THE DIRECT EVALUATION METHOD OF DEAD SHIP STABILITY FOR INTACT SHIP

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SUMMARY

The International Maritime Organization is currently establishing second generation intact stability criteria, the dead ship stability is considered one important criterion, so the development of its direct stability assessment regulation has become a topic undergoing close review. In this paper a peak-over-threshold (POT) method is proposed to evaluate the dead ship stability, which focuses on the statistical extrapolation that exceed the threshold, also the traditional Monte Carlo simulation is carried out to approve the method. On the basis of verification calculation of the sample ship CEHIPAR2792, the capsizing probability of a certain warship is also conducted. Moreover, the influence of initial stability height *GM* and effective wave slope coefficient γ on the capsizing probability is analysed. The results and the possible reason for the difference are examined. This study is expected to provide technical support for the second-generation stability criteria and establish the capsizing probability of damaged dead ship stability.

NOMENCLATURE

ϕ	Roll angle (rad)
μ	Linear roll damping coefficient (1/s)
β	Nonlinear roll damping coefficient (1/rad)
W	Displacement (*N*)
I_{xx}	Roll moment of inertia ($tf \cdot m \cdot s^2$)
J_{xx}	Added moment of mass inertia ($tf \cdot m \cdot s^2$)
GZ	Righting lever (*m*)
$M_{wind}(t)$	Heeling moment ($N \cdot m$)
$M_{wave}(t)$	Wave-exciting moment ($N \cdot m$)
$\Theta(t)$	Wave slope
ρ_{air}	Air density (kg/m^3)
C_m	Aerodynamic drag coefficient ()
U_w	Mean wind velocity (*m/s*)
$U(t)$	Fluctuating wind velocity (*m/s*)
A_L	Lateral windage area (m^2)
H_C	Wind force center's height (m)
γ	Effective wave slope coefficient
N_W	Regular waves number
H_S	Significant wave height (*m*)
T_Z	Mean wave period (*s*)
GM	Initial stability height (*m*)
ϕ_{m0}	Threshold of roll angle (deg)
IMO	International Maritime Organisation
POT	Peak-Over-Threshold
DOF	Degree-of-Freedom
λ_1	Exceedance rate of a threshold
λ_2	Conditional probability
f_{POT}	Probability density distribution of POT method
F_{POT}	Cumulative distribution function of POT method
GPD	Generalized Pareto distribution
ξ	Shape parameter
σ	Scale parameter

1. INTRODUCTION

Based on hydrodynamic theory, second generation stability criteria mainly focus on the following five failure modes: parametric roll, surf-riding/broaching, dead ship stability, pure loss of stability, and excessive acceleration. Dead ship stability refers to a ship that drifts freely in waves and winds due to power loss; in beam wind and wave, the ship will exhibit roll resonance and even capsize, which is the most dangerous phenomenon and extreme event in waves (Backalov, 2016). Owing to strongly nonlinear behaviours, capsize research under the dead ship condition includes nonlinear wave force, nonlinear damping force, short- and long-term environmental conditions, irregular wind, and a series of nonlinear dynamics, which is the most representative problem of stability in waves. Therefore, investigating the internal mechanisms of its occurrence is necessary to ensure utmost safety. Due to the dead ship stability failures are too rare to rely on direct statistical observations of these events obtained from model experiments or numerical simulations, the development of direct stability assessment regulations is also under consideration in the framework of IMO second generation intact stability criteria (Umeda, 2016), which could aid in operational guidance (Backalov, 2016).

Using numerical simulations to predict such extreme event is a commonly used method, a roll motion under dead ship condition have been conducted for more than 50 years by various researchers (Umeda, 2002; Paroka, 2006; Zeng, 2014; Ma, 2015). In these studies, a 1 DOF equation was used to analyze the roll motion, whereas the traditional solution uses Monte Carlo method to simulate real wind and wave conditions, which could obtain accurate result but require numerous calculations. Also, statistical extrapolation is focused on the use of observed statistics for the prediction of characteristics of rare event, which requires the least number of simulations for the reliable results, the probabilistic assessment for dealing with pure loss of stability in waves (Bulian, 2010) and roll motion

(Belenky, 2012) has been presented, as well as for the validation of the model and methods of prediction (Belenky, 2016). By means of probabilistic method, introducing a threshold allows considering the data that are more influenced by nonlinearity. So in this paper the direct evaluation method POT is adopted to evaluate the capsizing probability under dead ship extreme event, and Monte Carlo simulation is used to compare with the probabilistic method. The POT method is used as extrapolation method and the probability estimation of exceedance of a given level is described in the rest of the paper. The rolling equation is solved through a fourth-order Runge–Kutta algorithm in time domain. The damping coefficients used in the rolling motion equation are obtained through theoretical calculation. The numerical results of a sample ship, namely, CEHIPAR2792, were compared using two methods and literature. The capsizing probability of a certain warship is conducted to validate its performance. The influence of GM and γ on the capsizing probability and the possible reason for the difference between the two methods are analyzed.

2. MATHEMATICAL MODEL UNDER DEAD SHIP CONDITION

In the calculation of capsizing probability, the ship is assumed to be under dead ship condition in irregular waves and gusty winds for a specified exposure time, and the wind state is characterized by a mean wind speed and gustiness spectrum. The roll motion of the ship is also modelled as a 1 DOF system as follows:

$$\ddot{\phi}+2\mu\dot{\phi}+\beta\left|\dot{\phi}\right|\dot{\phi}+\frac{W}{(I_{xx}+J_{xx})}GZ(\phi)=\frac{M_{wind}(t)+M_{wave}(t)}{(I_{xx}+J_{xx})} \tag{1}$$

Where, $M_{wave}(t)$ is calculated based on Froude–Krylov assumption. The main reason is that roll diffraction and radiation moments due to a sway can contradict when the wavelength is longer than the ship breath. $M_{wave}(t)$ is calculated as follows:

$$M_{wave}(t)=W\cdot GM\cdot\gamma\cdot\Theta(t) \tag{2}$$

The calculation equation of $\Theta(t)$ is as follows:

$$\begin{aligned}\Theta(t)&=\sum_{i=1}^{N_w}\frac{\omega_i^2}{g}a_i\sin(\omega_i t+\varepsilon_i)\\ a_i&=\sqrt{2S_{wave}(\omega_i)\delta\omega}\end{aligned} \tag{3}$$

$$S_{wave}(\omega_i)=172.5\frac{H_S^2}{T_Z^4\omega_i^5}\exp\left(-\frac{691}{T_Z^4\omega_i^4}\right) \tag{4}$$

The excited moment caused by wind $M_{wind}(t)$ is calculated as follows:

$$M_{wind}(t)=0.5\times\rho_{air}C_mU_w^2A_LH_C+\rho_{air}C_mU_wA_LH_CU(t) \tag{5}$$

The fluctuating wind velocity is calculated by using the following equation:

$$\begin{aligned}U(t)&=\sum_{i=1}^{N_w}b_i\sin(\omega_i t+\varepsilon_i)\\ b_i&=\sqrt{2S_{wind}(\omega_i)\delta\omega}\\ S_{wind}(\omega_i)&=4K\frac{U_w^2}{\omega_i}\frac{X_D^2}{(1+X_D^2)^{4/3}}\end{aligned} \tag{6}$$

where $K=0.003,\ X_D=600\dfrac{\omega_i}{\pi U_w}$

3. CAPSIZING PROBABILITY MODEL OF THE DEAD SHIP STABILITY

3.1 PROBABILISTIC METHOD

The dead ship stability failure related to the ship' motions is characterized with the rarity of occurrence and strong nonlinearity, so it is difficult to evaluate the ship response accurately, and the direct assessment method like Monte Carlo requires large amount of time. So the extreme events response are separated into rare and non-rare problem. The non-rare problems mainly focus on evaluating the upcrossing rate, and the conditional probability evaluation is the objective of the rare problems, just as the equation (7-9) mentioned. And the stability failure is assumed as Poisson flow event. In this paper the POT method is adopted due to it could choose a small number of data to analyse according to the threshold (Wang, 2017).

3.1(a) POT method

$$\lambda=\lambda_1\cdot\lambda_2 \tag{7}$$

$$\lambda_1=\int_0^\infty\dot{\phi}f(\phi=\phi_{m0},\dot{\phi})\,d\dot{\phi} \tag{8}$$

$$\lambda_2=\int_{\phi_{m2}}^\infty f_{POT}(\phi)\,d\phi=1-F_{POT}(\phi_{m2}) \tag{9}$$

Here, λ_2 is calculated when the threshold has been crossed. In the viewpoint of statistical fit, the data above the threshold are used for extrapolation. The non-rare problem consists of counting the exceedances of a process over a given threshold. The threshold can be used to separate regions where a linear solution is applicable with the nonlinearity, which is significant for the failure event. The rare problem is solved by fitting an extreme value distribution to the data over the threshold.

The method is known as the POT method, and the method concept is shown in Figure.1. Taken ϕ_{m0} as a threshold and find the distribution of the data exceeding this threshold, at the given stability failure level ϕ_{m2}, upcrossing1 does not lead to stability failure, but upcrossing2 leads to stability failure.

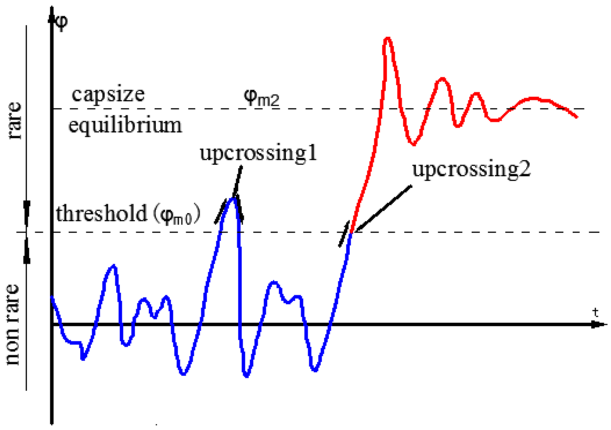

Figure.1 POT method

As the use of the POT method is to evaluate the probability of attaining large roll angle, the method could be adopted to handle the cases when Poisson distribution may not be applicable. According to the extreme value theory, the sample distribution exceeding the threshold is fitted, then to obtain the extreme distribution of actual sample and the fitted capsizing probability. The GPD is derived from the extreme value with the threshold condition applied. The cumulative distribution function of GPD is expressed as:

$$G(x-\phi_{m0},\xi,\sigma)=\begin{cases}1-(1+\xi\dfrac{x-\phi_{m0}}{\sigma})^{-1/\xi}, & \xi\neq 0\\ 1-\exp(\dfrac{x-\phi_{m0}}{\sigma}), & \xi=0\end{cases} \tag{10}$$

When ξ and σ choose the different value, the GPD could transform into different function, for the condition of $\sigma=1$, the GPD function turns into the standard one.

3.1(b) Threshold chosen

How to confirm the threshold is critical to the POT model, which is the premise of evaluation of parameter ξ and σ properly. If the threshold is too high, large feasible data have been wasted and the result will be more uncertainty than necessary, which will lead to the variance of parameter estimation increase. If the threshold is too low, though the sample number is large, the fitted function is not an approximation of the tail. There are different threshold setting methods (Campbell, 2016): stabilization of shape parameter, stabilization of modified scale parameter, and the method based on minimum absolute difference between the shape parameter and its median above the threshold and so on. In this paper for the simplification of the calculation, the maximum static heeling angle is adopted as threshold, and vanishing stability angle is chosen as the stability failure level, which could not exceed the maximum value of GZ curve.

3.2 MONTE CARLO SIMULATION

The Monte Carlo method (Maki, 2017) is adopted to carry out the time domain simulation, and the 1 DOF roll motion equation is solved through the fourth-order Runge–Kutta algorithm (Long, 2010). The assumption that the calculation time is 1h (3,600s) denotes that the capsizing probability of a ship is considered $p(0 < p < 1)$ per time; thus, the calculation is repeated n times under the assumption of Bernoulli process, and the number of capsizing is n_c. Therefore, the capsizing probability during n times is $p_c=n_c/n$, and the equation is as follows:

$$P(p_c=\frac{n_c}{n})=C_n^{n_c}p^{n_c}(1-p)^{n-n_c}\quad (n_c=0,1,\ldots\ldots,n) \tag{11}$$

The process satisfies normal distribution $N[p,\ p(1-p)]$ when n is sufficiently large to ensure that the deviation of probability p_c from probability p does not exceed 5% of the total standard deviation $p(1-p)$, and the interval confidence reaches 95%, in which each wind and wave condition simulation is at least 1600 times. The mean wind velocity U_w is calculated according to H_s with equation (12); based on the simulation times, the fluctuating wind velocity $U(t)$ is obtained by equation (6) given the different random numbers ε_i. The random wave is superimposed by sinusoidal waves of different frequencies and random numbers according to equation (3) and (4). Given a certain H_s, the short-term capsizing probability is gained. Combined with the wave spectrum of the North Atlantic, the long-term capsizing probability under certain loading conditions is obtained. A remarkable advantage of this method is its being sufficiently accurate.

$$U_w=(H_S/0.06717)^{2/3} \tag{12}$$

4. CASE STUDY

The calculation of the two abovementioned methods is conducted in this study using Visual Basic 6.0 language. CEHIPAR2792 is used to calculate the capsizing probability. The capsizing probability and influence factors of this warship have also been investigated. Relevant ship data of CEHIPAR2792 are listed in Table 1 (IMO, 2014).

Table 1 Ship data of CEHIPAR2792

Main parameter	Value	Unit
L_{PP}	205.7	m
B	32.0	m
d	6.6	m
GM	2.0	m
KG	15,858	m
Δ	24,585.65	t

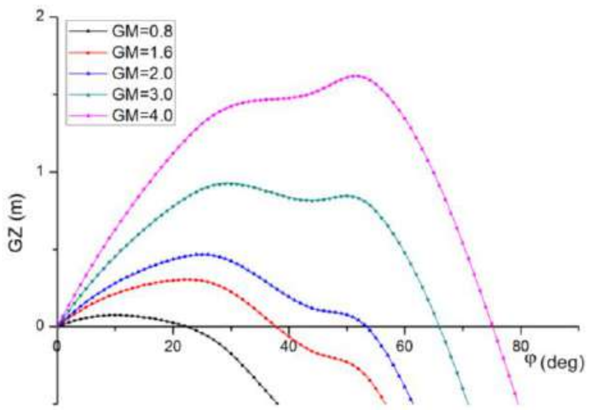

Figure.2 GZ with different *GM*

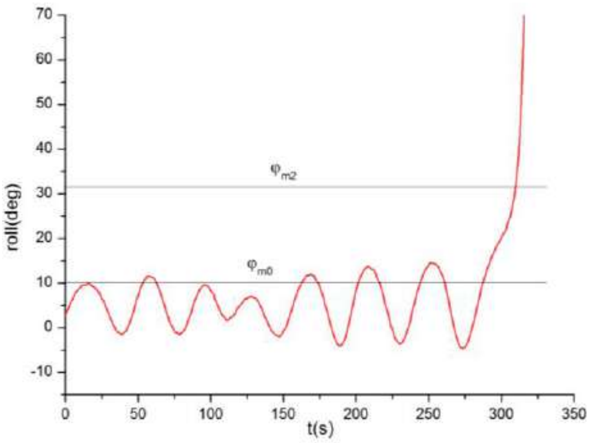

Figure.3 Sketch of capsizing process

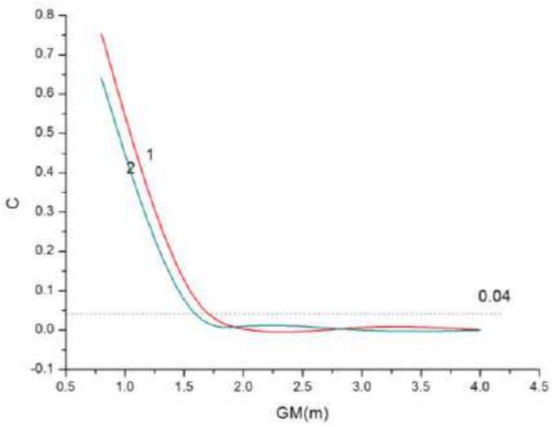

Figure.4 Capsizing probability through the two methods

Numerous *GM* values under the exposure time of 1 year are adopted with the loading condition of *d*=6.6m to assess the long-term capsizing probability. The results are illustrated in Figures 2–5. Figure. 2 depicts the *GZ* curve with different *GM* values; the stability of the ship improves with the increase in *GM*. The capsizing process in the time domain is demonstrated in Figure. 3 under the condition of H_S=2.5, T_Z=5.5, and *GM*=0.8m. The roll motion exceeds φ_{m0} near 60s but can return to the original equilibrium position. The rolling continues after 300s to increase until the threshold φ_{m2} is exceeded, and the ship capsizes.

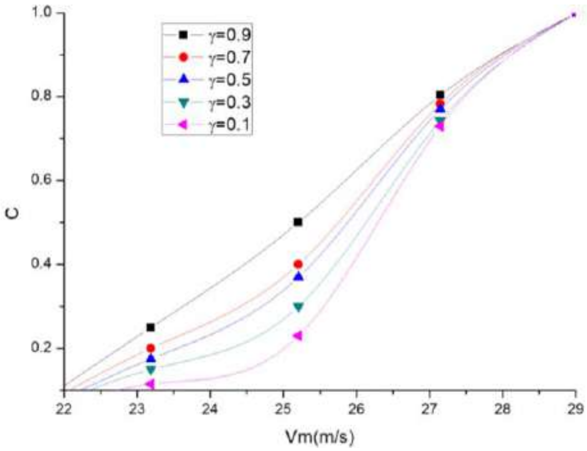

Figure.5 Capsizing probability result with different γ

To validate the feasibility of method adopted in this paper, Figure. 4 exhibits the capsizing probability result with the exposure time of 1 year through the two methods under different *GM* values. The "*C*" in the figure represents the long-term capsizing probability; curve "1" represents the result of the POT method, curve "2" denotes the result of the Monte Carlo simulation, and Figure. 4 displays that differences exist between the results, especially with the small *GM* value. The difference between the two methods is 0.1 when the *GM* value is approximately 1.0m; the difference and capsizing probability gradually decrease with the increase in *GM*. When *GM* =2.0m, the capsizing probability between two methods are nearly equal. If the two methods surpass the probability thresholds of 0.04 (IMO, 2014), then the *GM* value must be at least 1.5–1.75m. The tendency presented in Figure. 4, in which long-term capsizing probabilities differ from each other, particularly in the case of a small *GM* value. The result of POT method is more conservative than Monte Carlo simulation, which is more feasible in application. Figure. 5 illustrates the influence of different γ values on the short-term capsizing probability through the POT method. The result indicates that the capsizing probability decreases with γ ; this finding is consistent with the literature result (Zeng, 2015).

Table 2 Ship data of warship

Main parameter	Value			
L_{PP}	136			
B	17			
d	4.101	4.247	4.39	4.545
GM	1.195	1.312	1.334	1.454
KG	5.42	5.13	4.96	4.78
Δ	3683.73	3887.32	4090.91	4312.46

As we all know, warships have the same problems relative to stability failures of all ship designers. Furthermore, warships may not have the luxury of avoiding dangerous weather conditions when performing their missions. Thus these warships are frequently subject to further research and development. Therefore, this study uses a warship as a sample ship to investigate its capsizing probability. The loading conditions (including standard displacement, normal displacement, full load-displacement, and maximum displacement, which represent different *GM* values) of warship are used to calculate the capsizing probability through the abovementioned methods. The main data of this warship are summarized in Table 2.

The long-term capsizing probability result is demonstrated in Figure. 6, and the difference between the two methods changes with the *GM* values and within a maximum of 0.001. The reason that the difference varies with *GM* may be the *GM* with smaller value could lead to greater rolling period, the small change of rolling period can cause a great change in capsizing probability. Curve “1” represents the result of the POT method, whereas curve “2” represents the result of the Monte Carlo method. The capsizing probability evidently decreases with the increase in the *GM* value, until the two curves nearly coincide with each other. Figure. 7 presents the influence of the different γ values on the short-term capsizing probability with the POT method. Compared with Figure. 5, the influences of γ differ by the ship type, but the same tendency is that the capsizing probability increases with the large γ.

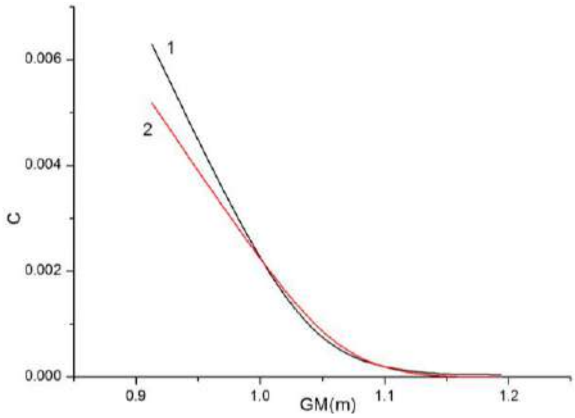

Figure.6 Capsizing probability through the two methods

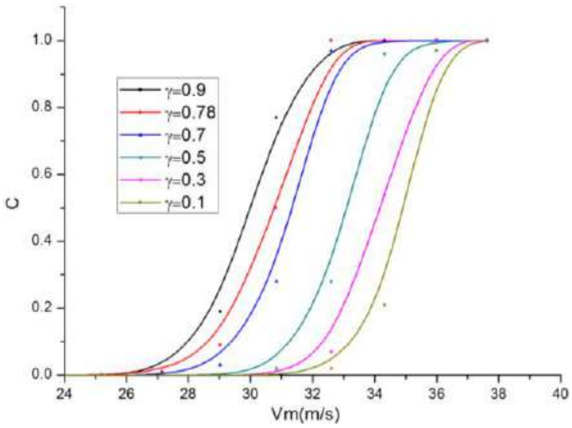

Figure.7 Capsizing probability result with different γ

Table 3 Short-term capsizing times through the POT method (*GM*=0.913m)

Hs/Tz	3.5	4.5	5.5	6.5	7.5	8.5	9.5	10.5	11.5	12.5	13.5	14.5	15.5	16.5	17.5	18.5
0.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6.5	0	0	0.002	0.165	2.958	7.076	0	0	0	0	0	0	0	0	0	0
7.5	0	0	0	0.708	12.881	44.764	41.715	14.162	0	0	0	0	0	0	0	0
8.5	0	0	0	0.625	13.492	74.727	133.460	90.213	28.131	5.035	0.614	0	0	0	0	0
9.5	0	0	0	0.2	4.3	33.2	98.359	132.181	84.838	29.392	6.540	1.092	0.154	0.019	0.002	0
10.5	0	0	0	0	1.2	10.7	37.9	67.5	69.963	45.095	18.661	5.403	1.236	0.239	0.039	0
11.5	0	0	0	0	0.3	3.3	13.3	26.6	31.4	24.7	14.125	6.220	2.203	0.585	0.148	0
12.5	0	0	0	0	0.1	1	4.4	9.9	12.8	11	6.8	3.3	1.3	0.4	0.1	0
13.5	0	0	0	0	0	0.3	1.4	3.5	5	4.6	3.1	1.6	0.7	0.2	0.1	0
14.5	0	0	0	0	0	0.1	0.4	1.2	1.8	1.8	1.3	0.7	0.3	0.1	0	0
15.5	0	0	0	0	0	0	0.1	0.4	0.6	0.7	0.5	0.3	0.1	0.1	0	0
16.5	0	0	0	0	0	0	0	0.1	0.2	0.2	0.2	0.1	0.1	0	0	0

Table 4 Short-term capsizing times through the Monte Carlo method (*GM*=0.913m)

Hs/Tz	**3.5**	**4.5**	**5.5**	**6.5**	**7.5**	**8.5**	**9.5**	**10.5**	**11.5**	**12.5**	**13.5**	**14.5**	**15.5**	**16.5**	**17.5**	**18.5**
0.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7.5	0	0	0	0	0	5.402	11.888	42.192	57.739	19.369	8.936	1.468	0.025	0.006	0.006	0
8.5	0	0	0	0	0	1.958	5.118	21.036	32.659	12.222	6.208	1.108	0.022	0.005	0.025	0
9.5	0	0	0	0.002	0.387	8.964	49.931	99.138	103.496	49.6	19.32	5.236	1.098	0.306	0.02	0
10.5	0	0	0	0	0.648	9.63	37.521	67.5	71.7	51.5	26.481	10.83	3.08	0.852	0.159	0
11.5	0	0	0	0	0.297	3.3	13.3	26.6	31.4	24.7	14.2	6.4	2.4	0.7	0.196	0
12.5	0	0	0	0	0.1	1	4.4	9.9	12.8	11	6.8	3.3	1.3	0.4	0.1	0
13.5	0	0	0	0	0	0.3	1.4	3.5	5	4.6	3.1	1.6	0.7	0.2	0.1	0
14.5	0	0	0	0	0	0.1	0.4	1.2	1.8	1.8	1.3	0.7	0.3	0.1	0	0
15.5	0	0	0	0	0	0	0.1	0.4	0.6	0.7	0.5	0.3	0.1	0.1	0	0
16.5	0	0	0	0	0	0	0	0.1	0.2	0.2	0.2	0.1	0.1	0	0	0

Under the condition of *GM*=0.913m, Table.3 and 4 depict the short-term capsizing time distribution through the POT and the Monte Carlo methods, respectively. The capsizing times are shown in yellow shadow part. The capsizing times distribution concentrate around T_z= 10.5*s* in Table.3, which indicate that synchronous rolling period is near T_z= 10.5*s*. However, the synchronous rolling period is indicated approximately T_z=11.5*s* in Table.4. The possible reason for this difference may be attributed to the POT method, which adopts the different threshold to affect the parameter ξ and σ, thus leading to different distribution function and obtaining different capsizing probability results. The final long-term capsizing probability results coincide with each other considering the capsizing times and their distributions synthetically, as exhibited in Figure. 6. The short-term capsizing times with the condition of *GM*=1.194m show the same tendency as Table.3 and 4 indicate, which is omitted in this paper.

5. CONCLUSION

The POT and Monte Carlo methods have been used to calculate the capsizing probability of the sample ship CEHIPAR2792, and the influence of *GM* and γ on the capsizing probability has been discussed. Based on the chosen data that modelling the tail, the POT method requires minimal calculation time and may produce conservative results, so the threshold has much to do with the data chosen, which is critical to the probabilistic evaluation. How to choose the reasonable threshold will be carried out in the further research. Whereas the Monte Carlo method is capable of sufficient accuracy but requires large number of calculation. The result indicates that the capsizing probability increases with the larger γ but the decreased *GM* value under the same loading condition. Moreover, the influences of γ differ by the ship type. The possible reason for the difference between the two methods may be the synchronous rolling period, which has much to do with the threshold choice by the POT method. This study is expected to provide technical support for the second-generation stability direct evaluation and establish the capsizing probability of a damaged ship under dead ship condition. Therefore, the capsizing probability of a damaged ship in waves and winds must be conducted in the near future.

6. ACKNOWLEDGMENTS

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