141 5. Preparation for departure deficient 0.018
6. Maintenance and handing of steering gear and navigation equipment deficient 0.018
7. Unskilled handling of ship 0.018 8. Anchoring/mooring of ship inappropriate 0.018
9. Management of ship operation inappropriate 0.006 10. Measures against rough sea weather inappropriate 0.006 11. Reporting and turnover of duties inappropriate 0.006 12. Construction, materials, repairs to hull, machinery and equipment deficient 0.006 Note:: $\Sigma I = 1.0$

Classification of Collision Casualties

1. Did not adhere to the navigation method prescribed in the regulation for preventing collision at sea 0.707

1.1 (Detailed causes of 1) Navigation for across the course of another ship 0.236 Navigation in restricted visibility condition 0.236 Inter ship navigation 0.107 Navigation having heels of other ship 0.079 Navigation to passing other ship 0.029 Navigation in narrow channel 0.024

1.2 (Human errors of 1, 1.1) Dozing while on duty 0.139 Made in error in recognizing the actual speed and bearing of other ship 0.124 Could not check stern light because of night navigation/ fog 0.103 Attention attracted by other ships 0.087 Drifted due to current/ wind 0.071 Could not check presence of other ship because of waves 0.055 Dangerous handling of ship 0.047 Careless supervision/ command 0.046 Radar surveillance inadequate 0.033

2. Did not display lights/ shapes nor blast whistle signals 0.150 3. Did not adhere to the provisions of the regulation for traffic at sea/ port regulations 0.055 4. Unskilled handling of ship 0.049
5. Considerations for weather/ sea conditions inadequate 0.016 6. Anchoring/ mooring inappropriate 0.010
7. Maintenance/ inspection of auxiliary machinery deficient 0.007 8. Preparations for departure deficient 0.003
9. Hydrographic surveys inadequate 0.003 Note: $\Sigma I = 1.0$

The causes mentioned above are the main cases of casualties, and as can be observed from the instance of this chapter, most of the causes are due to an overlapping of various human factors. In such analysis, the overlapping of various factors need to be considered. This aspect is not restricted to human elements alone. For instance, considering dozing while on duty, a collision cannot occur in waters where no other ships is present.

THEORY OF HUMAN RELIABILITY

Research on human engineering related to work started around the end of the 19 century.[5] Human reliability analysis(HRA) incorporating probability statistics make a start in the aircraft industry [5], were developed and practically applied in many industries. These methods are introduced together with probability of human elements in F, ETA, which express probability values of various events such as occurrence and development of casualties in tree-like forms. F, ETA comprise AND , OR and BRANCH gates. Therefore, the probability operations are multiplication and addition. In structural reliability, which has a relationship with grounding and collision, the factors, external forces and strength are treated as probabilistic variables[6]. As mentioned former, human elements can be also treated as probabilistic variables with distributive patterns, and there is adequate data[2] to treat them as probabilistic variables.

Logic equations for causes and results of casualties can be expressed by the Horn clause, which is the bases of the Prolog system[7]. The Horn clause, which is a prime formula, consists of the following head term B of the event, the sum of consequence predicates at the beginning of Eq.(1); a group of A, which are terms predicates, and the notation $<-$ expressing implication. For instance, the event B, which does not adhere to the provisions of the regulation for Preventing Collisions at Sea of the former mentioned collision classification, consists of some six events(term) A, such as across the course of a ship. B_i can be expressed by the logical sum(or $\vee$) or logical product (and $\wedge$) of several A_i terms. In turn, at the lower levels of the hierarchy, A_i can be expressed by the logical sum or logical product of several terms, as shown in Eq.(2),(3). The set condition(A_{i1} l A_{i2}) used in probability theory are the same as "and". As shown in Eq.(3), a set of several B's form a C at a higher level.

$$B_i \leftarrow A_1, A_2, A_3, ---A_n \tag{1}$$

$$A_i = A_{i1} \wedge A_{i2} \wedge A_{i3} ---, \quad or = A_{i1} \vee A_{i2} \vee A_{i3} ---, \quad or = A_{i1} \ A_{i2} \ A_{i3} --- \tag{2}$$

$$C_i \leftarrow B_1, B_2, B_3, ---B_n \tag{3}$$

Using the expressions of Horn's clause, F, ETA can be expressed by logical equations. Moreover, the predicates can be expressed by logical equations already derived from results of past research and programmed for computer[7]. The similarity between Prolog type logical equations and F, ETA is that the bottom-up and top-down strategies from the basic configuration. Considering the case of dozing while on duty, if the bottom-up statement is "miss operated, at that time dozed", the top-down statement could be something like"—dozed while on duty, committed an error in operation". These statements can be expressed as logical equations and also by F, ETA. The statements can be converted from bottom-up to top-down or vice versa. Often, the terms A,B,–which are predicates, are also probabilistic variables.

If the probabilistic variables are expressed by normal distribution, the sum and product of probabilistic variables in F, ETA or logical distribution will also be a normal distribution. The probability density function of a normal distribution in which x is a probabilistic variable, is given by Eq.(4). The sum and product of the probabilistic variables x_A and x_B in the normal distribution are taken as x_{AD} and x_{MP} respectively. Both probabilistic variables x_{AD} and x_{MP} are taken as normal distribution. The mean μ and the standard deviation σ of this distribution are given by Eq. (5)&(6).

$$f(x) = \frac{1}{\sqrt{2\pi\sigma}} e^{-\frac{(x-\mu)^2}{2\sigma^2}} \tag{4}$$

$$\text{for variables } x_{ad} = x_A + x_B \quad \mu_{ad} = \mu_A + \mu_B \quad \sigma_{ad} = \sqrt{\sigma_A{}^2 + \sigma_B{}^2} \tag{5}$$

$$x_{mp} = x_A \cdot x_B \quad \mu_{mp} = \mu_A \cdot \mu_B \quad \sigma_{mp} = \mu_{mp}\sqrt{(\sigma_A/\mu_A)^2 + (\sigma_B/\mu_B)^2} \tag{6}$$

Based on the investigations above, the logic equations used in human factors are incorporated in the reliability method[6] used in structural reliability to form the basic equations given below. The probabilistic variables x_i are taken as independent variables, assuming that they are at the same level for specific events. The probabilistic variables can be transformed to the space U, which is a collection of standard normal distribution for facilitating various operations. The standardization of the normal distribution is achieved by variable u in Eq.(7). With this transformation, the probability density function ϕ (u) and the density function Φ(u) are as given by Eq.(7).

$$\phi(u) = \frac{1}{\sqrt{2\pi}} e^{-\frac{1}{2}u^2} \quad \Phi = \int_{-\infty}^{u} \phi(u)du = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{u} e^{-\frac{1}{2}u^2} d\mu \quad u = (x-\mu)/\sigma \quad -\infty < u < \infty \tag{7}$$

The limit function g(x) of nth dimension variables, which defines the limit of incidence of events such as casualties, is given by Eq.(8).

$$g(u_1, u_2, u_3 ---, u_n) = \ > 0;\ Safe\ /\ \leq 0;\ Accident \tag{8}$$

If the joint probability function f_x of the basic probability vector X is replaced by Eq.(9), the incidence probability of event p_f will be given by Eq.(10).

$$f_X(u_1, u_2, u_3 ---, u_n) \quad \text{basic probability vector } X = (u_1, u_2, u_3, ---, u_n)^T \tag{9}$$

$$P_f = \int\int --- \int_{g(u)\leq 0} f_X(u_1, ---, u_n) du_1 -- du_n \tag{10}$$

If the conditions for navigation such as equipment and weather/topographic conditions of the route are taken as $u_1, u_2, — u_i$, and the human factors as $u_{i+1}, u_{i+2}, u_{i+3}, — u_n$, then g(x) in Eq.(8) becomes Eq.(11). The probabilistic variables u_i can be expressed as the sum of product of several variables u_{ij} at lower levels.

$$g(u) = u_1 \vee -- \vee u_i - u_{i+1} \vee -- \vee u_n = 0 \qquad u_k = u_{k1} \vee -- \vee u_{kj} \ \text{ or } \ = u_{k1} \wedge -- \wedge u_{kj} \tag{11}$$

If the limit state function g(x) is linear as in Eq.(8), the probability of a casualty will be given by Eq.(12). Here "dis" is the distance between the origin and the plane g(x)=0. If k,l are possible casualty combination, then "dis" is as in Eq.(12).

$$p_f = \Sigma\Phi(dis_{kl}) \qquad dis_{kl} = \frac{\mu_k - \mu_l}{\sqrt{\sigma_k^2 + \sigma_l^2}} \quad \begin{array}{l} \text{where} : 1 \le k \le i,\ (i+1) \le l \le n \\ k,l\ :\ \text{possible accident combination} \end{array} \qquad (12)$$

ANALYSIS OF GROUNDING AND COLLISION CASUALTIES

A large number of casualties were selected and their factors/causes were analyzed for safety assessment of grounding and collisions[2]. Causes of collision include human error, weather/current conditions, poor visibility, poor maneuverability of ship, failure of engine, rudder or propeller, etc. The parameters for occurrence or extend of casualty are angle of collision, ship's speed and its size, performance of machinery, level of training of crew, etc.

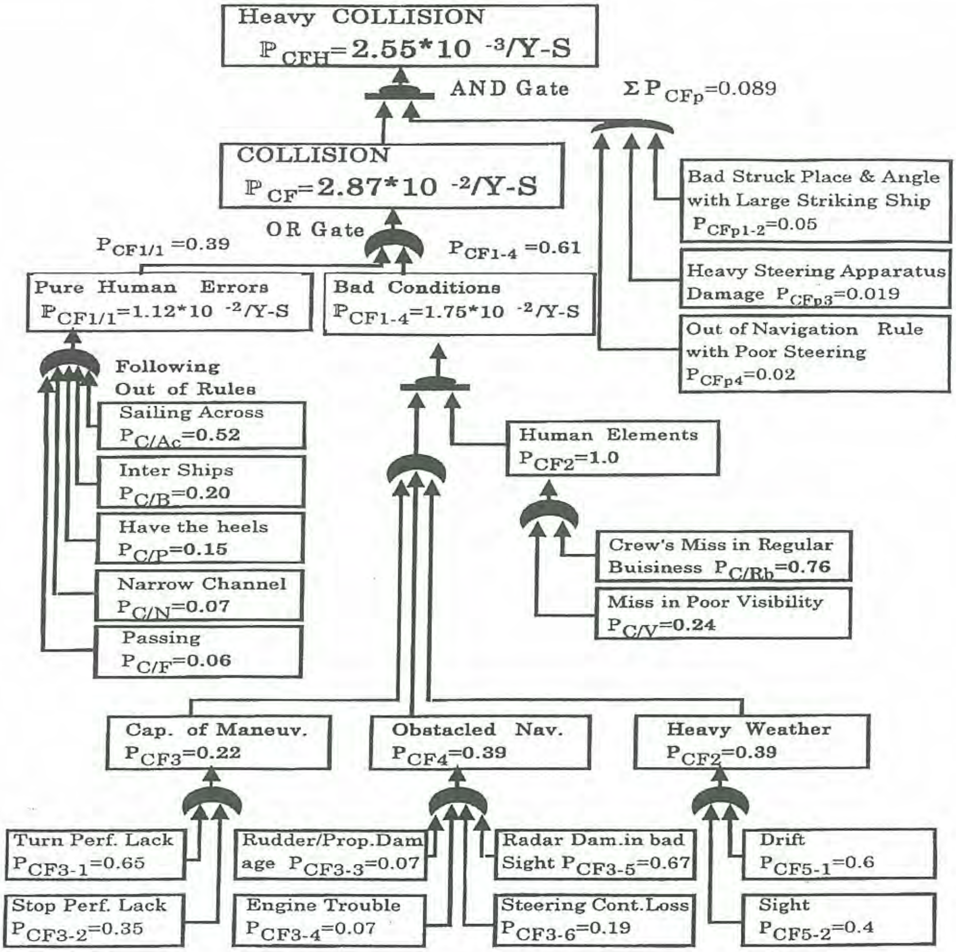

Fig.4 Fault Tree Analysis of Collision Casualties

After a casualty occurs, the effect of casualty varies depending on weather the cargo carried by the ship is flammable or not, fire fighting equipment, evacuation means, watertightness of bulkheads which affects capsizing of the ship, etc. The particulars for grounding are also almost similar. From records of casualties that have actually occurred and the reliability data sheets mentioned earlier, F, ETA of grounding and collision were prepared[2]. An example of the FTA for collision is shown in *Fig.4*. As observed from the figure, about 40% of the casualties are due to pure human errors when poor conditions do not occur. Poor conditions considered for overlapping may be divided into poor maneuverability or poor steering ability, failure of navigation equipment such as radar or rudder, and bad weather conditions. All these causes are related to human elements.

The imaginary afore-mentioned casualty (ref. to *Fig.5*) is considered here as an example of reliability analysis.

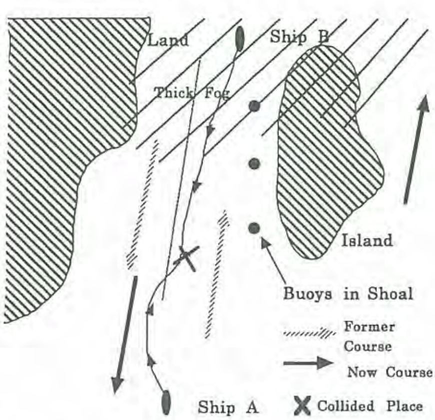

Fig.5 Imaginary Collision Casualty

Other assumptions were added for the analysis- both ships were assumed to be passenger ships of length 70m, speeds of both ships at the time of the collision assumed as 12 knots, and several deaths were assumed to have occurred after the collision. "Limited closed area" is defined as an area with risks of collision[9]. In this area, the ship's length Lm, the turning advance D_A, the turning diameter D_T, and the ship's speed V knot play important roles. The distance of the closed area r_F and the distance of the limited closed area r_L for similar ships sailing in opposite directions as in the case of this casualty may be expressed by Eq.(13)[8]. The relationship between the probability of collision p_c and the distance between the ships r confirmed visually can be expressed by Eq.(14).

The standard deviation of values obtained from the equations that includes the power n and variables such as turning diameter is n times the ratio standard deviation / mean (σ/μ) of the variables. If the value of speed V=12 knots, and the distance at which the other ship

$$r_F = L + 2 \cdot T \cdot V \text{ (m)} \qquad r_L = L + 0.2 \cdot (r_F - L) \quad \text{(m)} \tag{13}$$

where :

$$T = 0.67 \cdot [D_A{}^2 + (D_r / 2)^2]^{0.5} / V \text{ (sec)} \qquad \log(D_A / L) = 0.359 \cdot \log V + 0.095 \pm \sigma_A$$

$$\log(D_T / L) = 0.544 \cdot \log V - 0.08 \pm \sigma_T \quad \text{standard deviation } \sigma_A = 0.0825, \sigma_T = 0.0963$$

D and L are in meter, V is in knot

$$P_c = 1.0 - \sqrt{r / r_L} \ ; \ r \le r_L \tag{14}$$

where r is a inter ships distance at a observation of a opponent

is confirmed =70m are substituted in Eq.(13), the average of r_L $\pm$ standard deviation σ becomes 134$\pm$37(m),and p_c becomes 0.28$\pm$0.1. If both ships had reduced their speed to 5 knots, then r_L becomes 116$\pm$25(m) and p_c becomes 0.22$\pm$0.09. Even if the speed is reduced, the turning diameter reduces to only two-third the value. The probability of collision does not decrease to a very small value because the confirmation distance is small. If both ships had communicated with each other by radio, the probability of operational error may be considered to decrease by a factor of 0.37[2]. Radio confirmation is evidently more effective than speed reduction, but it can not be said that a collision will not occur. The change in route in the channel as shown in Fig.5 , subsequently as a measure for preventing collision. The probability of poor visibility conditions in navigation, such as in a fog is 0.1[2]. The probability of collision when navigating in poor visibility conditions is 0.238 of total collisions[2], which is 2.38 times that during other conditions. At areas where fogs are frequent, such as the Seto Island Sea of Japan, measures to prevent collision are particularly important. The proportion of collision casualties from all the cases observed is ; Coast-0.68, Open sea-0.2, Near port-0.12[2]. This shows that a large number of collision casualties occur in the coastal area. Measures for preventing collision are more important for passenger ships that ply in coastal areas, because the effect of loss of lives is more important than other effects.

REGULATORY IMPACT

Now the FSA[1] is in the stage of trial application. The final stage of FSA is to define the recommendations for decision making on regulations. In doing so, casualties effect on life, environment and properties must be considered. In the case of this imaginary casualty, main recommendation is to alter the regulation of local navigation route by local Coast Guard. Many recommendations may be derived from actual casualties, with probabilities and the effects. The following rules and regulations will be related to grounding and collision accident.
Main international rules: MARPOL(the prevention of pollution from ships); include recent double hull oil tanker rule to prevent oil leakage by damage STCW(standards of training and certification of watchkeepers); relate to human elements ISM(international safety management code); relate to navigation management and human elements IRPCU(the prevention of collision at sea); traffic rule that is also appeared in the imaginary accidents in this paper SOLAS(safety of life at sea); include fire fighting, life saving equipment and water tight bulkhead to prevent capsizing Local rules: Coast Guard, Environmental Agencies, Local Pilotage Regulations, Port State Domestic Marine Legislation, Port State Harbor Regulations, Rules by Classification Society
By some trial applications[2], the author has the prospects that the FSA of PSA is applicable to ship's rule making and revision process.

CONCLUSION

Compared to introducing human factors in conventional methods probabilistic safety assessment in which specific probabilities were assigned in FTA and ETA in fields other than the marine field, in this research, human elements were applied to grounding and collision casualties of ships, also taking into consideration the variation in the probability due to human error.
1) Logical equations were proposed for introducing human reliability methods, which are closely related to ± grounding and collision, after referring to processed data[2] of human behavioral elements related to grounding and collision casualties.
2) These methods were used to carry out a simple analysis of an example, and it was shown that they can be used for investigating measures to prevent casualties.
3) The author has the prospects that the FSA of PSA is applicable to ship's rule making and revision process, including human elements.

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