An Investigation of a Safety Level in Terms of Excessive Acceleration in Rough Seas

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ABSTRACT

A probability of occurrence of lateral acceleration owing to the rolling motion was evaluated to investigate a safety level for a prevention of the situation that excessive acceleration occurs. Firstly, sea state in the sea area of excessive acceleration accident was examined by means of hindcast wave data. Through the comparison of the long term prediction of lateral acceleration, the correlation between loading condition, sea state and long term probability was examined. It is clarified that threshold probability of excessive lateral acceleration depends on loading condition and sea state. Consequently, the safety level of excessive lateral acceleration was discussed.

Keywords: *new generation intact stability criteria, lateral acceleration, container vessel, long term prediction*

1. INTRODUCTION

Currently, the construction of a reliable methodology for estimating a capsizing probability is an urgent issue for the proper provision of the safety because the International Maritime Organization (IMO) started to develop the new-generation intact stability criteria for five major capsizing modes, which contains the stability under excessive acceleration, dead ship conditions, parametric rolling, broaching and pure loss of stability with performance based approaches.

With regard to the excessive acceleration, accidents of ballast loading container vessels due to excessive acceleration were the trigger for the new-generation intact stability criteria. In accordance with the casualty report of CHICAGO EXPRESS (Federal Bureau of Maritime Casualty Investigation of Germany, 2009), a very serious marine casualty occurred on board the 8749 TEU2 container vessel CHICAGO EXPRESS in the morning on 24 September 2008.

The vessel navigated in South China Sea from Hong Kong to Ningbo following instructions to shipping from the local port authority because of the approaching Typhoon “HAGUPIT”. After reaching the open sea, the CHICAGO EXPRESS encountered heavy winds and swell from a south-easterly direction; this exposed the vessel to rolling motions of up to approximately 32 degrees. The vessel was suddenly hit by a particularly violent wave coming from starboard just as she rolled to starboard. Following that, the CHICAGO EXPRESS keeled over severely several times, at which the inclinometer registered a maximum roll angle of 44 degrees for an estimated period of 10 seconds.

It is remarkable that requirement for the prevention of excessive lateral acceleration has the possibility to restrict GM and to be the opposite side of ensuring sufficient stability because current large vessel generally has sufficient GM to ensure the adequate safety for damage stability. On the other hand, if the ship has sufficient (or excessive) stability, large rolling angles can occur which then result in large lateral accelerations and cargo damage.

Typically, this situation occurs if the encounter frequency of the waves is in resonance to the natural roll frequency of the ship. This means that all types of ship have certain possibility to meet large acceleration. This also means that it is rational to prevent such a phenomenon that occurs frequently not only by the design criteria but also by the operational guidance or limitation.

Therefore, it is important to assess the probability of occurrence of excessive lateral acceleration and to provide the adequate information for adequate safety and operation.

Based on the background, first, a database of world wave and wind is constructed by means of the hindcast data, which can provide worldwide wind and wave data synchronized in space and time. Sea state in the sea area where accident of excessive acceleration occurred was examined by the comparison of a probability of occurrence of wave height. It is found that sea state in the sea area of accident was not necessarily severe compared with that of North Atlantic and North Pacific. This indicates that large lateral acceleration can occur in other sea areas.

Second, the correlation between realistic loading condition, sea state and probability of occurrence was examined by computation of the long term prediction of lateral acceleration. It is clarified that threshold probability of excessive lateral acceleration depends on the combination of loading condition and sea state. It is also clarified that excessive lateral acceleration occurs in a relatively high probability owing to the roll resonance. Finally, the safety level of excessive lateral acceleration is discussed.

2. CONSIDERATION OF SEA STATE AT THE SEA AREA OF ACCIDENT OWING TO EXCESSIVE ACCLERATION

2.1 Source Data of Wave and Wind

For the examination of correlation between winds and waves, it is preferable that wind data synchronizes with wave data in space and time. Based on this background, the wave and wind statistics are composed by the wave hindcasti data. The present hindcasting data is computed by means of the third generation wave hindcasting model of Global Climate by Japan Weather Association (JWA3G model). Grid point value (GPV) of sea winds, provided by the Meteorological Agency of Japan, is used as an input of this model. Significant wave height, wave period and peak direction of waves, mean wind speed and wind direction are computed. These are composed by lattice of 2.5 degree interval (all area from 70 degrees of North latitude to 70 degrees of South latitude). In the present study, data of the 10-year span from January 1997 to December 2006 are used.

The third generation wave hindcasting models basically adopt not conservative methods such as SMB (Sverdrup, Munk and Bretschneider) method or PNJ (Pierson, Neumann and James) method (e.g. British Maritime Technology Limited, 1985) but the spectral method, which is the mainstream of the ocean waves forecasting/hindcasting model. In a spectral method, individual growth and attenuation of each component wave was computed. Prior to the application, the validity of numerical computation of JWA3G model was verified (Japan Weather Association, 1993) through the numerical simulation in accordance with the SWAMP (Sea WAve Modeling Project) method (The SWAMP group, 1985), which is constructed as a verification method of the numerical computation of ocean wave in the world meteorological community.

2.2 Spatial Distribution of Wave Height

Figures 1 to 5 show the contour of average of significant wave height in annual and four seasons. It is found that wave in Southeast Asia is relatively calmer than that in North Pacific because wave of Southeast Asia is affected by weather from South Pole to the south Indian Ocean. On the other hand, it is also found that wave height in South China Sea is relatively higher than that in around South China Sea. It is remarkable in autumn and winter owing to low pressure and typhoon. It is clarified that these findings are consistent with existing findings.

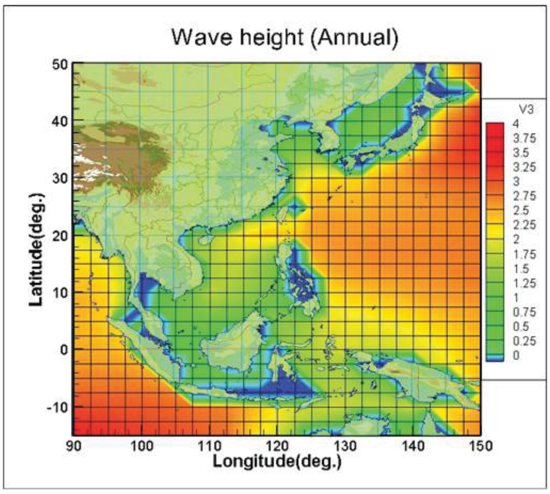


Figure 1 Contour of average of significant wave height (annual).

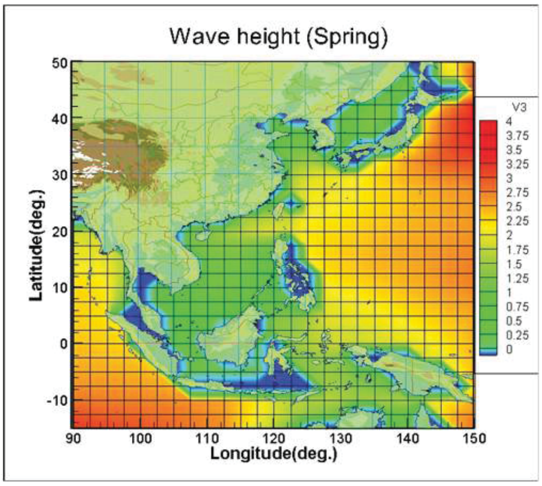


Figure 2 Contour of average of significant wave height (spring: March - May).

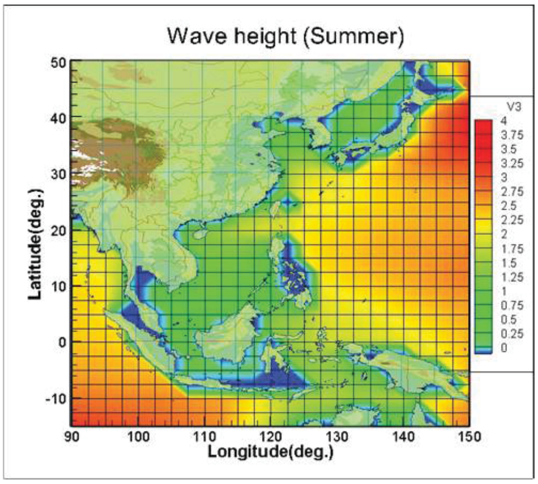


Figure 3 Contour of average of wave height (summer: June - August).

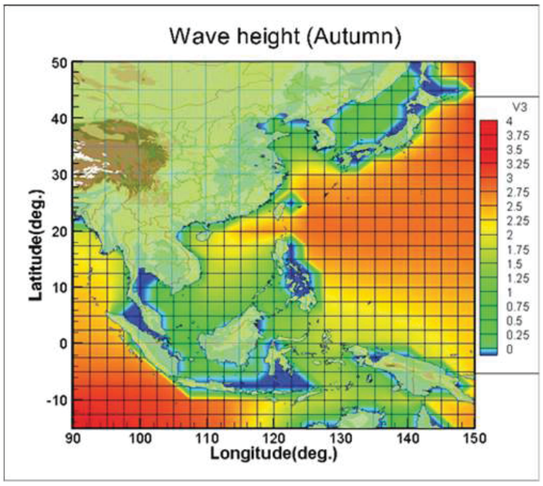


Figure 4 Contour of average of significant wave height (autumn: September - November).

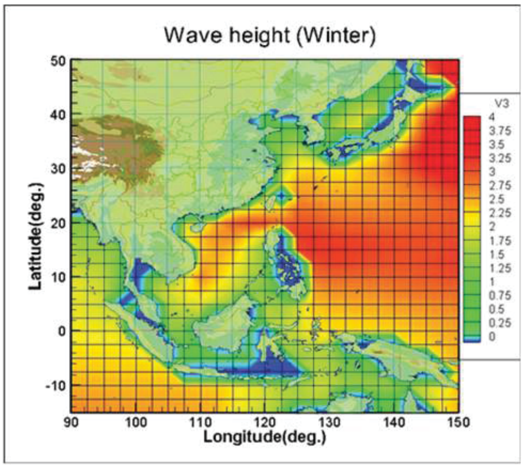


Figure 5 Contour of average of wave height (winter: December - February).

2.3 Statistical Characteristic of Wave Height

Probability of exceedance of wave height is evaluated based on the statistical analysis of wave and wind data. For the comparison of wave height between South China Sea, North Pacific and North Atlantic, the sea area in statistical analysis shown in Figure 6 is defined.

It is found that wave in South China Sea is relatively calmer than that in North Pacific and North Atlantic because wave of Southeast Asia is affected by weather from South Pole to the south Indian Ocean. On the other hand, in autumn, severe sea state in the area close to Hong Kong is similar to that in North Pacific and North Atlantic owing to typhoon in low pressure.

It is found that occurrence probability of sever sea state in North Atlantic and North Pacific is about 10 or 10^2 times higher than that in South China Sea. This means that large acceleration can occur in other sea area such as North Atlantic and North Pacific. Therefore, it is rational that long term prediction for the determination of safety level of lateral acceleration should be evaluated based on the long term probability in North Atlantic or North Pacific.

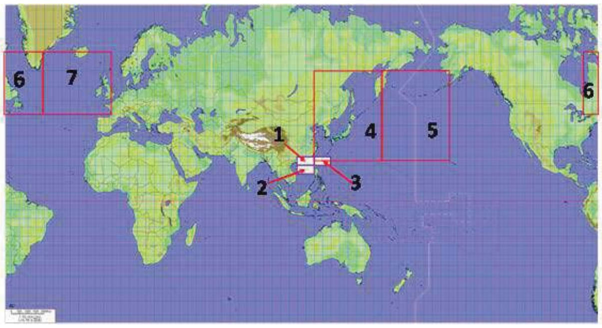
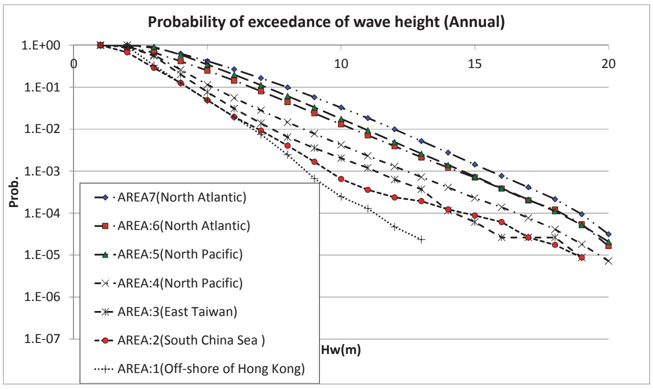
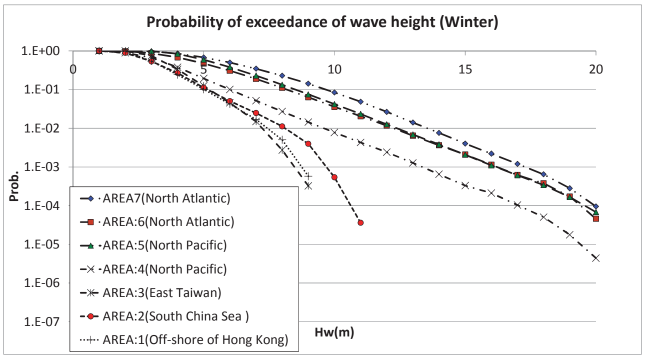
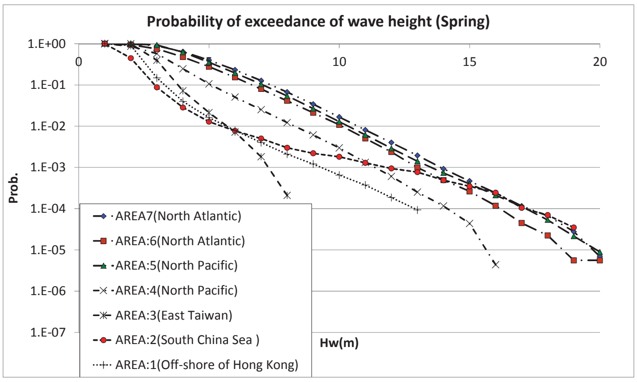
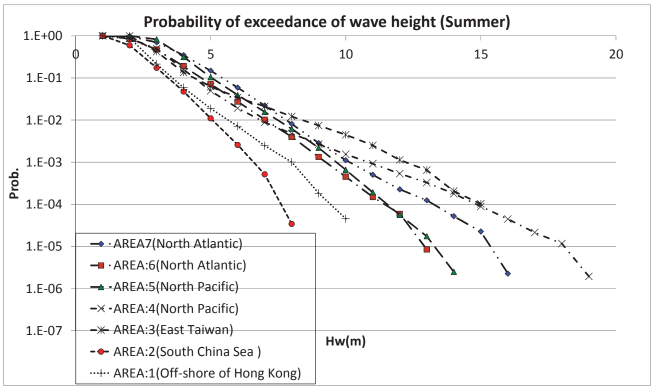


Figure 6 The sea area as the object of the present study









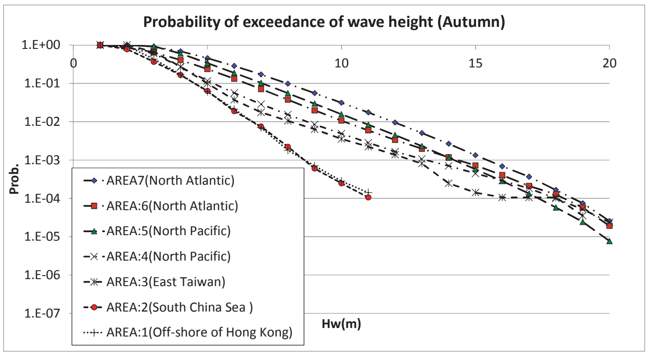


Figure 7 Probability of exceedance of wave height.

3. EVALUATION OF OCCURRENCE OF PROBABILITY OF EXCESSIVE ACCLERATION

3.1 Computation of Long term Probability

Short term and long term probability of lateral acceleration is computed based on the superposition of linear response amplitude operator (Price, W. G. and Bishop, R.E.D., 1974). Container ship and crude tanker were used for object ships in the present study. Table 1 indicates loading conditions of object ships. Loading conditions of them were assumed based on the loading manual of the same ship type.

Response amplitude operator of ship motion and acceleration was computed by means of linear strip method (NSM). ISSC Spectrum was used as a wave spectrum. Cosine square distribution was assumed as a wave directional spectrum. Ship speed in the computation was assumed as 3 knots.

Scatter diagrams of wave height and wave period in North Atlantic, North Pacific and South China Sea were made by means of hindcast data. Tables 2, 3 and 4 show these scatter diagrams. Area of North Atlantic, North Pacific and South China Sea corresponds to areas, which is shown in Figure 4, respectively.

Table 1 Loading conditions of object ships in the present study.

Ship type	Lpp (m)	Loading condition	draught (m)	GM (m)
Container ship	283.8	Full	14.0	1.0
		Partial	11.0	5.0
		Ballast	8.8	7.0
Crude tanker	307.0	Full	19.5	12.0
		Ballast	8.0	28.0

3.2 Short Term Probability of Lateral Acceleration

Standard deviation of lateral acceleration at bridge as a function of mean wave period is shown in Figures 8 to 12. It is found that standard deviation becomes larger in the case of large GM. In the accident of CHICAGO EXPRESS (Federal Bureau of Maritime Casualty Investigation of Germany, 2009), significant wave height and acceleration in the bridge were estimated to be 7.5m and 1G (=9.8m/s^2). In the case of ballast condition of object container ship, it is found that maximum acceleration exceeds 1G when wave height exceeds about 8m.

With regard to the object ships in the present study, it is important to examine long term probability of ballast condition because having sufficient stability could induce large rolling angles and resulting in large lateral accelerations.

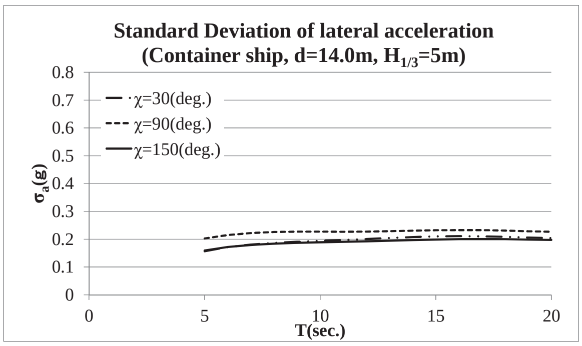


Figure 8 Standard deviation of lateral acceleration at bridge (Container ship, Full loading).

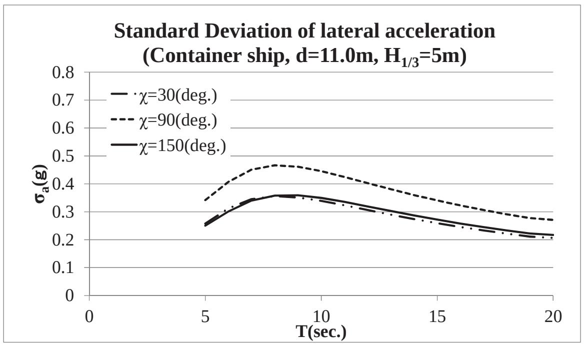


Figure 9 Standard deviation of lateral acceleration at bridge (Container ship, Partial condition).

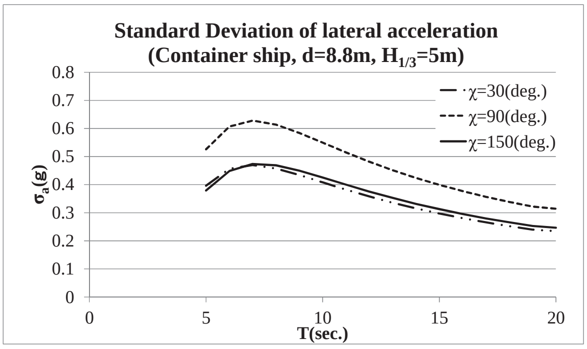


Figure 10 Standard deviation of lateral acceleration at bridge (Container ship, Ballast condition).

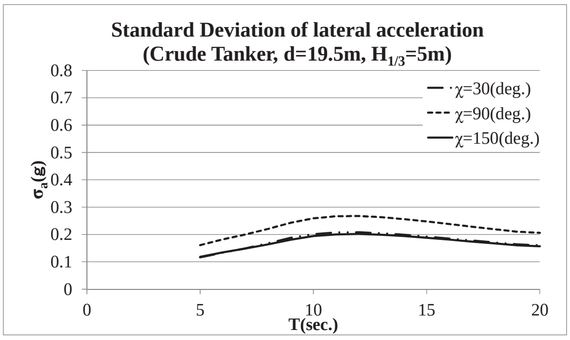


Figure 11 Standard deviation of lateral acceleration at bridge (Crude tanker, Full loading).

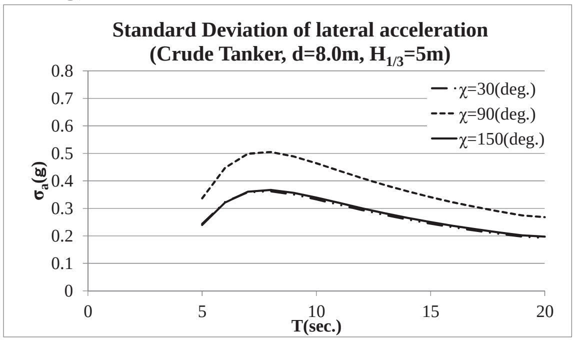


Figure 12 Standard deviation of lateral acceleration at bridge (Crude tanker, Ballast condition).

3.3 Long Term Probability of Lateral Acceleration

Figures from 13 to 15 show long term prediction of lateral acceleration of container ship using wave scatter diagram of North Atlantic, North Pacific and South China Sea, respectively. Figures from 16 to 18 show long term prediction of lateral acceleration at bridge of crude tanker.

It is found that long term probability in beam seas is higher than that in other wave direction because large lateral acceleration is caused by the rolling resonance. In the present computation, long term probability of 1G corresponds to about from $10^{2.5}$ to $10^{1.5}$ in beam seas. It is clarified that large acceleration can occur with high probability because large lateral acceleration is caused by the rolling resonance.

Figure 19 and Figure 20 show long term prediction of rolling of container ship and crude tanker, respectively. It is found that probability of occurrence of rolling corresponds to about from 25 to 30 at the same probability of acceleration of 1G. This is the same level as that in the casualty report of CHICAGO EXPRESS (Federal Bureau of Maritime Casualty Investigation of Germany, 2009).

It is clarified that probability of excessive lateral acceleration largely depends on the loading condition. It is also clarified that excessive lateral acceleration occurs in a relatively high probability owing to the roll resonance. This means that all types of ship have certain possibility to meet large acceleration. Therefore, it is basically difficult to exclude all risk of excessive lateral acceleration only based on the design criteria. It is essential to prevent such a phenomenon that occurs frequently by the combination of design criteria and operational limitation.

Table 2 Scatter diagram of wave height and wave period (South China Sea).

number of data	313698															
average(Hw)=	2.02															
average(Hp)=	6.57															
	T(sec.)															
Hw(m)	-5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
20	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
19	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	2.9E-06	2.9E-06	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
18	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	2.9E-06	2.9E-06	2.9E-06	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
17	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	2.9E-06	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
16	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	8.8E-06	2.9E-06	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
15	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	2.9E-06	1.2E-05	5.8E-06	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
14	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	5.8E-06	1.8E-05	2.9E-06	0.0E+00	0.0E+00	2.9E-06	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
13	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	4.4E-05	4.8E-05	1.6E-05	2.9E-06	2.9E-06	2.9E-06	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
12	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	8.0E-05	1.9E-05	8.8E-06	2.9E-06	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
11	0.0E+00	0.0E+00	0.0E+00	0.0E+00	4.4E-05	1.7E-04	2.7E-05	5.8E-06	0.0E+00	2.9E-06	0.0E+00	5.8E-06	0.0E+00	0.0E+00	0.0E+00	0.0E+00
10	0.0E+00	0.0E+00	0.0E+00	0.0E+00	1.3E-04	2.2E-04	3.1E-05	2.4E-05	5.8E-06	0.0E+00	2.9E-06	0.0E+00	0.0E+00	2.9E-06	0.0E+00	0.0E+00
9	0.0E+00	0.0E+00	0.0E+00	1.9E-05	5.3E-04	3.4E-04	4.5E-05	1.8E-05	1.2E-05	2.9E-06	5.8E-06	0.0E+00	6.8E-06	2.9E-06	0.0E+00	0.0E+00
8	0.0E+00	0.0E+00	0.0E+00	2.4E-04	1.8E-03	2.6E-04	5.6E-05	1.2E-05	2.9E-06	5.8E-06	3.9E-06	0.0E+00	1.3E-05	7.8E-06	0.0E+00	0.0E+00
7	0.0E+00	0.0E+00	5.8E-06	1.9E-03	3.6E-03	2.6E-04	5.1E-05	2.3E-05	5.8E-06	9.7E-06	8.8E-06	1.4E-05	2.3E-05	0.0E+00	0.0E+00	0.0E+00
6	0.0E+00	0.0E+00	3.1E-04	8.9E-03	3.3E-03	3.6E-04	1.2E-04	3.4E-05	1.6E-05	1.3E-05	1.9E-05	1.6E-05	0.0E+00	0.0E+00	0.0E+00	0.0E+00
5	0.0E+00	5.0E-05	1.0E-02	2.0E-02	2.9E-03	8.9E-04	4.1E-04	1.3E-04	1.1E-04	4.6E-05	1.3E-05	2.6E-05	2.4E-05	0.0E+00	0.0E+00	0.0E+00
4	5.8E-06	3.5E-03	4.7E-02	3.0E-02	7.6E-03	2.6E-03	1.1E-03	4.9E-04	2.4E-04	1.3E-04	3.1E-05	1.9E-05	5.8E-06	0.0E+00	0.0E+00	0.0E+00
3	1.6E-03	4.8E-02	9.1E-02	6.3E-02	2.4E-02	9.7E-03	2.4E-03	5.7E-04	4.6E-04	1.5E-04	6.8E-06	2.9E-06	0.0E+00	0.0E+00	0.0E+00	0.0E+00
2	4.1E-02	1.1E-01	1.5E-01	1.2E-01	4.0E-02	1.2E-02	2.3E-03	5.5E-04	2.7E-04	1.1E-04	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
1	4.8E-02	4.5E-02	2.3E-02	1.1E-02	2.9E-03	6.3E-04	3.5E-04	1.8E-05	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00

Table 3 Scatter diagram of wave height and wave period (North Atlantic).

number of data	2574108															
average(Hw)=	3.72															
average(Hp)=	7.51															
	T(sec.)															
Hw(m)	-5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
20	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	9.1E-06	1.4E-05	8.7E-07	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
19	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	1.2E-06	1.8E-05	2.9E-05	1.2E-06	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
18	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	7.6E-06	5.1E-05	3.5E-05	5.8E-07	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
17	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	2.9E-07	1.9E-05	8.9E-05	2.9E-05	5.8E-07	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
16	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	2.0E-06	6.8E-05	1.7E-04	2.8E-05	8.7E-07	0.0E+00	5.8E-07	0.0E+00	0.0E+00	0.0E+00	0.0E+00
15	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	6.1E-06	2.6E-04	2.0E-04	2.4E-05	2.6E-06	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
14	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	4.7E-05	6.4E-04	2.1E-04	2.0E-05	2.9E-06	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
13	0.0E+00	0.0E+00	0.0E+00	0.0E+00	5.0E-06	2.4E-04	1.2E-03	1.8E-04	2.1E-05	2.0E-06	8.7E-07	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
12	0.0E+00	0.0E+00	0.0E+00	0.0E+00	2.7E-05	1.2E-03	1.9E-03	1.8E-04	2.1E-05	4.1E-06	1.2E-06	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
11	0.0E+00	0.0E+00	0.0E+00	1.8E-06	2.5E-04	3.4E-03	1.9E-03	1.7E-04	2.2E-05	6.4E-06	8.7E-07	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
10	0.0E+00	0.0E+00	0.0E+00	2.8E-05	1.7E-03	6.6E-03	1.6E-03	1.8E-04	3.7E-05	1.1E-05	1.7E-06	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
9	0.0E+00	0.0E+00	0.0E+00	3.2E-04	7.2E-03	8.6E-03	1.5E-03	2.4E-04	7.2E-05	1.7E-05	1.5E-06	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
8	0.0E+00	0.0E+00	1.1E-05	2.6E-03	1.8E-02	8.1E-03	1.5E-03	4.7E-04	2.0E-04	2.6E-05	1.7E-06	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
7	0.0E+00	0.0E+00	2.8E-04	1.4E-02	2.6E-02	6.6E-03	2.2E-03	1.1E-03	2.3E-04	4.7E-05	1.1E-05	3.5E-06	0.0E+00	0.0E+00	0.0E+00	0.0E+00
6	0.0E+00	3.7E-05	3.0E-03	4.1E-02	2.4E-02	7.5E-03	5.3E-03	1.3E-03	2.8E-04	8.4E-05	1.8E-05	6.4E-06	0.0E+00	0.0E+00	0.0E+00	0.0E+00
5	1.5E-06	7.1E-04	2.2E-02	5.4E-02	2.4E-02	1.8E-02	7.2E-03	1.1E-03	2.5E-04	7.3E-05	1.4E-05	3.5E-06	1.2E-06	2.9E-07	2.9E-07	0.0E+00
4	1.3E-04	8.5E-03	4.9E-02	5.9E-02	4.5E-02	2.2E-02	5.1E-03	6.7E-04	1.5E-04	7.1E-05	1.5E-05	3.5E-06	2.3E-06	2.9E-07	5.8E-07	1.5E-06
3	4.2E-03	3.8E-02	6.6E-02	8.1E-02	4.2E-02	1.0E-02	2.0E-03	4.5E-04	1.4E-04	6.0E-05	9.3E-06	5.2E-06	2.0E-06	2.9E-07	0.0E+00	0.0E+00
2	2.7E-02	4.4E-02	5.8E-02	3.8E-02	9.2E-03	2.5E-03	8.5E-04	2.4E-04	8.6E-05	4.0E-05	9.9E-06	5.6E-06	0.0E+00	0.0E+00	0.0E+00	0.0E+00
1	3.0E-02	9.8E-03	6.5E-03	4.5E-03	2.2E-03	1.2E-03	6.2E-04	1.5E-04	7.3E-05	3.4E-05	6.7E-06	1.2E-06	0.0E+00	0.0E+00	0.0E+00	0.0E+00

Table 4 Scatter diagram of wave height and wave period (North Pacific).

number of data	5067073															
average(Hw)=	3.27															
average(Hp)=	7.69															
	T(sec.)															
Hw(m)	-5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
20	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	3.5E-06	9.1E-06	1.2E-06	0.0E+00	1.6E-07	0.0E+00	0.0E+00	0.0E+00	0.0E+00
19	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	2.6E-07	1.1E-05	8.2E-06	1.7E-06	1.6E-07	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
18	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	3.1E-06	2.2E-05	1.1E-05	3.5E-06	4.2E-07	1.6E-07	0.0E+00	0.0E+00	0.0E+00	0.0E+00
17	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	2.6E-07	9.9E-06	4.0E-05	1.4E-05	2.9E-06	4.2E-07	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
16	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	3.5E-05	7.5E-05	9.9E-06	1.0E-06	1.6E-07	1.6E-07	0.0E+00	0.0E+00	0.0E+00	0.0E+00
15	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	4.0E-06	1.1E-04	9.3E-05	1.2E-05	4.2E-06	6.4E-07	0.0E+00	1.6E-07	0.0E+00	0.0E+00	0.0E+00
14	0.0E+00	0.0E+00	0.0E+00	0.0E+00	1.6E-07	2.5E-05	2.7E-04	1.1E-04	1.3E-05	3.8E-06	1.2E-06	1.6E-07	0.0E+00	0.0E+00	0.0E+00	0.0E+00
13	0.0E+00	0.0E+00	0.0E+00	0.0E+00	1.9E-06	1.1E-04	5.2E-04	1.0E-04	1.3E-05	4.2E-06	1.2E-06	1.6E-07	0.0E+00	0.0E+00	0.0E+00	0.0E+00
12	0.0E+00	0.0E+00	0.0E+00	0.0E+00	1.6E-05	5.1E-04	8.1E-04	9.6E-05	1.3E-05	3.5E-06	9.0E-07	1.3E-06	1.6E-07	0.0E+00	0.0E+00	0.0E+00
11	0.0E+00	0.0E+00	0.0E+00	8.4E-07	1.5E-04	1.5E-03	9.6E-04	9.3E-05	1.7E-05	4.8E-06	2.2E-06	1.4E-06	8.4E-07	0.0E+00	0.0E+00	0.0E+00
10	0.0E+00	0.0E+00	0.0E+00	1.4E-05	8.9E-04	3.1E-03	8.9E-04	9.6E-05	2.0E-05	1.1E-05	3.6E-06	1.6E-06	1.0E-06	5.2E-07	0.0E+00	0.0E+00
9	0.0E+00	0.0E+00	0.0E+00	2.0E-04	3.9E-03	4.4E-03	8.4E-04	1.3E-04	4.3E-05	1.8E-05	6.2E-06	3.0E-06	1.1E-06	0.0E+00	0.0E+00	0.0E+00
8	0.0E+00	0.0E+00	9.0E-06	1.7E-03	9.9E-03	4.6E-03	8.9E-04	2.6E-04	1.5E-04	5.0E-05	1.3E-05	7.4E-06	2.3E-06	0.0E+00	0.0E+00	0.0E+00
7	0.0E+00	0.0E+00	1.9E-04	8.8E-03	1.6E-02	4.5E-03	1.4E-03	7.2E-04	2.8E-04	1.1E-04	2.7E-05	8.1E-06	1.5E-06	0.0E+00	0.0E+00	0.0E+00
6	0.0E+00	1.7E-05	2.2E-03	2.6E-02	1.7E-02	5.4E-03	4.3E-03	1.5E-03	4.5E-04	1.4E-04	3.0E-05	5.8E-06	1.0E-06	2.6E-07	0.0E+00	0.0E+00
5	4.2E-07	5.4E-04	1.5E-02	4.0E-02	1.9E-02	1.5E-02	9.4E-03	2.6E-03	5.2E-04	1.2E-04	1.8E-05	5.1E-06	6.8E-07	7.8E-07	5.2E-07	5.2E-07
4	8.8E-05	5.9E-03	3.9E-02	5.6E-02	4.5E-02	3.3E-02	1.5E-02	1.8E-03	2.3E-04	4.7E-05	1.9E-05	6.2E-06	1.6E-06	4.2E-07	7.8E-07	0.0E+00
3	2.7E-03	2.8E-02	6.6E-02	9.9E-02	8.4E-02	3.7E-02	7.3E-03	5.5E-04	1.2E-04	4.6E-05	1.7E-05	2.6E-06	5.2E-07	2.6E-07	2.6E-07	7.8E-07
2	2.0E-02	2.7E-02	4.3E-02	6.3E-02	2.7E-02	6.1E-03	1.7E-03	4.4E-04	1.2E-04	3.7E-05	9.5E-06	3.9E-06	5.2E-06	1.3E-06	0.0E+00	0.0E+00
1	3.9E-02	7.7E-03	5.9E-03	4.7E-03	2.8E-03	1.8E-03	1.2E-03	5.7E-04	2.3E-04	7.7E-05	1.7E-05	5.7E-06	4.9E-06	2.6E-07	0.0E+00	0.0E+00

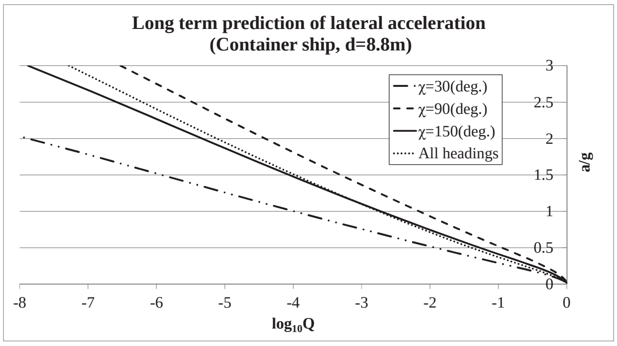


Figure 13 Long term prediction of lateral acceleration at bridge of container ship (Ballast condition, wave scatter diagram: South China Sea).

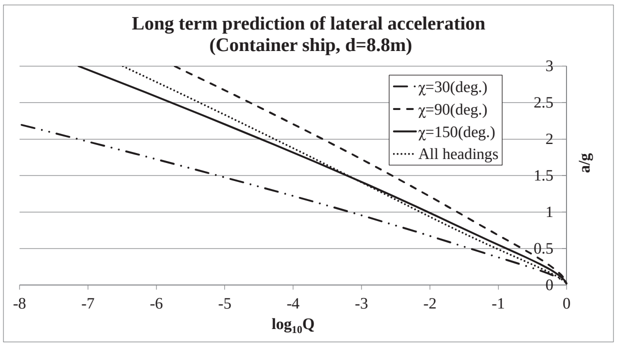


Figure 14 Long term prediction of lateral acceleration at bridge of container ship (Ballast condition, wave scatter diagram: North Atlantic).

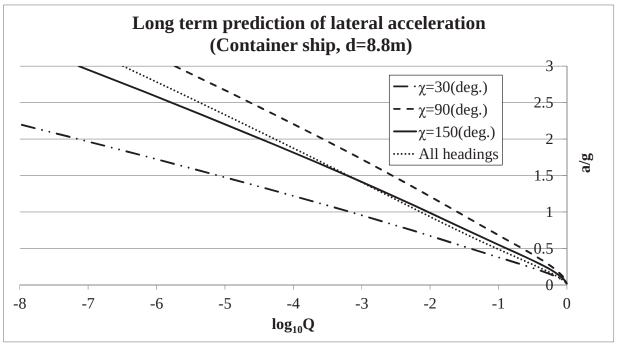


Figure 15 Long term prediction of lateral acceleration at bridge of container ship (Ballast condition, wave scatter diagram: North Pacific).

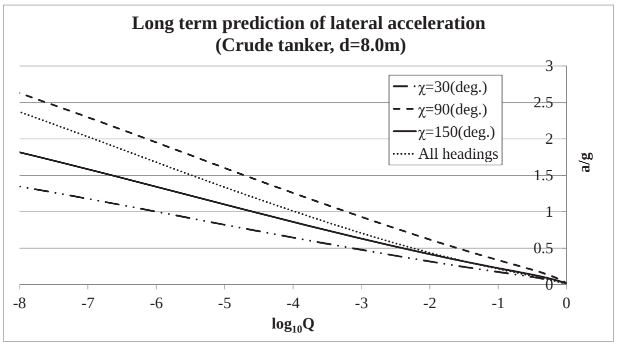


Figure 16 Long term prediction of lateral acceleration at bridge of crude tanker (Ballast condition, wave scatter diagram: South China Sea).

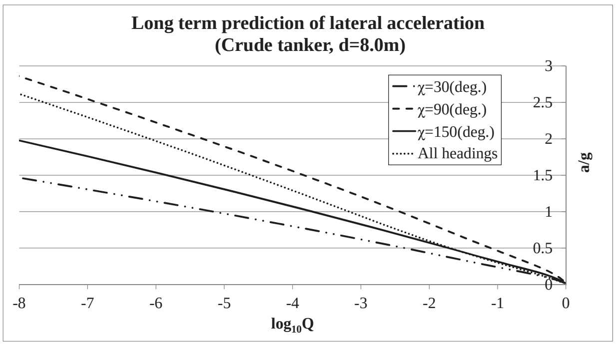


Figure 17 Long term prediction of lateral acceleration at bridge of crude tanker (Ballast condition, wave scatter diagram: North Atlantic).

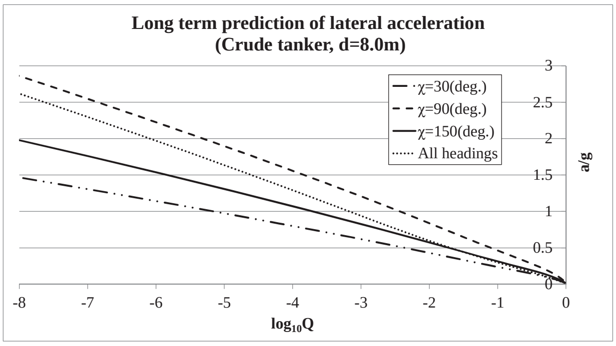


Figure 18 Long term prediction of lateral acceleration at bridge of crude tanker (Ballast condition, wave scatter diagram: North Pacific).

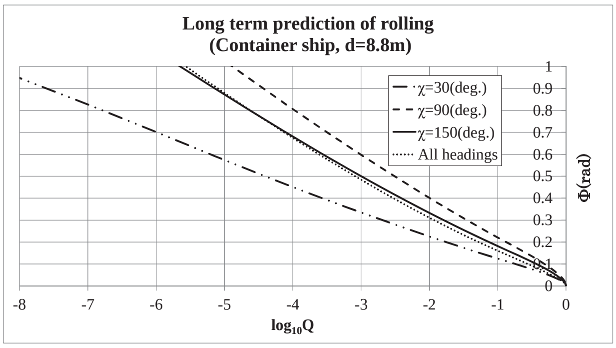


Figure 19 Long term prediction of rolling of container ship (Ballast condition, wave scatter diagram: South China Sea).

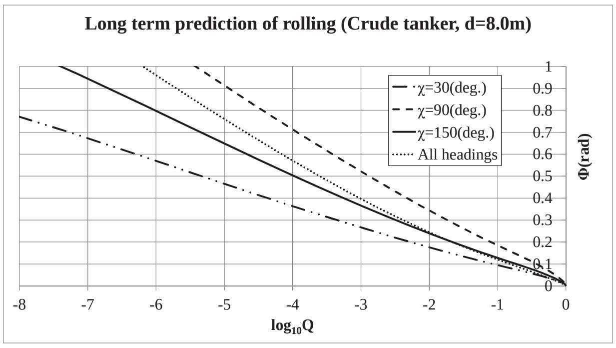


Figure 20 Long term prediction of rolling of crude tanker (Ballast condition, wave scatter diagram: South China Sea).

4. CONCLUSIONS

For the assessment of the correlation between loading condition, sea state and probability of occurrence of lateral acceleration, the short term and long term probability of lateral acceleration was computed. Conclusions are as follows:

1) Sea state in North Atlantic and North Pacific is severer than that in South China Sea although wave becomes severer in the area close to Hong Kong.

2) Lateral acceleration of the object ships in this study becomes larger in the ballast condition.

3) Excessive lateral acceleration occurs in a relatively high probability owing to the roll resonance.

4) It is rational to prevent such a phenomenon that occurs frequently not only by the design criteria but also by the operational guidance or limitation.

5. ACKNOWLEDMENTS

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6. REFERENCES

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