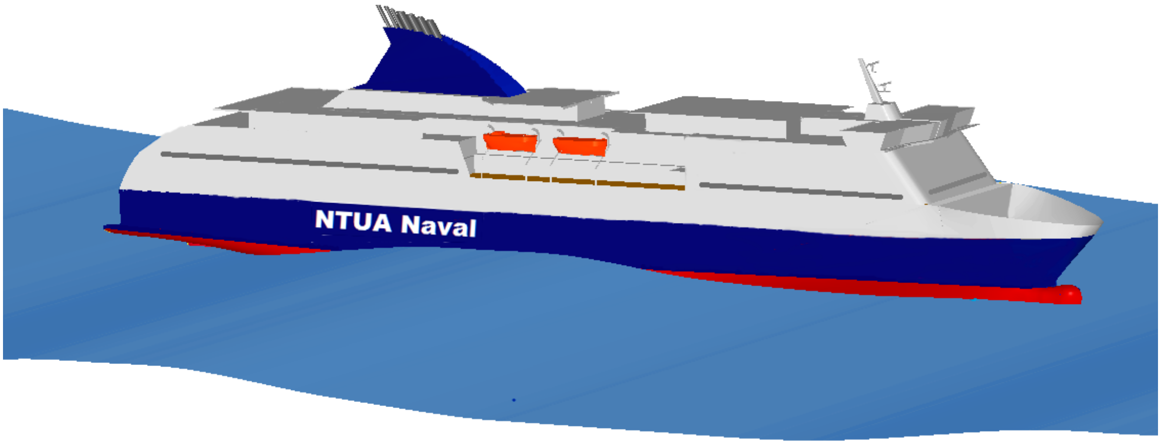
**NATIONAL TECHNICAL UNIVERSITY OF ATHENS**
**SCHOOL OF NAVAL ARHITECTURE AND MARINE ENGINEERING**
DIVISION OF SHIP DESIGN AND MARINE TRANSPORTS

DIPLOMA THESIS

**STEFANOS C. PANAGIOTELLIS**

# EVALUATION OF IMO's 'SECOND GENERATION' INTACT STABILITY CRITERIA

# INVESTIGATION FOR THE POSSIBLE IMPACT ON RO-RO SHIP DESIGN AND OPERATION

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**ΕΘΝΙΚΟ ΜΕΤΣΟΒΙΟ ΠΟΛΥΤΕΧΝΕΙΟ**
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**ΣΤΕΦΑΝΟΣ ΠΑΝΑΓΙΩΤΕΛΛΗΣ**

# ΑΞΙΟΛΟΓΗΣΗ ΤΩΝ ΚΡΙΤΗΡΙΩΝ ΆΘΙΚΤΗΣ ΕΥΣΤΑΘΕΙΑΣ ΔΕΥΤΕΡΗΣ ΓΕΝΙΑΣ ΤΟΥ IMO

# ΔΙΕΡΕΥΝΗΣΗ ΓΙΑ ΤΙΣ ΠΙΘΑΝΕΣ ΕΠΙΠΤΩΣΕΙΣ ΤΟΥΣ ΣΤΗ ΣΧΕΔΙΑΣΗ ΚΑΙ ΤΗ ΛΕΙΤΟΥΡΓΙΑ Ε/Γ-Ο/Γ ΚΑΙ Φ/Γ-Ο/Γ ΠΛΟΙΩΝ

ΕΠΙΒΛΕΠΩΝ

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# Ευχαριστίες

Θα ήθελα να εκφράσω τις ευχαριστίες μου στον επιβλέποντα, καθηγητή κ. Κωνσταντίνο Σπύρου, για την συνεργασία την υποστήριξη και την άμεση ανταπόκριση σε οτιδήποτε χρειάστηκα κατά τη διάρκεια εκπόνησης της εργασίας αυτής, καθώς επίσης και την ανάθεση του ενδιαφέροντος αυτού θέματος μέσα από το οποίο είχα την ευκαιρία να εμβαθύνω σε ζητήματα σχεδίασης και ασφάλειας των πλοίων Ro-Ro, και να αποκτήσω σημαντικές δεξιότητες στο προγραμματισμό μέσω της εκτενούς χρήσης του πακέτου Matlab.

Ευχαριστώ ακόμα τον φίλο και συνάδερφο Βασίλη Μουλό και την αδερφή μου Βασιλική για την σημαντική συμβολή τους στη γλωσσική επιμέλεια του κειμένου.

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Στέφανος Χ. Παναγιωτέλλης

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# Abstract

International Maritime Organization (IMO) is currently developing new intact stability regulations known as second generation intact stability criteria which aim to reduce the probability of a vessel's capsize due to well-known stability failures in waves. This phenomena concern parametric roll, pure loss of stability, surf riding-broaching to failure modes. In addition in the framework of second generation intact stability criteria is expected the revision of the weather criterion that adopted by IMO in 1985 and examined the vessel's safety under the action of beam seas waves known as 'dead ship condition'.

The purpose of this diploma thesis is to evaluate the current form of draft regulations by applying them on a series of RoRo Passenger (RoPax) and RoRo Cargo ships and interpreting the results. However, some problems concerning the applicability are revealed. In addition their credibility and the extent in which they are able to reduce the probability of accidents is investigated. Furthermore some modifications are proposed which seem to be prone to improving the draft regulations. RoRo and container vessels are the two basic types of ships that will be mostly affected by the second generation intact stability criteria

It is found that, generally, the current form of the draft criteria need some improvement as well as further processing, before their finalization.

All calculations were carried out by using the programming environment of Matlab, All the ships were modelled in Rhino 3d and then were imported into stability module of Maxsurf software that offers special capabilities in hydrostatic and stability calculations in longitudinal waves.

# Περίληψη

Ο Διεθνής ναυτιλιακός οργανισμός (IMO) βρίσκεται σε διαδικασία ανάπτυξης κανονισμών που έχουν γίνει γνωστοί ως second generation intact stability criteria, που θα ελαττώνουν τον κίνδυνο ανατροπής ενός πλοίου, λόγω φαινομένων αστάθειας σε κυματισμούς. Τα φαινόμενα αυτά αφορούν τη παραμετρική αστάθεια (parametric roll) τη αυθεντική απώλεια ευστάθειας (pure loss of stability) το φαινόμενο της κατευθυντικής αστάθειας στη διαμήκη κίνηση του πλοίου (broaching-to). Επίσης στα πλαίσια των κανονισμών ευστάθειας δεύτερης γενιάς αναμένεται και η αναθεώρηση του γνωστού κριτηρίου καιρού που υιοθετήθηκε από τον IMO το 1985 και εξετάζει τη ασφάλεια ενός πλοίου σε περίπτωση απώλειας της πρόωσης όπου οι κυματισμοί το έχουν στρέψει και προσπίπτουν κάθετα σε αυτό, κατάσταση γνωστή ως dead ship condition.

Σκοπός της διπλωματικής αυτής εργασίας είναι η αξιολόγηση των προτεινόμενων προσχεδίων για τους κανονισμούς αυτούς, εφαρμόζοντας τους σε μια σειρά επιβατηγών/οχηματαγωγών (Ε/Γ-Ο/Γ-RoPax) και φορτηγών/οχηματαγωγών (Φ/Γ-Ο/Γ-RoRo Cargo) πλοίων, ώστε να αναδειχθούν τυχόν προβλήματα σχετιζόμενα με την εφαρμογή, αλλά και να αξιολογηθεί η αξιοπιστία τους όσον αφορά το βαθμό που είναι σε θέση να μειώσουν την πιθανότητα ατυχήματος. Τα πλοία RoRo από κοινού με τα πλοία τύπου container vessel, λόγω της μορφής της γάστρας αυτών, αποτελούν τους δύο θεμελιώδεις τύπους πλοίων τους οποίους θα αφορούν τα κριτήρια ευστάθειας δεύτερης γενιάς.

Γενικότερα προκύπτει πως τα προσχέδια των κανονισμών έχουν ακόμα αρκετά προβλήματα και η ανάγκη βελτίωσης τους είναι επιτακτική πριν την έκδοση την τελικής μορφής τους.

Οι υπολογισμοί πραγματοποιήθηκαν χρησιμοποιώντας την προγραμματιστική πλατφόρμα του Matlab, Τα πλοία μοντελοποιήθηκαν χρησιμοποιώντας το Rhino 3d και στην συνέχεια εισήχθησαν στο ναυπηγικό πακέτο Maxsurf και ειδικότερα το υποπρόγραμμα Stability, το οποίο παρέχει εξαιρετικές δυνατότητες στον υπολογισμό υδροστατικών χαρακτηριστικών και χαρακτηριστικών ευστάθειας σε διαμήκης κυματισμούς.

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# Chapter 1 – Introduction

## 1.1. MOTIVATION AND CONTENT OF THESIS

The behavior of a ship in rough sea and her dynamic stability represent issues of complex nature that are strongly connected with the specific design characteristics of a vessel. Stability failures in waves such as parametric rolling and reduction of stability on the wave crest in following seas have been observed since the 19th century. Constant efforts from various researchers aided from the developments of computational methods have today set new standards in understanding and handling dynamic stability aspects. However, efforts towards setting a regulatory framework by the International Maritime Organization, that could ensure more safety against stability failures in waves have been delayed, due to specific reasons, mainly concerning the priority of setting regulations for damage stability failures that are connected with major accidents of RoRo Passenger ships, as well as because of the fact that the nature of dynamic stability is more complex.

Accidents related with intact stability failures in waves were firstly observed in container vessels with parametric rolling incidents, as well as on small fishing vessels with surf riding and broaching-to incidents that have led to capsize in some cases. Although the probability of capsize due to parametric roll or pure of stability on containerships is not significant, loss of containers due to lashing failures are usually observed. The accident of the containership 'APL China' in 1998 was the first verified parametric roll serious accident, 'Nedlloyd Genova', in 2006 and 'Chicago Express' in 2009 were followed. On RoRo vessels the probability of accident due to parametric roll or stability reduction in waves was very small until the introduction of finer hull forms with similar to containerships characteristics. A series of accidents with RoRo ships between 2006 and 2009 ('Finnbirch', 'Aratere', 'Cougar Ace', 'Riverdance' 'Ariake') have led to total loss of the vessels and loss of lives such as in the case of Finnbirch

In 2002 IMO assigned to the sub-committee on stability, loadlines and fishing vessel safety (SLF) to start the procedures for the development of improved intact stability criteria. Until then, it had become evident that the introduction of more efficient but also more susceptible to stability failures in waves, vessels, had made the introduction of dynamic stability regulations necessary.

The first draft regulation containing first and second level vulnerability criteria was published in 2014 including crteria for parametric roll, pure loss of stability, surf riding-broaching to and excessive accelerations. In 2015 the draft regulation for the dead ship stability failure was added.

The basic framework of this thesis constituting from 5 basic chapters. Chapter 7 is dedicated to dead ship condition failure mode, Chapter 8 to Pure loss of stability, Chapter 9 to parametric rolling, Chapter 10 to excessive accelerations, The last chapter, Chapter 11 is dedicated to the investigation of the impact that 2nd generation intact stability may bring to RoRo ship design.

## 1.2 THESIS CONTRIBUTIONS

The main part of this thesis is covered by calculations of the second generation criteria on the principal loading conditions of modern RoRo vessels. Although there are results for many sample ships in a variety of paper, there are not so many for RoRo ships. Especially level 2 criterion for dead ship stability have not extensively been applied in RoPax ships which is one of the most characteristic for the criterion type of ship. In this thesis the behavior of the criterion is deeply investigated and many critical issues are highlighted. Furthermore, parametric rolling phenomenon in modern RoRo ships has not investigated to a large extent in comparison with container vessels, in the current thesis except for the results concerning parametric roll criteria, many issues relevant to the parametric roll behavior of RoRo vessels are indicated. Apart from the calculations, the evaluation that was carried out in the current thesis covers and indicates many critical aspects that seem to need more attention.

# Chapter 2 – Brief Critical Review

The proposed dynamic stability criteria is an effort of IMO in the direction of setting a regulatory framework prone to improve the safety of ships in rough seas. The last decades a significant progress in understanding ship stability dynamics and their underlying physics has been noticed. Nevertheless, the intact stability regulations are still based on the empirical stability criteria that were introduced in 1969 and constitute an analysis of the righting arm of vessels with completely different characteristics from the modern ones. The only exception is the so-called weather criterion that was adopted by IMO in 1985 as an effort to improve the stability of vessels with large superstructures exposed to wind in beam seas. The criterion is based on a Japanese criterion of 1950 and is still in force despite the notice it has received.

Generally speaking there are many types of ship instabilities except from the problem of resonance in beam waves, relevant to the angle between ship and waves. Vessels with fine hull forms can be prone to stability alterations when sailing in longitudinal waves, a problem that leads to parametric roll resonance, while in following waves where the frequency of encounter is near to 0 pure loss of stability could be experienced, in waves with length comparable to ship length, when the initial metacentric height is low. Broaching-to phenomenon is also a dangerous type of instability in following seas and many small ships have experienced such serious accidents. The broaching-to phenomenon is critical for Froude numbers above 0.3. However, other ships like RoRo ships could also be vulnerable, due to the fact that many of them sail at Froude numbers from 0.3 to 0.4.

Although some of this instabilities have been detected since the 19th century, the mathematical modelling of such phenomena and as a result the detail study of them constitutes an achievement of the last decades. Decisions regarding intact stability criteria at International Maritime Organization are historically delayed, as happened with the first intact stability code which was implemented in 1969 around 30 years after the work of Rahola (in which it is based), the discussion about the development of a new generation intact stability framework that would include criteria for preventing accidents form the known instabilities in waves, started in 2002, and is not yet clear when the criteria will be implemented

## 2.1 RECENT STUDIES FOR THE STABILITY OF DISPACEMENT-TYPE SHIPS IN WAVES

In 2004 American Bureau of Shipping presented a guide for the assessment of parametric roll resonance in the design of container carriers [43]. In the first part of the paper the physical background of parametric roll resonance in following and head seas is explained, omitting the modelling of the phenomenon in order to be accessible to engineers with a variety of backgrounds. In the second part susceptibility criteria with respect to the hazard of the development of parametric roll in longitudinal waves and calculation methods for the roll amplitudes were proposed. The mathematical model based on which amplitudes are calculated is based on the one degree of freedom differential equation of roll motion, with restoring term to be calculated as a periodic functions based on the mean value and mean amplitude of GM in the wave.

In 2005, Spyrou [33] proposed design criteria for the prevention of parametric roll. The amplitude of the metacentric height variations was calculated based on initial GM in calm water. The model describing the roll motion is based on Mathieu equation, with a linear damping term. The restoring force was modelled based on 5th order fitting. Closed-form algebraic formulas for the calculation of parametric roll amplitude were also introduced, deriving from the application of the analytical harmonic balance method.

Umeda et.al [40] in 2003 presented a study where GZ curve is described as a nonlinear function of wave steepness in experimental, and analytical level. The model describing the roll motion is based on the roll equation with 2 damping terms. In the same paper an averaging method for the calculation of the steady parametric roll amplitude based on the numerical solution of a high order algebraic equation was applied. Maki et.al [41] in 2011 presented a new formula for the restoring term that is modelled based not only on restoring coefficients in calm water as in the previous studies but also in coefficients that express the wave effect on restoring moment. In this study an averaging method was also created, based on the roll model. This averaging formula was proposed to be used in the level 2B criterion for parametric rolling, but it has not gained acceptance due to inconsistencies when compared to direct numerical solution of the roll equation.

Spyrou in 2006 [45] shown that a simple prediction formulae for the higher limit of asymmetric surging (threshold of global surf-riding) is possible to be obtained, this formula is based on Melnikov's method. The development of the level 2 criterion for surf riding in second generation intact stability was based on this study.

In 2010 at the final report of the German project Lasse [36], a study for the development of threshold values for a minimum stability criterion based on full scale accidents. was introduced. On the framework of this project accidents that ended up to capsize in rough seas were examined and analyzed based on methods and procedures such as the direct computation of the motion of the ship in time domain for irregular wave environment.

## 2.2 RECENT STUDIES FOR THE SECOND GENERATION INTACT STABILITY CRITERIA WITH EMPHASIS IN RORO SHIPS

Peters et. al presented at SNAME Transactions in 2011, a paper [7] with all the development about the second generation intact stability criteria. This study had three basic objectives. First, it is a brief review of related IMO developments to the direction of setting the framework of the new criteria. Second, the paper describes the physical background of each involved instability, and the strong mathematical background of each criterion connecting with the underlying physics of each problem. Last, the paper reviews available technologies for development of direct stability assessment methods or performance-based criteria that should be available for those rare cases when susceptibility to this modes of failures is too high.

A number of studies concerning the application and the evaluation of the second generation intact stability criteria have been presented in international stability workshops, some of them were focused on RoRo ships. In 2013 Kruger et.al [42] presented a paper on the investigation of the second generation intact stability criteria for ships vulnerable to parametric rolling in following seas. In this study, a typical RoRo vessel was used as reference ship. It was revealed using model tests and computational methods that the current intact stability limit cannot ensure safety against capsize from pure loss of stability on the wave crest or parametric rolling in irregular ships for specific wave cases. Furthermore the damage stability limit of the reference ship was below intact stability especially weather criterion, a fact that highlights the difference between RoRo Passenger, (where damage stability could ensure a safety level for dynamic stability) and RoRo Cargo ships. In the last part of the study the criteria of second generation were applied on the reference ship and GM limit curves were presented.

Tompuri et.al [6] in 2015 applied the second generation intact stability criteria in the initial design of a fast displacement type RoPax ship. In the initial design there are characteristics of the vessel that are not yet well defined, so the study was focused on the sensitivity of the criteria on small difference on design characteristics of the vessel. GM limit curves are also presented indicating the fact that 2nd generation criteria require less stability than the current intact stability (2008 IS Code), especially in light drafts, something that is a basic inference of this thesis too. Another critical aspect highlighted by the study is the broaching criterion's behavior on fast RoPax ships. The limit speed for the passing of the criterion is around to 23 Kn, whereas the design speed of the ship is around to 26 Kn

# Chapter 3 – Intact Stability Regulations

## 3.1 HISTORICAL BACKGROUND

The origins of intact stability criteria can be traced back to the PhD thesis of Rahola (1939) [46] as well as the first versions of a criterion developed in the works of Yamagata in Japan (1950s) for the evaluation of a ships safety under extreme weather condition, including the action of a severe wind gust on the top of a wave effect. The criterion was firstly implemented on Japanese passenger ships and its concept was based on previous works like those of Pierrottet as well as other Russian scientists such as Blagoveschensky. This were the first attempts at setting standards based on scientific rather than empirical methods, as long as Rahola's work was basically a statistical analysis of the hydrostatic stability of 30 vessels that capsized in Baltic sea. Rahola also suggested stability criteria based on righting lever curve till 40 degrees.

The need of setting criteria for the intact stability is first highlighted by SOLAS 60 about 10 years after the foundation of the International Maritime Consultative Organization (IMCO) renamed later to IMO. SOLAS 60 conclude that further study about intact stability should be carried out and called the countries to submit their proposals. However the first intact stability code IMO Res. A.167 was adopted in 1968, and it was based on Rahola's work. It is still in force today as a part of IS Code 2008. Res. A.167 was adopted about 1.5 years after one of the worst maritime disasters took placed in Greece with the loss of the ship 'Heraklion' in the middle of the route from Chania-Crete to Piraeus in the Aegean sea, under harsh weather conditions. 'Heraklion' was a cargo ship converted to RoRo Passenger. Although her loss had not to do directly with an intact stability failure, the ship exhibited heavy rolling before the occurrence of flooding through the opened garage door.

In 1985 with Res A.562, IMO adopted the weather criterion, that was based on Japanese criterion of 1956 and was the first dynamic stability criterion. In 1993 the *first generation intact stability* code was adopted by IMO with the Res A.749(18) which was the joining of A.167 and A.562 to a single code [7]. Res A.749 was implemented with its original form until 2002 where the intact stability working group was re-formed by IMO in order to discuss amendments on intact stability code as an answer to the request of some countries that claimed that the weather criterion was too strict for ships with large roll period (above 20 sec) and large B/d ratio like modern large cruise ships. Indeed, the weather criterion due to the fact that it was based on Japanese criterion of 1950s was tuned with a population of ships with completely different characteristics from the modern ones. The problems were focused on the formula for the calculation of roll back angle $\varphi_1$ ,where effective wave slope coefficient $r$ and steepness $s$ which is calculated as a function of roll period lead to large $\varphi_1$ angles for some type ships. Eventually SLF 45 in 2002 concluded that intact stability code had to be revised with special attention to the weather criterion. In the mean time until the introduction of the new I.S. stability code the sub-committee agreed that calculation of $s$ parameter of the weather criterion could be calculated based on reviewed values, and effective wave slope $r$ should not have a value above 1. In 2008 IMO responded with the intact stability code IS Code 2008 where the criteria of A.749 for GZ curve and the weather criterion were not amended. Nevertheless an alternative experimental approach for the estimation of $\varphi_1$ angle on the weather criterion were introduced with the guidance MSC.1/Circ. 1227 for ships with parameters outside specific limits, on which weather criterion's formulas are based.

It should be mentioned that IMO published in October 1995 the so called *guidance to the master for avoiding dangerous situation in following and stern quartering seas* [44] which was revised in 2007 as a step in order to reduce the danger of accidents due to well-known instabilities in waves.

### 3.2 THE SECOND GENERATION INTACT STABILITY CRITERIA

The onset year in the development of *second generation intact stability* criteria, was 2002 as it had become perceptible that the development of naval architecture in the hydrodynamic section had led to the introduction of finer hull forms for containerships and RoRo ships, with by far greater efficiency but on the other hand more prone to stability failures in waves such as restoring arm variation problems. However, due to the priority of revising IS Code, the actual work on second generation intact stability criteria was started in September 2005 where the 48th session of SLF working group decided that the second generation intact stability criteria should be performance based and focused on three modes of stability failures

1. Parametric excitation and pure loss of stability
2. Stability under dead ship condition
3. Maneuvering related problems such as broaching-to

After years of discussion the first draft of the second generation intact stability criteria was published in December 2014 by Sub-Committee of ship design and construction.

The multi-tiered approach that regulation will use is shown in the following figure

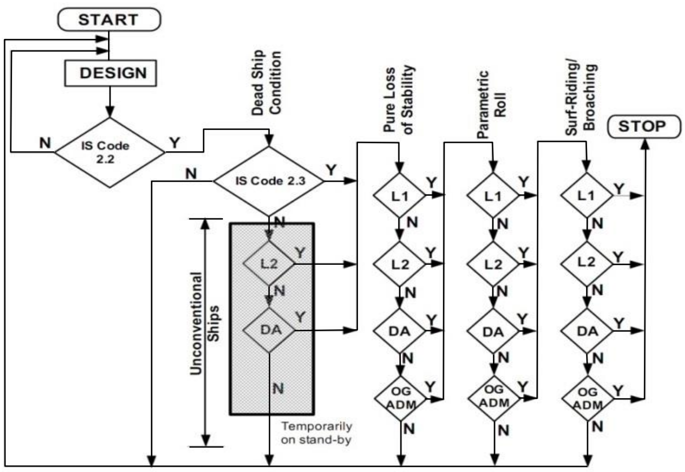



Figure 3.1 Multi-Tiered Approach for the Second Generation Intact Stability Criteria [7]

<u>Level 1</u> check requires simple calculations in order to detect apparent vulnerabilities and its concept is highly conservative in an effort to ensure that a vessel does not have the danger of capsizing in waves in any case. For instance it is widely understood that bulk carriers or VLCC vessels do not comfort problems with restoring arm variation in waves, due to their hull form design. However a

such type ship will pass easily level 1 check for pure loss of stability and parametric rolling in contrast with a container vessel or a fine-designed RoRo ship.

Level 2 , on the other hand, check requires quite complex calculations which include the numerical solution of high order algebraic equations or numerical solution of non-linear ordinary differential equations, or even numerical solution of integral equations. They are also based on a risk assessment procedure in order to include the probability of capsize in a proven dangerous sea-state condition. The wave cases on which calculation are based are those of IACS wave scatter diagram of North Atlantic at winter that correspond to the most adverse weather conditions, and as a result will be connected with an unrestricted operation.

Table 3.1 IACS North Atlantic's wave statistics at winter [50]

| | Tz (s) = average zero up-crossing wave period Number of occurrences 100.000 | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $H_S$ (m) | **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** | 1.3 | 133.7 | 865.6 | 1186.0 | 634.2 | 186.3 | 36.9 | 5.6 | 0.7 | 0.1 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| **1.5** | 0.0 | 29.3 | 986.0 | 4976.0 | 7738.0 | 5569.7 | 2375.7 | 703.5 | 160.7 | 30.5 | 5.1 | 0.8 | 0.1 | 0.0 | 0.0 | 0.0 |
| **2.5** | 0.0 | 2.2 | 197.5 | 2158.8 | 6230.0 | 7449.5 | 4860.4 | 2066.0 | 644.5 | 160.2 | 33.7 | 6.3 | 1.1 | 0.2 | 0.0 | 0.0 |
| **3.5** | 0.0 | 0.2 | 34.9 | 695.5 | 3226.5 | 5675.0 | 5099.1 | 2838.0 | 1114.1 | 337.7 | 84.3 | 18.2 | 3.5 | 0.6 | 0.1 | 0.0 |
| **4.5** | 0.0 | 0.0 | 6.0 | 196.1 | 1354.3 | 3288.5 | 3857.5 | 2685.5 | 1275.2 | 455.1 | 130.9 | 31.9 | 6.9 | 1.3 | 0.2 | 0.0 |
| **5.5** | 0.0 | 0.0 | 1.0 | 51.0 | 498.4 | 1602.9 | 2372.7 | 2008.3 | 1126.0 | 463.6 | 150.9 | 41.0 | 9.7 | 2.1 | 0.4 | 0.1 |
| **6.5** | 0.0 | 0.0 | 0.2 | 12.6 | 167.0 | 690.3 | 1257.9 | 1268.6 | 825.9 | 386.8 | 140.8 | 42.2 | 10.9 | 2.5 | 0.5 | 0.1 |
| **7.5** | 0.0 | 0.0 | 0.0 | 3.0 | 52.1 | 270.1 | 594.4 | 703.2 | 524.9 | 276.7 | 111.7 | 36.7 | 10.2 | 2.5 | 0.6 | 0.1 |
| **8.5** | 0.0 | 0.0 | 0.0 | 0.7 | 15.4 | 97.9 | 255.9 | 350.6 | 296.9 | 174.6 | 77.6 | 27.7 | 8.4 | 2.2 | 0.5 | 0.1li |
| **9.5** | 0.0 | 0.0 | 0.0 | 0.2 | 4.3 | 33.2 | 101.9 | 159.9 | 152.2 | 99.2 | 48.3 | 18.7 | 6.1 | 1.7 | 0.4 | 0.1 |
| **10.5** | 0.0 | 0.0 | 0.0 | 0.0 | 1.2 | 10.7 | 37.9 | 67.5 | 71.7 | 51.5 | 27.3 | 11.4 | 4.0 | 1.2 | 0.3 | 0.0 |
| **11.5** | 0.0 | 0.0 | 0.0 | 0.0 | 0.3 | 3.3 | 13.3 | 26.6 | 31.4 | 24.7 | 14.2 | 6.4 | 2.4 | 0.7 | 0.2 | 0.0 |
| **12.5** | 0.0 | 0.0 | 0.0 | 0.0 | 0.1 | 1.0 | 4.4 | 9.9 | 12.8 | 11.0 | 6.8 | 3.3 | 1.3 | 0.4 | 0.1 | 0.0 |
| **13.5** | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.3 | 1.4 | 3.5 | 5.0 | 4.6 | 3.1 | 1.6 | 0.7 | 0.2 | 0.1 | 0.0 |
| **14.5** | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.1 | 0.4 | 1.2 | 1.8 | 1.8 | 1.3 | 0.7 | 0.3 | 0.1 | 0.0 | 0.0 |
| **15.5** | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.1 | 0.4 | 0.6 | 0.7 | 0.5 | 0.3 | 0.1 | 0.1 | 0.0 | 0.0 |
| **16.5** | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.1 | 0.2 | 0.2 | 0.2 | 0.1 | 0.1 | 0.0 | 0.0 | 0.0 |

Level 3 ,finally will probably include state of the art computational fluid dynamics methodologies and/or experimental procedures in order predict a vessel's vulnerability for capsize. However many methods and numerical codes may occur, and the issue that arises is how the compatibility between them will be verified.

Generally, It should be mentioned that the concept of the criteria is based on the assumption that a more detailed analysis is carried out on every next level so the difficulty of passing is being reduced as the level is increasing.

# Chapter 4 – RoRo Ships

## 4.1 GENERAL INFO

The modern ro-ro ship can trace its origin to the early days of the steam train more than one hundred years ago. Specially designed ships were introduced in order to carry trains across rivers. An example is the Firth of Forth ferry that began operations in 1851 in Scotland. RoRo concept was extensively used during Second War World, due to the need of fast transportation of caterpillar track vehicles. A lot of cargo ships were converted, so doors and ramps were added. The idea of applying ro-ro principle to merchant shipping became practicable after the Second War World when technological developments on land boosted the number of vehicles, namely trucks and private cars. [47] The first original RoRo passenger ships were introduced around 1957 on European short-sea ferry routes. They were designed to carry vehicles containers and passengers, gaining popularity very soon, as they offered a number of advantages over the other types of vessels, with the most significant being the speed of loading and discharging procedures, as by that time cars and trucks had to be loaded on ships by the use of cranes.

RoRo Ship is today one of the most successful type of ship. The worldwide fleet can be divided into several categories. The two major ones concern passenger ships (RoRo Passenger/RoPax) intended to carrying private cars, trucks on 1 until 3 ro-ro decks, as well as a large or a limited number of passengers usually on short voyage, and cargo ships (RoRo Cargo) intended to carrying road trailers, cars and sometimes containers on 2 until 4 ro-ro decks as well as until 12 passengers (as cargo ships) on short or long voyages

RoPax ships can also be divided into categories as far as size is concerned as follow

- Small: $70<L_{BP}<100$
- Handysize: $80<L_{BP}<140$
- Medium: $80<L_{BP}<170$
- Large: $170<L_{BP}<210$

- Conventional ferries: $0.2<Fn<0.3$
- Conventional fast displacement ferries: $0.3<Fn<0.4$


Figure 4.1 Typical RoPax ships (source: Deltamarin)

On the other hand RoRo cargo ships can be divided into two major categories as far as size is concerned

- Small: $110<L_{BP}<150$ (3 ro-ro decks/ lower hold, main deck, weather deck)
- Large: $150<L_{BP}<210$ (3 to 4 ro-ro decks/ lower hold, main & upper decks, weather deck)

Speeds and Froude numbers are not varying and both medium and large ships sails at around 19 to 22 kn while the large vessels until 24 kn, where the Froude number is around 0.28


Figure 4.2 Typical large RoRo cargo ships (source: Knud E. Hansen)

**4.2 RO-RO SHIP DESIGN**

The first RoRo passenger ships in Europe were designed to carry a limited number of passengers and were equipped with a small sized accommodation superstructure. The hulls were designed based on well-known hull form series such as series 60, BSRA, SSPA and later Formdata [45] based on which the cargo ships were designed, with the difference that the aft body of the ship was different because of the introduction of the transom stern, whereas the stern frames below the transom had the well-known V-type form. The same trends in European ferry design were continued at 70s and 80s but on the bow part of the ship the bulbous bow was gradually introduced. The $C_B$ values were not fixed till 90s and varied form extremely small values such as 0.54 to extremely high such as 0.68, while speed did not overcome 20 kn for the majority of vessels. By the mid-80s, the V-type stern had been replaced by the well-known barge type stern that permits more cargo accommodation.

The benchmark period of RoRo design in Europe was not to begin till mid-90s, when the development of the fast high displacement ferries started. This ships are conventional vessels able to sail at high froude number above 0.32 and even near to 0.40. It was then, when hull forms changed radically, L/B ratio was fixed between 6.0 and 7.0, $C_B$ between 0.52 and 0.60, the tunnel-type frames below the barge type sterns, the 'ducktail' at stern and the 'goose-neck' bulb were implemented. In addition the developments on containership-design were implemented on RoRo ships too, so large flares occurred for the better occupancy of vessel's breadth on the whole vessel's length. The first fast high displacement ferry was routed between Greece (Patras) and Italy (Ancona) in 1995 and the trip was reduced from 33 to 21 hours. The vessel had an L/B ratio equal to 6.5, Froude number equal to 0.352 (V=27 Kn), and the installed power was 31670 kW. It should be mentioned that the first fast high displacement ferry in Europe was 'Finnjet' in 1977 a ship that sailed at 31 kn (Fn=0.36), the installed power was 55000 kW. Her hull had not the characteristics analyzed before, so the increased resistance, along with the small propeller efficiency and the increased fuel consumption of the gas-turbines on which propulsion was based, led the company to withdraw the ship. Until 2005 all the ferries designed in Europe could be listed as fast type, However, until nowadays speeds are being gradually reduced and vessels with moderate speeds around 20-23 kn are designed, although the hull form characteristics have not changed since 90s

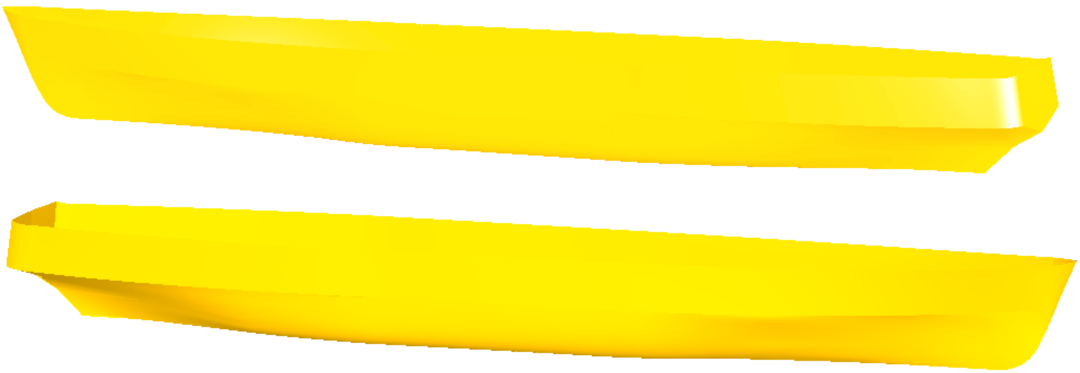


Figure 4.3 The hull of a RoPax ship designed in Europe in 1965
(absence of bulb and bow flare, V-type stern, $LCB/L_{WL}$=0.438)

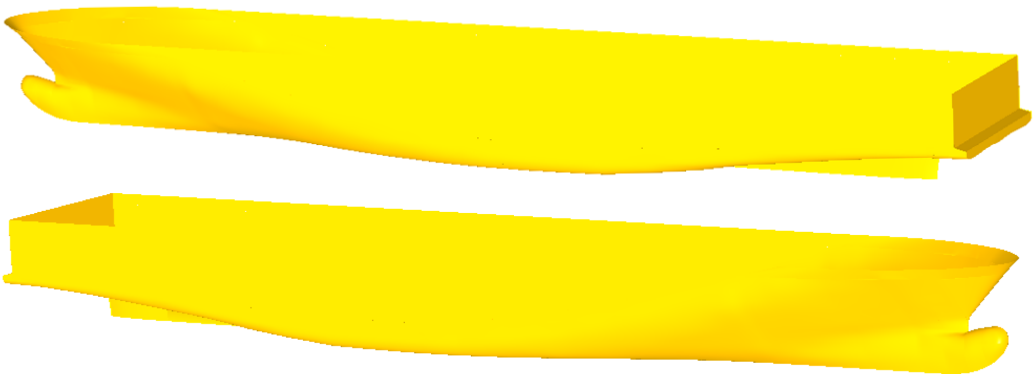


Figure 4.4 The hull of a RoPax ship designed in Europe in 2000
(large flare, goose-neck bulb, tunnel-type frames at stern, barge type stern, ducktail
$LCB/L_{WL}$=0.436)

On the other side, the country that pioneered in designing and routing RoRo ships on national sea network was Japan. Japanese naval architects seem to have achieved very soon, even from the middle of 60s, to design RoRo ships with hulls that performed large B/d ratio with very low $C_B$ values around 0.50, round bilge forms, very high froude numbers and good behavior at swell systems of Japanese archipelago and Pacific ocean. The hull forms did not change to a large extent until nowadays and the hull characteristics that have been adopted in Europe did not implemented in Japan. It should be mentioned that the first fast displacement ferries in the world were the sister vessels 'Takachiho' and 'Mimitsu Maru'. They were designed in Japan in 1970 and performed an L/B ratio equal to 7.56, froude number equal to 0.347 and the installed power was 26480 KW.

### 4.3 DYNAMIC STABILITY OF RO-RO SHIPS

The development of RoRo ships at late 90's where the hull forms acquired characteristics similar to those of the containerships, coincided with the implementation of well-known strict damage stability criteria of SOLAS 90 and Stockholm agreement, as a result of the catastrophic accidents that took place in Europe until 1994, so on the one hand RoPax ships became more prone to dynamic stability failures in waves such as parametric roll and pure loss of stability, due to the introduction of the new hull forms, but on the other hand, the strict damage stability regulations required high GM values, and as a result the safety against intact stability failures was improved to a considerable extent.

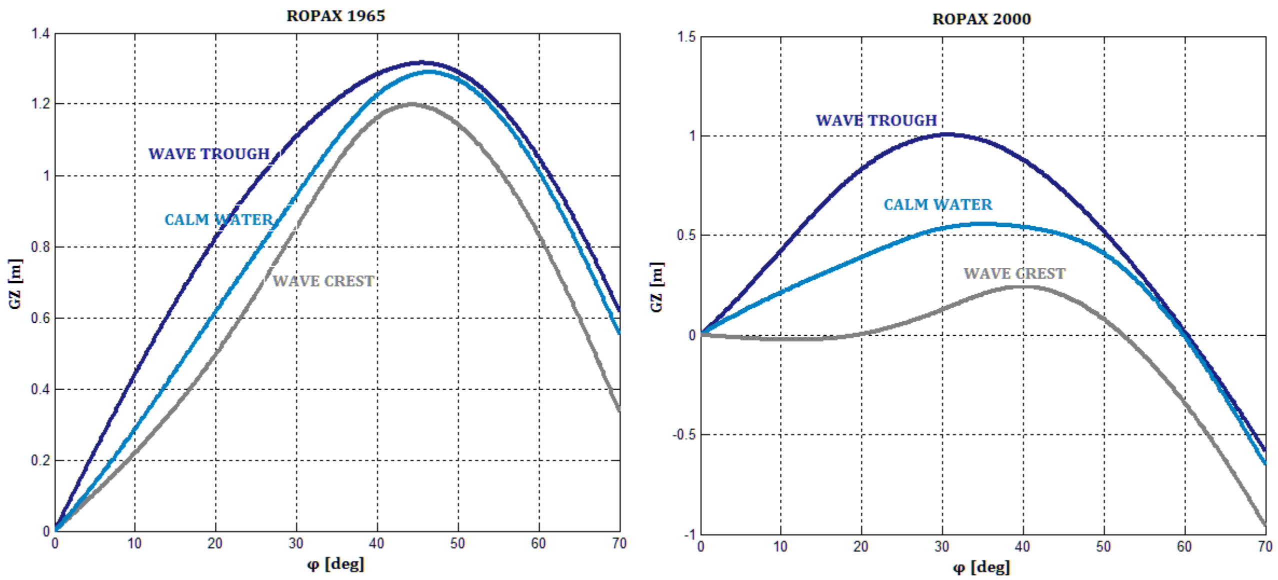



Figure 4.5 Comparison of GZ in waves, for the same vessel's characteristics ($L_{BP}$=128 m B=21 m, GM around 1.5 m) indicating the trend for parametric rolling

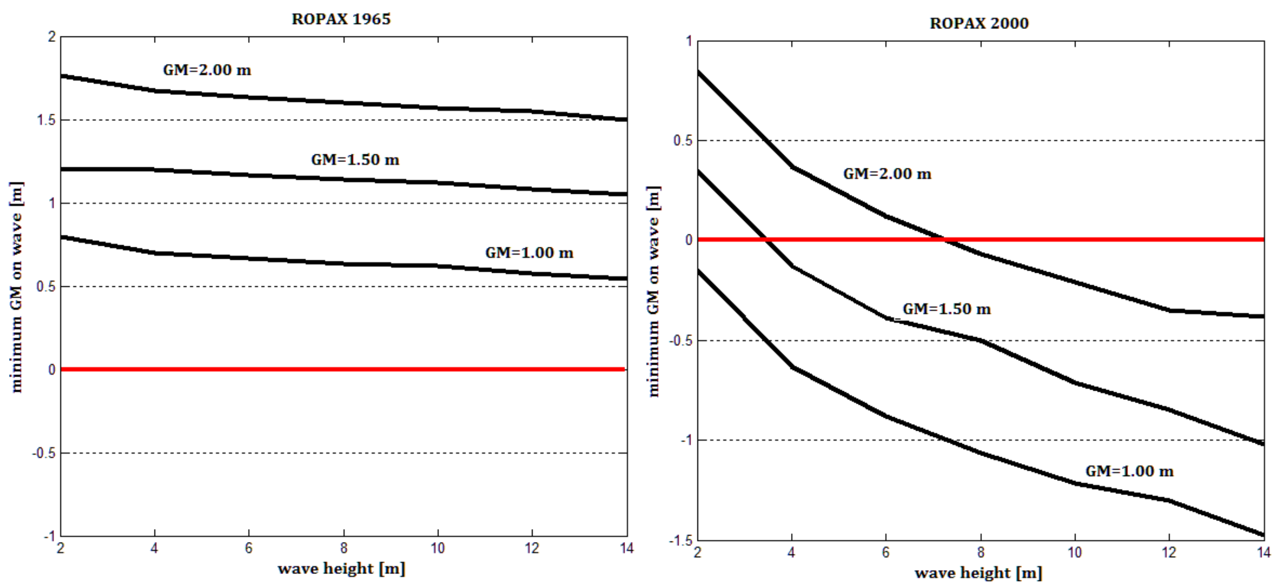



Figure 4.6 Comparison of minimum GM in waves, for the same vessel's characteristics for $\lambda=L_{BP}$ $H/\lambda=0.0334$ and various initial GM values, indicating the trend for pure loss of stability

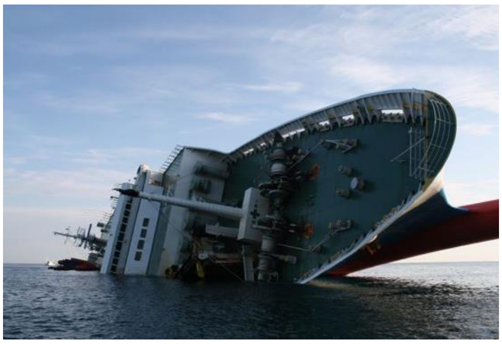
We can observe that the two hull forms have very different dynamic stability characteristics. The hull of 1965 shows insignificant GZ alternations in waves and is not probably prone to parametric roll resonance. Furthermore pure loss of stability failure has never occurred even for high wave heights and low GM values. On the other hand the hull of 2000 is very prone to both parametric roll and pure loss of stability. In fact, the problem is more intense when the initial GM value is low. The modern RoPax ships operate on high GM values due to damage stability restrictions. However, the requirements of damage stability and the requirements for safety against intact stability failures in waves seem to coincide. On the other hand, RoRo Cargo ships on which two-compartment and water on deck requirements are not implemented, operate on lower GM values than passenger ships and only the weather criterion governs their design, so this ships seem to be even more prone to dynamic stability failures.

The weather criterion was an effort to improve the safety of vessels under the action of a wind gust and synchronous rolling from waves a well-known problem that concerns the behavior of vessels with large superstructures exposed to wind such as ro-ro ships at beam seas. On some large RoPax and cruise ships the design is mainly governed by the weather criterion, especially on light drafts and not by damage stability, so the weather criterion that requires high GM values too is also setting a safety margin against dynamic stability failures.

Finally, it should be mentioned that although accidents with RoRo ships related to intact stability failures in waves have been reported, and many of them are sadly connected with a lot of fatalities, intact stability aspects have never been dealt with the same strictness as damage stability maybe due to the complex nature of dynamic stability problems.

# Chapter 5 – Accidents of Ro-Ro Ships Related to Stability Failures in Waves

## 5.1 CAPSIZE OF 'ARIAKE' (photo taken from [24])



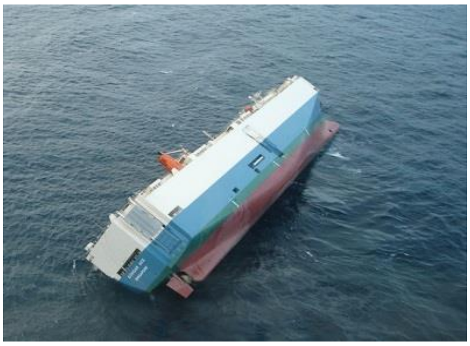
'Ariake' was a Japanese 4292 DWT and 150 meters ($L_{BP}$), RoRo/Container Passenger ship built in 1995, which capsized in south east of Kiho town in Japan on 13 November 2009**.** The ship was loaded with 150 containers, while 7 passengers and 20 crew members were on board. She was sailing in stern-quartering sea with waves of a length approximately equal to the ship's length, a period of about 10 sec and a significant wave height of about 4.6 m, individual waves were estimated to had a height of 6.9 m (1.5 the significant wave height). According to Japan transport safety board the ship listed of about $25^{o}$, to starboard when she encountered a wave of 7 meters high on the port stern from about 40 deg. The list caused cargo shifting and an even larger list developed when the vessel encountered a second wave of the same characteristics. *Passengers and crew members were rescued* and the vessel eventually grounded and fell on its side in the near shore after drifting on beam seas. According to investigations the ship was probably sailing in the dangerous zone of successive high wave attack in stern quartering seas of IMO Guidance MSC.1/Circ.1228 for avoiding dangerous situations in adverse weather conditions. It is worth to be mentioned that neither the master nor the officers had knowledge of the dangerous zone and the master thought that the ship would not be greatly influenced by stern-quartering seas because he had not experienced a significant roll motion.

## 5.2 CAPSIZE OF 'RIVERDANCE' (photo taken from [53])

'Riverdance' was a 3000 DWT and 103 meters ($L_{BP}$) RoRo Cargo ship built in 1977, which capsized near Blackpool at Lancashire in the U.K on 31 January 2008. She was loaded with semi-trailers. The weather was adverse with winds 9 to 10 Beaufort, significant wave height was approximately 7 m. The ship was operated with a small GM value near to 0.8 m, a value which is typical for some RoRo Cargo ships on the other hand. As she was sailing in following seas a heavy list was experienced and cargo shifting followed. The ship grounded in shore while *passengers and crew members were all rescued*. Accident's investigation [22] showed that pure loss of stability phenomenon was probably liable for vessel's capsize because negative GM was arisen as a wave passed the ship, and the speed of the vessel was slightly slower than waves velocity. It was revealed that master was unaware about IMO Guidance MSC.1/Circ.1228

### 5.3 CAPSIZE OF 'COUGAR ACE' (photo taken from [52])

'Cougar Ace' was a Singapore flagged 190 meter ($L_{BP}$) pure car carrier vessel built in 1993, which



capsized on 24 July 2006 in the Pacific Ocean as she was in route from Japan to Vancouver loaded with 4812 vehicles. It is known that the crew were running a ballast operation during which the ship developed list which reached 60 deg. Due to her tight superstructure the vessel remained afloat with a massive heel angle. *All crew members were rescued, although economic damage is estimated at about $117 million.* The sea state was characterized by swell-systems of long crested waves with period between 9 and 11 sec periods which related with wave lengths from 130 to 180 metres. The significant wave height was about 3-4 metres. It is estimated according to weather that the vessel was travelling in following or stern quartering seas at the time of the accident, with a speed of about 18.6 kn. The most probable explanation for the accident is the scenario of completely stability loss on the wave crest during ballast water operation. [36] The vessel had departed from Japan with a GM value of about 2.00 m near to the intact stability limit in order to barely comply with the weather criterion. During ballast operation GM value was reduced, with result the total stability loss on wave crest.

### 5.4 CAPSIZE OF 'FINNBIRCH' (photo taken from [20])

'Finnbirch' was a 8500 DWT and 137 meters ($L_{BP}$) typical RoRo Cargo ship which capsized in Baltic

Sea on 1 November 2006 during a trip from Helsinki (Finland) to Arhus (Denmark). In her last voyage Finnbirch was loaded with semi-trailers and a consignment of block stowed paper reels. The weather was hard with winds at 20 m/s and gusts up to 26-29 m/s. Significant wave height was approximately 4 m with a dominant period of 6.7 sec. Individual waves can therefore had reached a height of approximately 7-8 m. The ship was sailing at a speed of 17.5-18.5 kn in following seas. Investigation [20] revealed that the accident occurred due to complete loss of stability on the wave crest. The vessel heeled heavily which resulted in cargo shift deteriorating further her condition until she finally capsized after drifting for some time in beam seas. From the 14-member crew *2 were fatally injured* and 12 survived. Investigation after the sinking revealed also, the fact that the master was not informed about the dangers that may occur to a ship in following seas and was not also informed about IMO Guidance MSC.1/Circ.1228. The ship had been designed in order to load trailers on three decks, although a major conversion took place in order one extra trailer deck to be added. However, the addition of sponsons was inevitable for the vessel's compliance with intact (weather criterion) and damage stability regulations. Obviously the addition of sponsons made the vessel more susceptible to righting level alternations.

## 5.5 CAPSIZE OF ZAKYNTHOS AND CHRISSI AVGI

Two very similar accidents took place in Greece in 23 February 1983 'Chrissi Avgi' ($L_{OA}$=58 m) between Rafina (Athens) and the island of Andros with *28 fatalities* and in 28 December 1989 'Zakynthos' ($L_{OA}$=87 m) between Kyllini (Peloponese) and the island of Zakynthos, with *1 fatality* The sequence of events was exactly the same in both cases as follows. A small RoPax ship was travelling under harsh weather, loaded with tank oil trucks as RoRo cargo ship, a day when passenger ship's sailing had been prohibited due to harsh weather conditions according to national legislation. Nevertheless truck drivers were on board. A large heel angle suddenly occurred and shifting of trucks on the one side of the car deck followed. After a short period of time an explosion took place leading to the vessel's capsizing and eventually sinking. However, pure loss of stability or broaching-to phenomenon may be the cause of capsize in both cases


Photo: P. Lelekis (Taken from factaomfartyg.se)

## 5.6 OTHER MAJOR FERRY DISASTERS

Many other major accidents have occurred in the so called under-development countries where unworthy to sail vessels are in service, overloaded in the most cases. Obviously none international regulation is in force in those countries so when an accident happens it is never being reported or investigated, despite its tragic nature.

The most typical example is the sea transports in Philippines's archipelago where many ferry disasters have occurred during the last decades due to weather conditions, explosions or collisions. All those disasters have led to the loss of thousands of people. In addition ferry disasters have occurred in countries such as Senegal were the ferry *'Le Joola'* sunk under harsh weather condition on 26 of Sept. 2002 with a loss of nearly 2000 people, or Zanzibar where the open-type ferry *'Spice islander 1'* sunk on 10 of Sept. 2011 after the loss of her power as she was sailing, overloaded with around 500 passengers in a storm. From people onboard around 150 were lost. 'Spice Islander 1' was an open ferry constructed in Greece in 1967 and had been operating until 2002 with the name 'Apostolos' in the sheltered area of Saronic gulf focused on the transport of cars and a limited number of passengers. Despite that the vessel ended up operating in the Indian ocean.

It is evident that many significant accidents have occurred due to failure relevant to dynamic stability. [26] Although many of them are connected to many victims, the conditions and causes under which those ships capsized is not known. In the following table the majority of accidents occurred due to an intact stability failure in waves are summarized

Table 5.1 Significant accidents that took place due to a dynamic stability failure

| VESSEL'S NAME | TYPE | DATE | PLACE | FATALITIES |
|---|---|---|---|---|
| Spice Islander 1 | Open type RoPax | 09/2011 | Zanzibar | 150 |
| Superferry 9 | RoPax | 05/2009 | Philippines | 10 |
| Ariake | RoPax | 11/2009 | Japan | 0 |
| Riverdance | RoRo Cargo | 01/2008 | U.K | 0 |
| Don Dexter Kathleen | RoPax | 11/2008 | Philippines | 49 |
| Blue Water Princess | RoPax | 07/2007 | Philippines | 100 |
| Mae an | RoPax | 05/2006 | Philippines | 28 |
| Cougar Ace | Pure Car Carrier | 07/2006 | Pacific Ocean | 0 |
| Finnbirch | RoRo Cargo | 11/2006 | Baltic | 2 |
| Le Joola | RoPax | 09/2002 | Senegal | 2000 |
| Jan Heweliusz | RoPax | 01/1993 | Poland | 55 |
| Zakynthos | RoPax | 12/1989 | Greece | 1 |
| Chrissi Avgi | RoPax | 02/1983 | Greece | 28 |
| Tev Wahine | RoPax | 05/1968 | New-Zealand | 52 |

Some other incidents where RoRo or Passenger ships suffered from instabilities in waves have been reported. In those accidents loss of lives did not occur and the ship did not capsize or sunk, In some cases only extensive damages on cargo occurred. The most significant incidents are summarized in the followings

Table 5.2 Incidents that took place due to a dynamic stability failure

| VESSEL'S NAME | TYPE | DATE | PLACE | CAUSES & RESULTS |
|---|---|---|---|---|
| Spirit of Tasmania 2 | RoPax ship | 05/2016 | Tasmanian sea | Giant waves-large heel angles cargo shift and extensive damages on cargo into the car decks |
| Pacific Star | Cruise ship | 07/2008 | New Zealand | Sudden large roll amplitudes (probably parametric roll) |
| Aratere | RoPax ship | 03/2006 | New Zealand | Large waves-heavy roll-cargo shift and extensive damages on vehicles |
| Grand Explorer | Cruise ship | 02/2005 | Mediterranean sea | Waves cracked bridge and the ship lost her power and stopped, large roll amplitudes on head seas at zero speed |

# Chapter 6 – The Examined RoRo Ships

On this thesis five RoRo ships are used for the application and evaluation of second generation intact stability criteria. The first three are RoPax Ships (one medium one handy and one small). The medium and handy one are two fast displacement-type RoPax ships that usually operate in lower than the design speed and the other two are RoRo cargo ships (one medium and one large). On the following tables the basic particulars are shown as well as the loading conditions to which criteria are applied. For the medium and handy RoPax ships the criteria are applied on the three loading conditions based on drafts used in SOLAS 2009 damage stability calculations. For the two RoRo cargo ships the criteria are applied on full load arrival condition

## 6.1 RO-RO PASSENGER SHIPS

### RoPax 160

Figure 6.1: Render views of the hull-form of RoPax 160

Table 6.1 : Basic particulars of RoPax 160

| | | | |
|---|---|---|---|
| $L_{OA}$ | 174.8 m | Lightship | 10127 tons |
| $L_{BP}$ | 157.6 m | DWT at design $T_{DESIGN}$ | 4695 tons |
| B (moulded) | 25.2 m | $C_B$ | 0.568 |
| D (to main deck) | 9.1 m | $C_M$ | 0.935 |
| D (to upper deck) | 14.6 m | $V_{S\ \text{USUAL OPERATIONAL SPEED}}$ | 21 kn |
| $T_{DESIGN}$ | 6.4 m | $V_{MAX\ \text{DESIGNED SPEED}}$ | 26 kn |
| Trailers Lanes m. | 1800 m | lBK/$L_{BP}$ (bilge keel length to $L_{BP}$) | 0.30 |
| Pass. (Summer) | 1650 persons | bBK/B (bilge Keel breadth to B) | 0.0159 (0.4 m) |

Three loading conditions selected, based on drafts required from SOLAS 2009 damage stability regulations dp= dl+0.6 (ds-dl)

Table 6.2 : RoPax 160, Basic particulars of the examined loadcases

| **Loadcase** | **(DS) Deepest Draft Full Load Departure** | **(DP) Partial Draft Full Load Arrival** | **(DL) Lightest Draft Ballast Arrival** |
|---|---|---|---|
| Displacement [tons] | 14822 | 13690 | 11159.3 |
| Draft [m] | 6.5 | 6.05 | 5.30 |
| Trim [m] | -0.15 | 0.25 | 0.39 |
| GM [m] | 2.077 | 1.624 | 2.801 |
| KG (FSM) [m] | 11.491 | 12.105 | 11.423 |
| Roll Period [sec] | 13.685 | 15.806 | 12.444 |
| Flooding Angle [deg] | 41.8 | 43.6 | 47.6 |
| Windage Area [m$^2$] | 3683 | 3746 | 3868 |
| $Z_{WINDAGE}$ [m] | 14.97 | 14.97 | 14.99 |

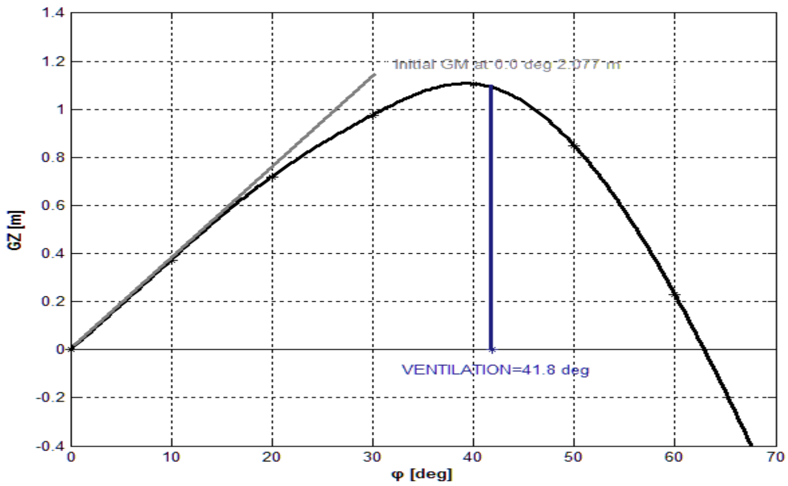



Figure 6.2 : RoPax 160, GZ curve for DS

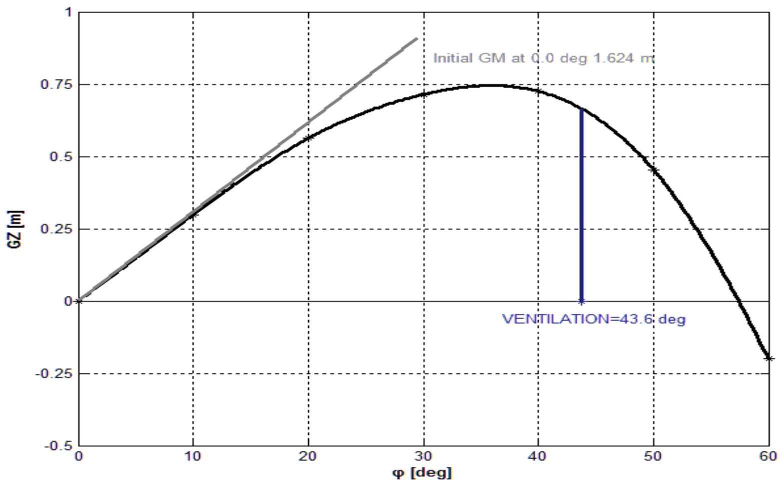



Figure 6.3 : RoPax 160, GZ curve for DP

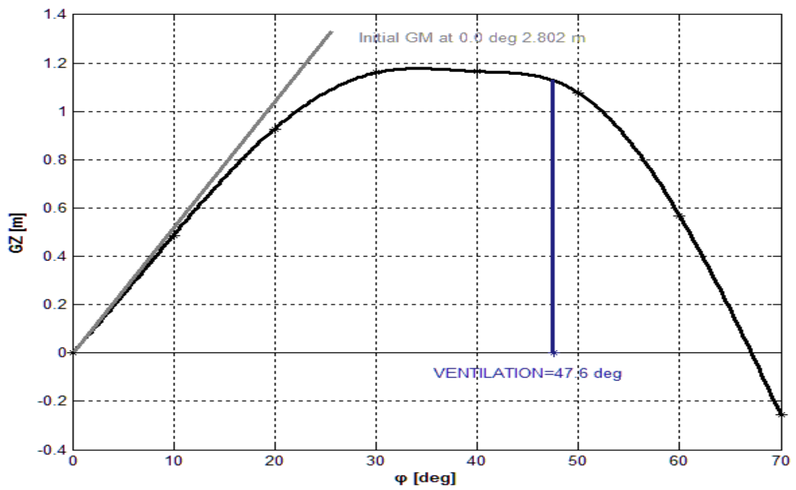



Figure 6.4 : RoPax 160, GZ curve for DL

**RoPax 110**

Figure 6.5: Render views of the hull-form of RoPax 110

Table 6.3 : Basic Particulars of RoPax 110

| | | | |
|---|---|---|---|
| $L_{OA}$ | 124 m | Lightship | 4597 tons |
| $L_{BP}$ | 108.6 m | DWT at design $T_{DESIGN}$ | 1281 tons |
| B (moulded) | 18.4 m | $C_B$ | 0.58 |
| D (to main deck) | 7.05 m | $C_M$ | 0.962 |
| D (to upper deck) | 12.05 m | $V_S$ | 21 kn |
| $T_{DESIGN}$ | 4.90 m | $V_{MAX}$ | 23 kn |
| Trailers Lanes m. | 350 m | lBK/$L_{BP}$ (bilge keel length to $L_{BP}$) | 0.25 |
| Pass. (Summer) | 1200 persons | bBK/B (bilge Keel breadth to B) | 0.0218(b=0.4 m) |

Three loading conditions selected based on drafts required from SOLAS 2009 damage stability regulations

Table 6.4 : RoPax 110, Basic particulars of the examined loadcases

| **Loadcase** | **(DS) Deepest Draft Full Load Departure** | **(DP) Partial Draft Full Load Arrival** | **(DL) Lightest Draft Ballast Arrival** |
|---|---|---|---|
| Displacement [tons] | 6264 | 5849 | 5280 |
| Draft [m] | 5.10 | 4.87 | 4.53 |
| Trim [m] | -0.08 | 0.32 | 0.31 |
| GM [m] | 1.904 | 1.834 | 2.304 |
| KG (FSM) [m] | 8.433 | 8.69 | 8.076 |
| Roll Period [sec] | 10.80 | 11.11 | 10.12 |
| Flooding Angle [deg] | 46.8 | 48.6 | 50 |
| Windage Area [m²] | 1795 | 1816 | 1854 |
| $Z_{WINDAGE}$ [m] | 10.84 | 10.83 | 10.83 |

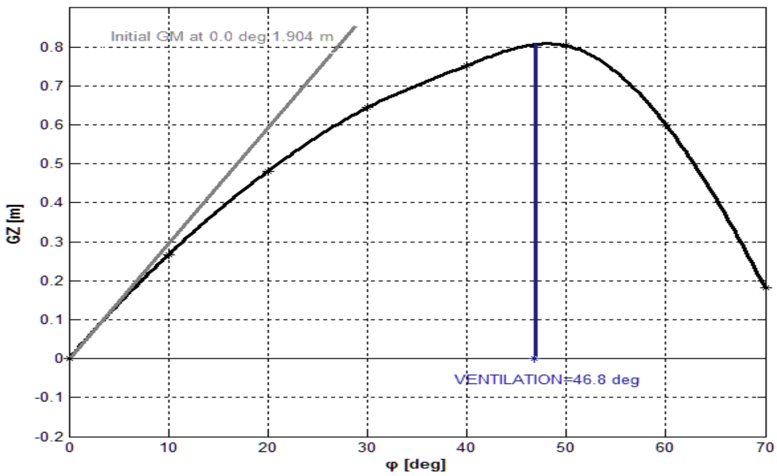



Figure 6.6 : RoPax 110, GZ curve for DS

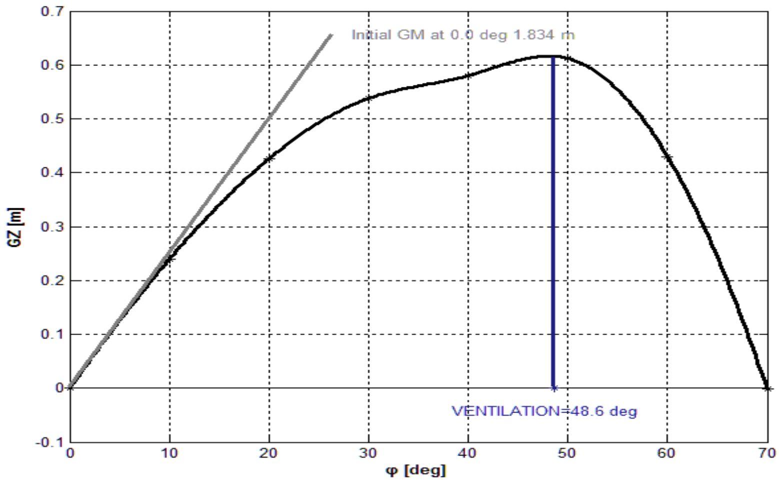



Figure 6.7 : RoPax 110, GZ curve for DP

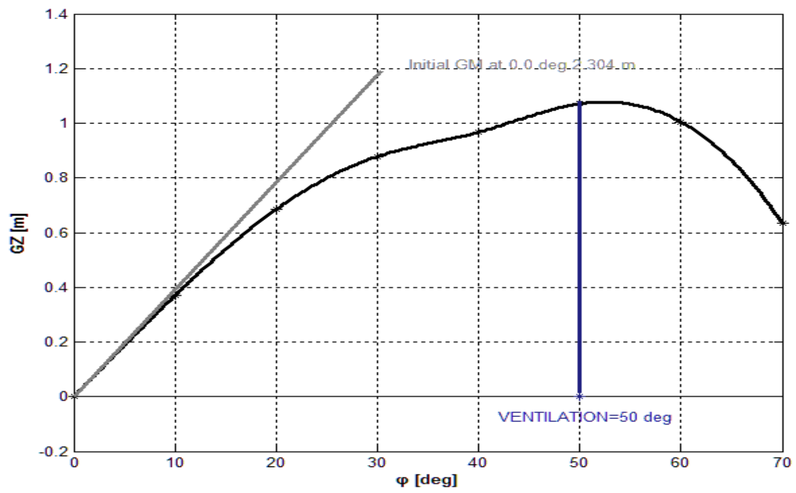



Figure 6.8 : RoPax 110, GZ curve for DL

**RoPax 75**

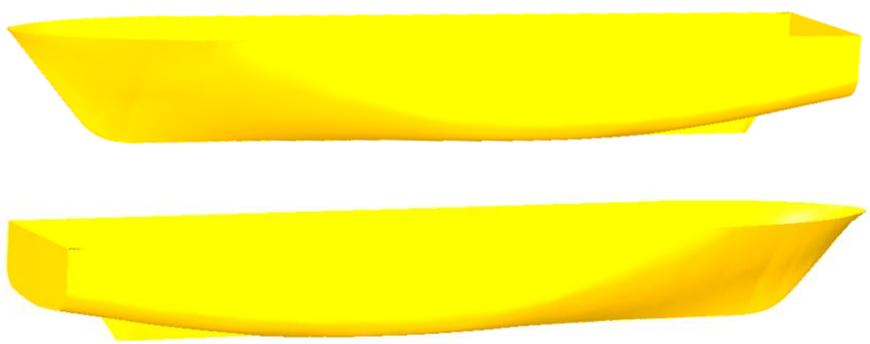


Figure 6.9: Render views of the hull-form of RoPax 75

Table 6.5 : Basic particulars of RoPax 75

| | | | |
|---|---|---|---|
| $L_{OA}$ | 84.20 m | Pass. (Summer) | 550 persons |
| $L_{BP}$ | 74.20 m | $C_B$ | 0.568 |
| B (moulded) | 14.4 m | $C_M$ | 0.884 |
| D (to main deck) | 5.8 m | $V_S$ | 15 kn |
| D (to upper deck) | 10.8 m | $V_{MAX}$ | 18 kn |
| $T_{DESIGN}$ | 4.00 m | $lBK/L_{BP}$ (Bilge keel length to $L_{BP}$) | 0.3 |
| Trailers Lanes m. | 250 m | bBK/B (Bilge Keel Breadth to B) | 0.027 (0.4 m) |

Table 6.6 : RoPax 75, Basic particulars of the examined loadcases

| **Loadcase** | **(DS) Deepest Draft / Full Load Departure** |
|---|---|
| Displacement [tons] | 2705 |
| Draft [m] | 4.25 |
| Trim [m] | -0.35 |
| GM [m] | 1.57 |
| KG (FSM) [m] | 6.36 |
| Roll Period [sec] | 9.57 |
| Flooding Angle [deg] | 42.3 |
| Windage Area [m²] | 920 |
| $Z_{WINDAGE}$ [m] | 8.08 |

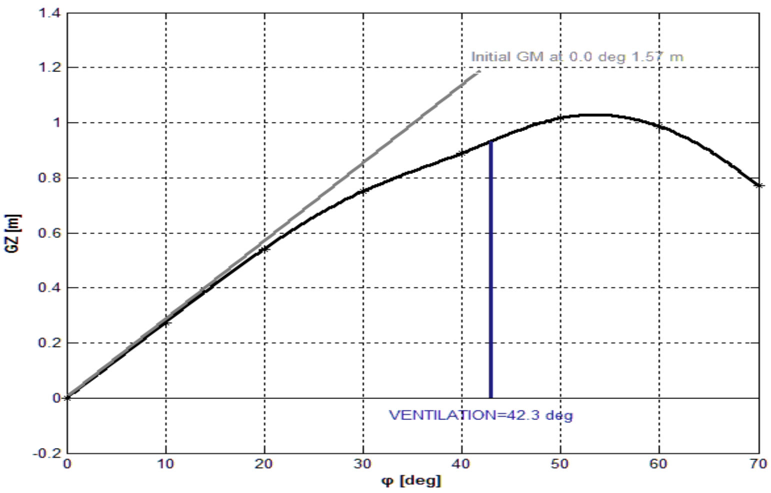



Figure 6.10 : RoPax 75, GZ curve for DS

## 6.2 RO-RO CARGO SHIPS

### RoRo 180

Table 6.7 : Basic particulars of RoRo 180

| | | | |
|---|---|---|---|
| $L_{OA}$ | 185 m | Pass. | 12 persons |
| $L_{BP}$ | 179.4 m | $C_B$ | 0.578 |
| B (moulded) | 25.6 m | $C_M$ | 0.920 |
| D (to main deck) | 8.5 m | $V_S$ | 21 kn |
| D (to upper deck) | 16.6 m | $V_{MAX}$ | 24 kn |
| $T_{DESIGN}$ | 6.4 m | $lBK/L_{BP}$ (Bilge keel length to $L_{BP}$) | 0.30 |
| Trailers Lanes m. | 3900 m | bBK/B (Bilge Keel Breadth to B) | 0.0156 (0.4 m) |

Table 6.8 : RoRo 180, Basic particulars of the examined loadcases

| **Loadcase** | **(FLD) Full Load Departure** | **(FLA) Full Load Arrival** | **(BD) Ballast Departure** |
|---|---|---|---|
| Displacement [tons] | 19890 | 19408 | 14005 |
| Draft [m] | 7.00 | 6.87 | 5.4 |
| Trim [m] | 0.05 | 0.24 | 0.26 |
| GM [m] | 0.716 | 0.742 | 3.931 |
| KG (FSM) [m] | 12.245 | 12.3 | 9.550 |
| Roll Period [sec] | 22.95 | 22.63 | 10.47 |
| Flooding Angle [deg] | 50 | 51.9 | 60 |
| Windage Area [$m^2$] | 3790 | 3817 | 4026 |
| $Z_{WINDAGE}$ [m] | 14.30 | 14.30 | 14.71 |

**RoRo 130**

Table 6.9 : Basic particulars of RoRo 130

| | | | |
|---|---|---|---|
| $L_{OA}$ | 140 m | Pass. | 12 persons |
| $L_{BP}$ | 132.6 m | $C_B$ | 0.578 |
| B (moulded) | 23.2 m | $C_M$ | 0.920 |
| D (to main deck) | 8.00 m | $V_S$ | 19 kn |
| D (to upper deck) | 15.6 m | $V_{MAX}$ | 21 kn |
| $T_{DESIGN}$ | 6.20 m | $l_{BK}/L_{BP}$ (Bilge keel length to $L_{BP}$) | 0.25 |
| Trailers Lanes m. | 1600 m | $b_{BK}/B$ (Bilge Keel Breadth to B) | 0.017 |

Table 6.10 : RoRo 130, Basic particulars of the examined loadcases

| **Loadcase** | **(FLD)** **Full Load Departure** | **(FLA)** **Full Load Arrival** | **(BD)** **Ballast Departure** |
|---|---|---|---|
| Displacement [tons] | 12420 | 12115 | 8450 |
| Draft [m] | 6.5 | 6.4 | 4.87 |
| Trim [m] | 0.05 | 0.26 | 0.32 |
| GM [m] | 0.808 | 0.764 | 3.756 |
| KG (FSM) [m] | 10.85 | 10.93 | 8.40 |
| Roll Period [sec] | 21.46 | 21.14 | 10.20 |
| Flooding Angle [deg] | 42.8 | 43.4 | 45 |
| Windage Area [$m^2$] | 2267 | 2280 | 2310 |
| $Z_{WINDAGE}$ [m] | 12.19 | 12.19 | 12.3 |

# Chapter 7 – Dead Ship Stability

## 7.1 PHYSICAL BACKGROUND

Stability under dead ship codition assuming a ship that has lost its power and has turned into beam seas and she is rolling under the action of waves and drifting under the action of the wind as well as the hudrodynamic reaction cause by the transverse motion of the ship. Then a sudden and long gust of wind occurs

The scenario of stability failure under dead ship condition is decribed in [9] as follow:

1. A ship has lost its power and has turned into beam seas, she is rolling in waves and drifts under the wind
2. A sudden (and long) wind gust has occurred when the ship rolled windward
3. The ship starts to roll back under combined wave and wind action. Velocity of drift and drift reaction start to increase
4. The ship continues to roll leeward, while drift velocity and drift reaction continue to increase, providing additional heeling moment
5. The ship reaches a maximum roll angle on the leeward side. This is most likely the instant for stability failure.

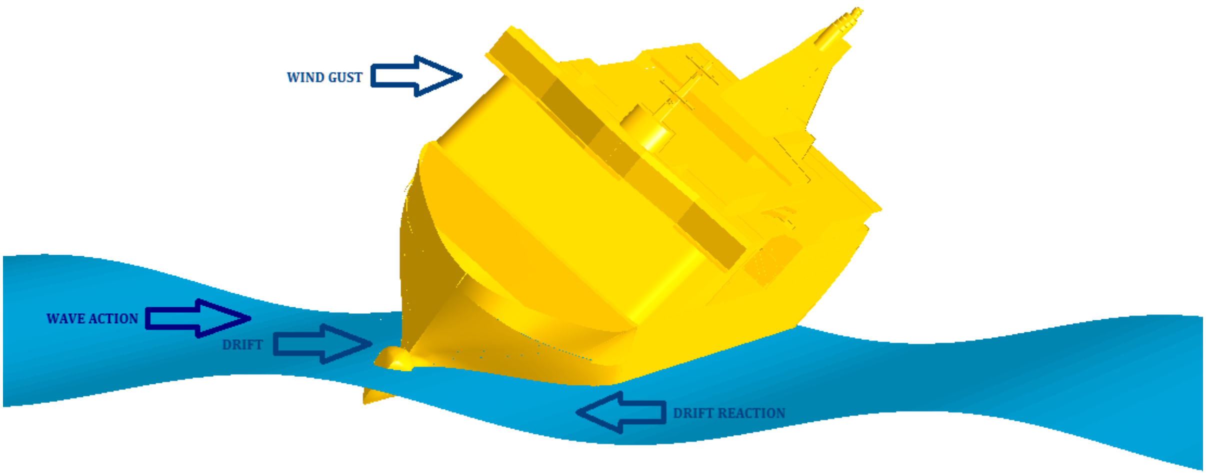



Figure 7.1: Scenario of dead ship stability failure mode

## 7.2 LEVEL 1 VULNERABILITY CRITERION FOR DEAD SHIP CONDITION

According to draft regulation the requirements of the current 'severe wind and rolling criterion' weather criterion) of 2008 IS Code [14], are going to be used for the level 1 vulnerability check, but the wave steepness factor *s* the table 7.1 should be used in lieu of table 2.3.4-4 of the weather criterion

Table 7.1 values of wave steepness factor

| **Rolling Period, *T* (s)** | **Wave steepness factor, *s*** |
|---|---|
| <=6 | 0.100 |
| 7 | 0.098 |
| 8 | 0.093 |
| 12 | 0.065 |
| 14 | 0.053 |
| 16 | 0.044 |
| 18 | 0.038 |
| 20 | 0.032 |
| 22 | 0.028 |
| 24 | 0.025 |
| 26 | 0.023 |
| 28 | 0.021 |
| >=30 | 0.020 |

The formulas of the weather criterion have been developed based on a population of ships having the following parameters

| |
|---|
| B/d < 3.5 |
| -0.3 < (KG/d – 1 ) < 0.5 |
| T < 20 sec |

For ships and loading conditions with parameters outside the above limits a level 2 check or an experimental procedure according to MSC.Circ 1200 will be required.

## 7.3 LEVEL 2 VULNERABILITY CRITERION FOR DEAD SHIP CONDITION

Level 2 vulnerability check for dead ship stability has been proposed by the delegation of Italy and concerns a methodology that takes into account the combined effect of wind and waves in a stochastic environment. However, sea and wind spectra are used, from which the roll spectrum is derived using a simplified linearization approach where nonlinear damping and a derivative of nonlinear GZ curve are used. The probability of capsize is calculated using an analytical formulae that assumes a Gaussian behavior for the roll motion and Poison distribution for the capsize events during a time interval ($T_{exp}$) [9] [10]

The roll motion of the ship under the action of waves and wind can be expressed by the following equation

$$\ddot{\varphi}+2\mu\cdot\dot{\varphi}+\beta\cdot\dot{\varphi}\cdot\left|\dot{\varphi}\right|+\delta\dot{\varphi}^{3}+\frac{\omega_0{}^2}{GM}\cdot GZ(\varphi)=\omega_0{}^2\cdot\left(\frac{\bar{M}_{wind}(t)}{\Delta\cdot GM}+\frac{\bar{M}_{waves}(t)}{\Delta\cdot GM}\right) \qquad (7.1)$$

Where $\mu,\beta,\delta$ are the linear, quadratic and cubic roll damping coefficients respectively that are derived from the fitting procedure of eq.5.2 where $B_{44}$ is the damping coefficient that is obtained from Ikeda simplified method. $M_{wind}$ is total instantaneous moment due to wind and $M_{waves}$ is the total instantaneous moment due to waves.

$$\frac{B_{44}(\phi_a)\cdot\omega_0^2}{2\cdot\Delta\cdot\overline{GM}} \rightarrow \mu+\frac{4}{3\cdot\pi}\cdot\beta\cdot\omega_0\cdot\phi_a+\frac{3}{8}\cdot\delta\cdot\omega_0^2\cdot\phi_a^2 \quad (7.2)$$

The roll equation is replaced by the following equivalent linear equation where m(t) is the total non-dimensional moment due to waves and wind

$$\ddot{x}+2\mu_e(\sigma_{\dot{x}})\cdot\dot{x}+\omega_{0,e}\cdot x=\omega_0{}^2\cdot m(t) \quad (7.3)$$

by introducing the linear roll damping coefficient $\mu_e(\sigma_{\dot{x}})$ that is defined as

$$\mu_e(\sigma_{\dot{x}})=\mu+\sqrt{\frac{2}{\pi}}\cdot\beta\cdot\sigma_{\dot{x}}+\frac{3}{2}\cdot\delta\cdot\sigma_{\dot{x}}{}^2 \quad (7.4)$$

Where $\sigma_{\dot{x}}$ is the standard deviation of roll velocity which is obtained by solving numerically the following integral equation

$$\sigma_{\dot{x}}{}^2-\int_0^{\infty}\frac{\omega^2\cdot\omega_0^4}{\left(\omega_{0,e}^2(\phi_S)-\omega^2\right)^2+\left(2\cdot\left(\mu+\sqrt{\frac{2}{\pi}}\cdot\beta\cdot\sigma_{\dot{x}}+\frac{3}{2}\cdot\delta\cdot\sigma_{\dot{x}}{}^2\right)\cdot\omega\right)^2}\cdot\frac{\left(r(\omega)\cdot\Delta\cdot GM_{res}(\varphi_S)\right)^2\cdot S_{aa}(\omega)+S_{\delta M_{wind,tot}}(\omega)}{\left(\Delta\cdot\overline{GM}\right)^2}d\omega \quad (7.5)$$

as well as the modified roll frequency $\omega_e$ that is taking into account the value of $GM_{res}$ the local $GM$ at $\varphi_s$ that is the angle of equilibrium due to the action of mean wind moment) and is defined as

$$\omega_{o,e}(\varphi_s)=\omega_o\cdot\sqrt{\frac{GM_{res}(\varphi_s)}{GM}} \quad (7.6)$$

Assuming wind and wave moments to be Gaussian processes the total spectrum of the response x can be obtained from eq.5.7 as the sum of non-dimensional wind gust $S_{\delta Mwind,tot}$ and wave slope $S_{aa,c}$ moment spectra as follows

$$S(\omega)=\frac{\omega^4+(2\cdot\mu_e\cdot\omega)^2}{\left(\omega^2{}_{0,e}(\varphi_s)-\omega^2\right)^2+(2\cdot\mu_e\cdot\omega)^2}S_{aa,c}(\omega)+\frac{\omega_0{}^4}{\left(\omega^2{}_{0,e}(\varphi_s)-\omega^2\right)^2+(2\cdot\mu_e\cdot\omega)^2}\frac{S_{\delta M_{wind,tot}}(\omega)}{(\Delta\cdot GM)^2} \quad (7.7)$$

However, the approximate mean value of the roll motion is known and is the angle of equilibrium $\varphi_s$. The spectrum $S(\omega)$ expresses the roll motion around this angle, $x=\varphi-\varphi_s$. The variance of the roll motion is the area under the spectrum $S(\omega)$. There is not any dependence on the roll angle standard deviation due to the fact that equivalent linear frequency $\omega_{0,e}$ have been introduced.

The wave slope spectrum $S_{aa,c}(\omega)$ is defined as

$$S_{aa,c}(\omega)=r(\omega)^2\cdot\frac{\omega^4}{g^2}S_{zz}(\omega) \quad (7.8)$$

where $S_{zz}(\omega)$ is the Pierson-Moskowitz spectrum $S_{zz}(\omega)=\frac{4\cdot\pi^2\cdot H_S^2}{T_Z^4}\cdot\omega^{-5}\cdot\exp\left(\frac{16\cdot\pi^3}{T_Z^4}\cdot\omega^{-4}\right)$ (7.9)

and $r(\omega)$ is the effective wave slope function that is calculated according to a methodology [8] or equivalent methods

The wind gust $S_{\delta Mwind,tot}$ is defined as

$$S_{\delta M_{wind},tot}(\omega)=\left[\rho_{air}\cdot U_w\cdot C_m\cdot A_L\cdot Z\right]^2\cdot 4\cdot K\cdot\frac{U_w^2}{\omega}\cdot\frac{X_D^2}{\left(1+X_D^2\right)^{\frac{4}{3}}} \quad \left(\mathrm{m/s}\right)^2/\left(\mathrm{rad/s}\right) \quad (7.10)$$

With, $\rho_{air}$ =1.222 kg/m$^3$, $U_w=(H_S/0.06717)^{2/3}$, $C_m$=1.22, $K$=0.003, $X_D=600\omega/(\pi U_w)$

Capsize is defined as the up-crossing of a certain 'equivalent area capsize angle' $\varphi_{vw}$ that is defined for both leeward and windward in order to take into account the actual shape of the righting lever and is obtained from the following formulas

$$\begin{aligned} leeward: \quad & \varphi_{EA+}=\varphi_s+\sqrt{\frac{2}{GM_{res}(\varphi_s)}\cdot\int_{\varphi_s}^{\varphi_{cap+}}\left(GZ(\varphi)-l_{wind,tot}\right)d\varphi} \\ windward: \quad & \varphi_{EA+}=\varphi_s-\sqrt{\frac{-2}{GM_{res}(\varphi_s)}\cdot\int_{\varphi_{cap-}}^{\varphi_s}\left(GZ(\varphi)-l_{wind,tot}\right)d\varphi} \end{aligned} \quad (7.11)$$

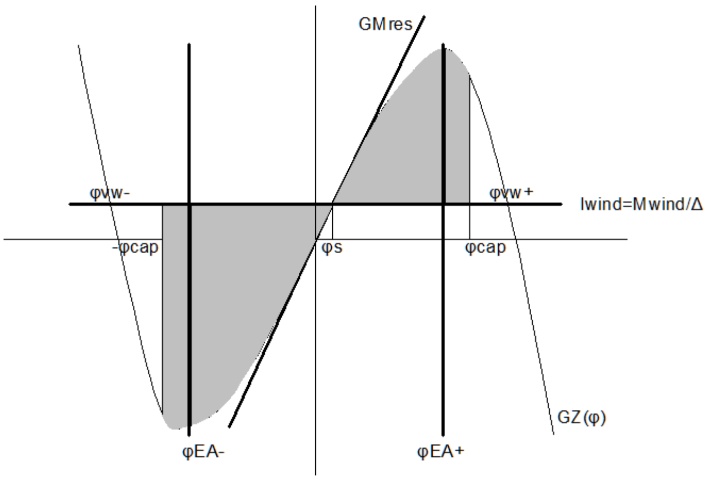



Figure 7.2 Graphical representation of the relevant angles for the calculation of the dead ship index using the 'equivalent area' approach.

The capsize is modelled as a Poisson process and the probability of capsize or better the 'capsize index', due to the large number of assumption that have been introduced, is given by the following expression for the exposure time interval $T_{exp}$ = 3600 s

$$C_S = 1 - \exp\left(-\frac{T_{\exp}}{T_{Z,Cs}} \cdot \left[\exp\left(-\frac{1}{2 \cdot RI^2_{EA+}}\right) + \exp\left(-\frac{1}{2 \cdot RI^2_{EA-}}\right)\right]\right) \quad (7.12)$$

Where $T_{Z,Cs}$ is the reference average zero up-crossing period of the relative roll motion under the action of wind and waves and is given from the eq.5.13

$$T_{Z,Cs} = 2\pi \cdot \sqrt{\frac{\int_0^\infty S(\omega)d\omega}{\int_0^\infty \omega^2 S(\omega)d\omega}} = 2\pi \cdot \sqrt{\frac{m_0}{m_2}} \quad (7.13)$$

And $RI$ is the risk index defined as

$$RI_{EA+} = \frac{\sigma_{Cs} = \int_0^\infty S(\omega)d\omega = m_0}{\Delta\varphi_{res,EA+}} \quad with \ \Delta\varphi_{res,EA+} = \varphi_{EA+} - \varphi_S$$

$$RI_{EA-} = \frac{\sigma_{Cs} = \int_0^\infty S(\omega)d\omega = m_0}{\Delta\varphi_{res,EA-}} \quad with \ \Delta\varphi_{res,EA-} = \varphi_S - \varphi_{EA+} \quad (7.14)$$

$C_{S,i}$ is the short-term dead ship stability probability index. The sum $\sum C_{S,i} W_i$, for a number of short–term environmental conditions characterized by *Hs* and *Tz* give the long term probability index *C* that examine the vulnerability of the ship to a stability failure under dead ship condition.

## 7.4 APPLICATION OF DEAD SHIP STABILITY CRITERIA ON RO-RO PASSENGER SHIPS

### 7.4.1 Vessel: RoPax 160 / Loading Condition: Partial Draft (DP)

***Level 1 Vulnerability Check***

Table 7.2: RoPax 160, Level 1 Parameters for the partial load

| | | |
|---|---|---|
| 1. | B/d = 4.17 > 3.5 | Fail |
| 2. | -0.3 < (KG/d – 1 = 1.004 ) > 0.5 | Fail |
| 3. | T = 15.81 < 20 sec | Ok |

As long as the above parameters do not meet limit values, loading condition proceeds to level 2 vulnerability check

***Level 2 Vulnerability Check***

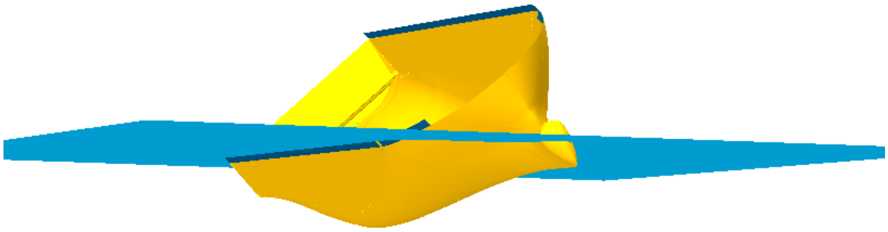


Figure 7.3 RoPax 160 immersion of unprotected openings, critical heel angle of 43.5 deg that define stability range for DP

Table 7.3: RoPax 160, Level 2 variables criterion related to GZ curve for DP

| Hs | U [m/s] | $l_{WIND}$ [m] | φs [rad] | Ares+ [m·rad] | Ares- [m·rad] | GMres [m] | Δφres,EA+ [rad] | Δφres,EA- [rad] |
|---|---|---|---|---|---|---|---|---|
| **0.5** | 3.8124 | 0.0046 | 0.0027 | 0.385 | 0.3921 | 1.7124 | 0.6706 | 0.6767 |
| **1.5** | 7.9301 | 0.02 | 0.0117 | 0.3734 | 0.4039 | 1.7123 | 0.6604 | 0.6869 |
| **2.5** | 11.148 | 0.0395 | 0.0231 | 0.3589 | 0.4191 | 1.7122 | 0.6475 | 0.6997 |
| **3.5** | 13.951 | 0.0619 | 0.0361 | 0.3425 | 0.4368 | 1.7118 | 0.6326 | 0.7144 |
| **4.5** | 16.495 | 0.0865 | 0.0505 | 0.3248 | 0.4567 | 1.7112 | 0.6161 | 0.7306 |
| **5.5** | 18.856 | 0.1131 | 0.0661 | 0.3061 | 0.4785 | 1.7101 | 0.5983 | 0.7481 |
| **6.5** | 21.078 | 0.1413 | 0.0826 | 0.2867 | 0.5021 | 1.7082 | 0.5793 | 0.7667 |
| **7.5** | 23.188 | 0.171 | 0.1 | 0.2667 | 0.5274 | 1.705 | 0.5594 | 0.7866 |
| **8.5** | 25.206 | 0.202 | 0.1182 | 0.2465 | 0.5545 | 1.7001 | 0.5385 | 0.8077 |
| **9.5** | 27.146 | 0.2343 | 0.1372 | 0.226 | 0.5832 | 1.6925 | 0.5167 | 0.8302 |
| **10.5** | 29.019 | 0.2678 | 0.157 | 0.2054 | 0.6137 | 1.6813 | 0.4943 | 0.8544 |
| **11.5** | 30.833 | 0.3023 | 0.1776 | 0.1848 | 0.6458 | 1.6652 | 0.4712 | 0.8807 |
| **12.5** | 32.595 | 0.3379 | 0.1991 | 0.1644 | 0.6796 | 1.643 | 0.4474 | 0.9095 |
| **13.5** | 34.311 | 0.3744 | 0.2215 | 0.1443 | 0.7151 | 1.6126 | 0.423 | 0.9417 |
| **14.5** | 35.986 | 0.4118 | 0.2449 | 0.1245 | 0.7523 | 1.572 | 0.3979 | 0.9783 |
| **15.5** | 37.622 | 0.4501 | 0.2696 | 0.1051 | 0.7914 | 1.5185 | 0.3721 | 1.0209 |
| **16.5** | 39.223 | 0.4892 | 0.2958 | 0.0864 | 0.8322 | 1.4489 | 0.3453 | 1.0718 |

Effective wave slope function *r(ω)* as obtained by the standard method is shown in the following figure

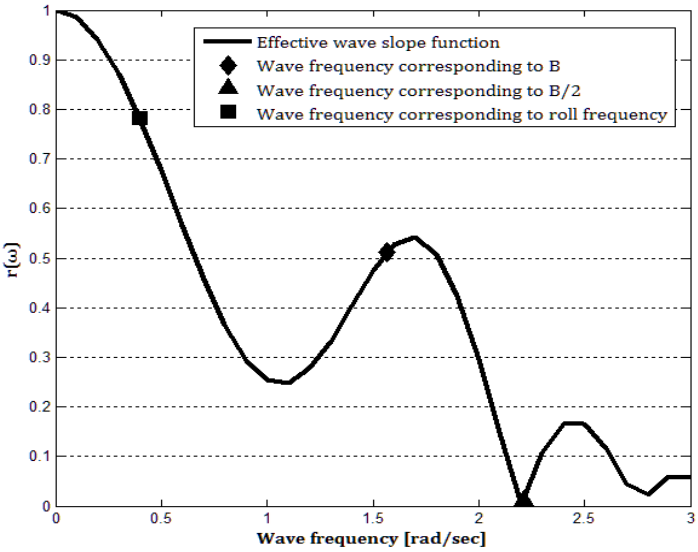



Figure 7.4: RoPax 160 Effective wave slope function for DP

Damping characteristics, that are derived from Ikeda simplified method and methodology for estimation roll damping coefficients are shown in the following figures

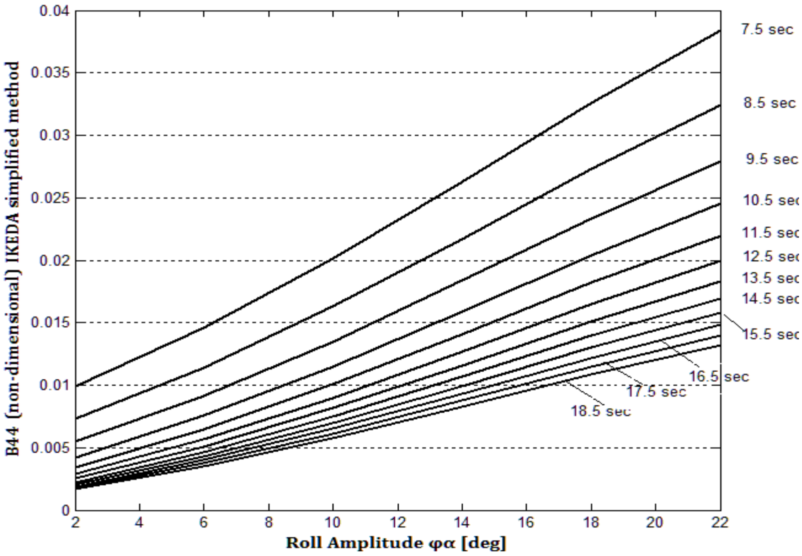



Figure 7.5: RoPax 160, Roll damping coefficient, $B_{44}$ for DP

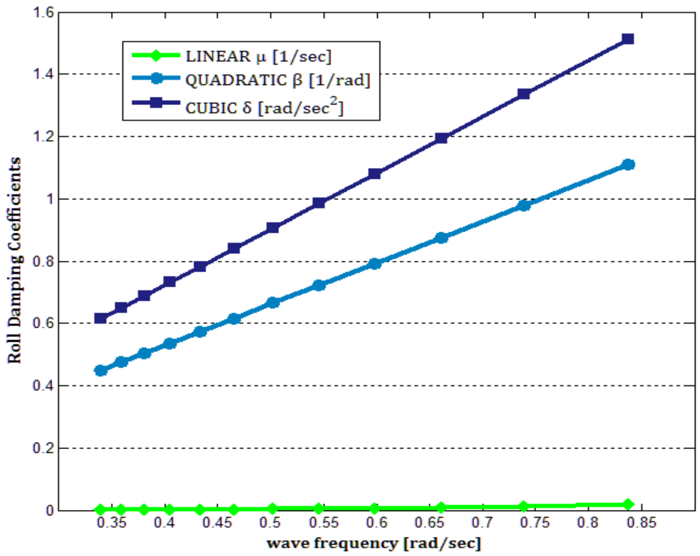



Figure 7.6: RoPax 160, Roll damping coefficients $\mu,\beta,\delta$ for DP

The value of short-term probability index *Csi* multiplied with the wave probability *Wi*, for each combination of significant wave height and mean zero crossing wave period

Table 7.4: RoPax 160, *WiCi* for wave periods between 3.5 and 10.5 sec for DP

| Tz<br>Hs | 3.5 | 4.5 | 5.5 | 6.5 | 7.5 | 8.5 | 9.5 | 10.5 |
|---|---|---|---|---|---|---|---|---|
| **0.5** | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 |
| **1.5** | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 |
| **2.5** | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 |
| **3.5** | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 8.8E-17 |
| **4.5** | 0.0E+00 | 0.0E+00 | 4.0E-20 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 1.7E-14 | 1.1E-10 |
| **5.5** | 0.0E+00 | 0.0E+00 | 4.0E-14 | 3.4E-16 | 3.0E-16 | 2.1E-13 | 8.1E-10 | 1.8E-07 |
| **6.5** | 0.0E+00 | 0.0E+00 | 4.8E-11 | 9.2E-12 | 2.1E-11 | 1.6E-09 | 3.5E-07 | 1.2E-05 |
| **7.5** | 0.0E+00 | 0.0E+00 | 0.0E+00 | 2.4E-09 | 1.0E-08 | 2.8E-07 | 1.2E-05 | 1.5E-04 |
| **8.5** | 0.0E+00 | 0.0E+00 | 0.0E+00 | 5.1E-08 | 3.5E-07 | 5.8E-06 | 1.0E-04 | 6.2E-04 |
| **9.5** | 0.0E+00 | 0.0E+00 | 0.0E+00 | 2.9E-07 | 2.5E-06 | 3.1E-05 | 2.9E-04 | 1.0E-03 |
| **10.5** | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 5.2E-06 | 5.5E-05 | 3.0E-04 | 6.5E-04 |
| **11.5** | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 2.9E-06 | 3.2E-05 | 1.3E-04 | 2.7E-04 |
| **12.5** | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 1.0E-06 | 1.0E-05 | 4.4E-05 | 9.9E-05 |
| **13.5** | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 3.0E-06 | 1.4E-05 | 3.5E-05 |
| **14.5** | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 1.0E-06 | 4.0E-06 | 1.2E-05 |
| **15.5** | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 1.0E-06 | 4.0E-06 |
| **16.5** | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 1.0E-06 |

Table 7.5: RoPax 160, *WiCi* for wave periods between 11.5 and 18.5 sec for DP

| Tz<br>Hs | 11.5 | 12.5 | 13.5 | 14.5 | 15.5 | 16.5 | 17.5 | 18.5 |
|---|---|---|---|---|---|---|---|---|
| **0.5** | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 |
| **1.5** | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 |
| **2.5** | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 |
| **3.5** | 1.3E-13 | 1.7E-12 | 1.2E-12 | 2.4E-13 | 2.2E-14 | 1.2E-15 | 5.0E-17 | 0.0E+00 |
| **4.5** | 6.0E-09 | 1.8E-08 | 0.0E+00 | 2.3E-09 | 3.0E-10 | 2.9E-11 | 2.1E-12 | 0.0E+00 |
| **5.5** | 1.9E-06 | 3.0E-06 | 1.5E-06 | 3.7E-07 | 6.4E-08 | 9.0E-09 | 1.2E-09 | 6.4E-11 |
| **6.5** | 5.7E-05 | 6.4E-05 | 3.0E-05 | 8.4E-06 | 1.7E-06 | 2.9E-07 | 1.9E-08 | 2.7E-09 |
| **7.5** | 4.2E-04 | 3.9E-04 | 1.8E-04 | 5.6E-05 | 1.3E-05 | 2.7E-06 | 2.5E-07 | 7.4E-08 |
| **8.5** | 1.2E-03 | 9.1E-04 | 4.3E-04 | 1.5E-04 | 4.1E-05 | 9.7E-06 | 2.0E-06 | 3.6E-07 |
| **9.5** | 1.3E-03 | 9.1E-04 | 4.5E-04 | 1.7E-04 | 5.4E-05 | 1.1E-05 | 3.3E-06 | 8.1E-07 |
| **10.5** | 7.1E-04 | 5.1E-04 | 2.7E-04 | 1.1E-04 | 4.0E-05 | 1.2E-05 | 3.0E-06 | 9.9E-07 |
| **11.5** | 3.1E-04 | 2.5E-04 | 1.4E-04 | 6.4E-05 | 2.4E-05 | 7.0E-06 | 2.0E-06 | 1.0E-06 |
| **12.5** | 1.3E-04 | 1.1E-04 | 6.8E-05 | 3.3E-05 | 1.3E-05 | 4.0E-06 | 1.0E-06 | 0.0E+00 |
| **13.5** | 5.0E-05 | 4.6E-05 | 3.1E-05 | 1.6E-05 | 7.0E-06 | 2.0E-06 | 1.0E-06 | 0.0E+00 |
| **14.5** | 1.8E-05 | 1.8E-05 | 1.3E-05 | 7.0E-06 | 3.0E-06 | 1.0E-06 | 0.0E+00 | 0.0E+00 |
| **15.5** | 6.0E-06 | 7.0E-06 | 5.0E-06 | 3.0E-06 | 1.0E-06 | 1.0E-06 | 0.0E+00 | 0.0E+00 |
| **16.5** | 2.0E-06 | 2.0E-06 | 2.0E-06 | 1.0E-06 | 1.0E-06 | 0.0E+00 | 0.0E+00 | 0.0E+00 |

Summing up all values in Tables 7.4 and 7.5 the long term probability index is obtained as follows

$$C = 0.0138 = 1.38 \cdot 10^{-2}$$

However, loading condition is not considered vulnerable to dead ship stability failure either $R_{DS}$ is 0.04 or 0.06

Table 7.6: RoPax 160, The value of long term probability index *C* for all examined loading conditions

| **Loading condition** | **Long-term index [C]** | **Status if $R_{DS}$=0.04** | **Status if $R_{DS}$=0.06** |
|---|---|---|---|
| Deepest | 0.0052 | Pass | Pass |
| Partial | 0.0138 | Pass | Pass |
| Lightest | 0.0055 | Pass | Pass |

### 7.4.2 Vessel: RoPax 110 / Loading Condition: Partial Draft (DP)

***Level 1 Vulnerability Check***

Table 7.7: RoPax 110, Level 1 Parameters for DP

| | | |
|---|---|---|
| 1. | B/d = 3.91 > 3.5 | Fail |
| 2. | -0.3 < (KG/d – 1 = 0.83 ) > 0.5 | Fail |
| 3. | T = 11.11 < 20 sec | Ok |

As long as the above parameters do not meet limit values, loading condition proceeds to level 2 vulnerability check

***Level 2 Vulnerability Check***

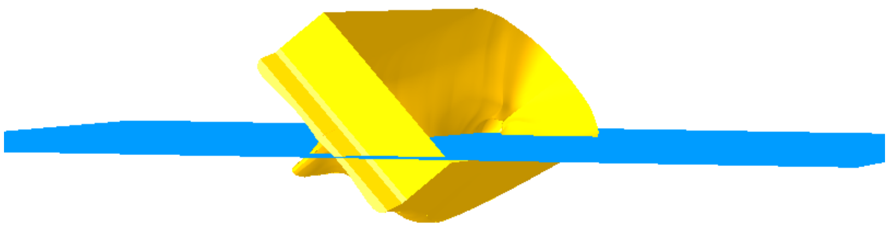


Figure 7.7 RoPax 110 immersion of unprotected openings, critical heel angle of 48.6 deg that define stability range for DP

Table 7.8: RoPax 110, Level 2 variables criterion related to GZ curve for DP

| **Hs** | **U [m/s]** | **$l_{WIND}$ [m]** | **φs [rad]** | **Ares+ [m·rad]** | **Ares- [m·rad]** | **GMres [m]** | **Δφres,EA+ [rad]** | **Δφres,EA- [rad]** |
|---|---|---|---|---|---|---|---|---|
| **0.5** | 3.8124 | 0.0037 | 0.0162 | 0.3459 | 0.3852 | 1.5877 | 0.6601 | 0.6966 |
| **1.5** | 7.9301 | 0.0161 | 0.024 | 0.3356 | 0.396 | 1.5844 | 0.6509 | 0.707 |
| **2.5** | 11.1475 | 0.0318 | 0.0339 | 0.3228 | 0.4097 | 1.5784 | 0.6396 | 0.7205 |
| **3.5** | 13.9507 | 0.0497 | 0.0453 | 0.3083 | 0.4257 | 1.569 | 0.6269 | 0.7366 |
| **4.5** | 16.4952 | 0.0695 | 0.0579 | 0.2925 | 0.4435 | 1.5556 | 0.6133 | 0.7551 |
| **5.5** | 18.8564 | 0.0908 | 0.0717 | 0.2758 | 0.4629 | 1.5376 | 0.599 | 0.776 |
| **6.5** | 21.0778 | 0.1135 | 0.0865 | 0.2584 | 0.4839 | 1.5144 | 0.5842 | 0.7994 |
| **7.5** | 23.1877 | 0.1374 | 0.1023 | 0.2404 | 0.5064 | 1.4855 | 0.5689 | 0.8257 |
| **8.5** | 25.2055 | 0.1623 | 0.1193 | 0.222 | 0.5303 | 1.4503 | 0.5533 | 0.8552 |
| **9.5** | 27.1456 | 0.1883 | 0.1374 | 0.2034 | 0.5557 | 1.4085 | 0.5374 | 0.8883 |
| **10.5** | 29.0186 | 0.2152 | 0.1567 | 0.1845 | 0.5824 | 1.3595 | 0.521 | 0.9256 |
| **11.5** | 30.8329 | 0.2429 | 0.1774 | 0.1656 | 0.6106 | 1.3031 | 0.5042 | 0.968 |

| Hs | U [m/s] | $l_{WIND}$ [m] | φs [rad] | Ares+ [m·rad] | Ares- [m·rad] | GMres [m] | Δφres,EA+ [rad] | Δφres,EA- [rad] |
|---|---|---|---|---|---|---|---|---|
| **12.5** | 32.5954 | 0.2715 | 0.1998 | 0.1468 | 0.6402 | 1.239 | 0.4868 | 1.0165 |
| **13.5** | 34.3114 | 0.3008 | 0.224 | 0.1281 | 0.6712 | 1.1674 | 0.4685 | 1.0724 |
| **14.5** | 35.9856 | 0.3309 | 0.2505 | 0.1098 | 0.7039 | 1.0885 | 0.4491 | 1.1372 |
| **15.5** | 37.6216 | 0.3616 | 0.2797 | 0.0918 | 0.7381 | 1.0032 | 0.4279 | 1.213 |
| **16.5** | 39.2228 | 0.3931 | 0.3123 | 0.0745 | 0.774 | 0.913 | 0.4039 | 1.3022 |

Effective wave slope function *r(ω)* as obtained by the standard method is shown in the following figure

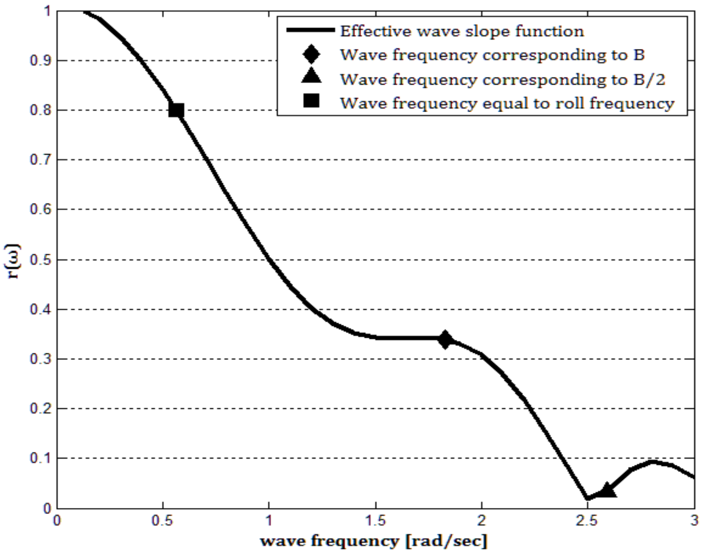



Figure 7.8: RoPax 110, Effective wave slope function for DP

Damping characteristics that are derived from Ikeda simplified method and methodology for estimation roll damping coefficients are shown in the following figures

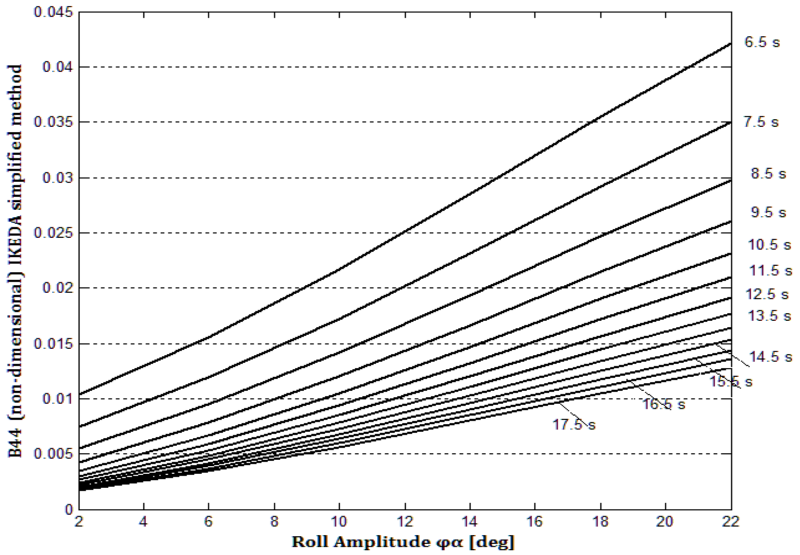



Figure 7.9: RoPax 110, Roll damping coefficient $B_{44}$ for DP

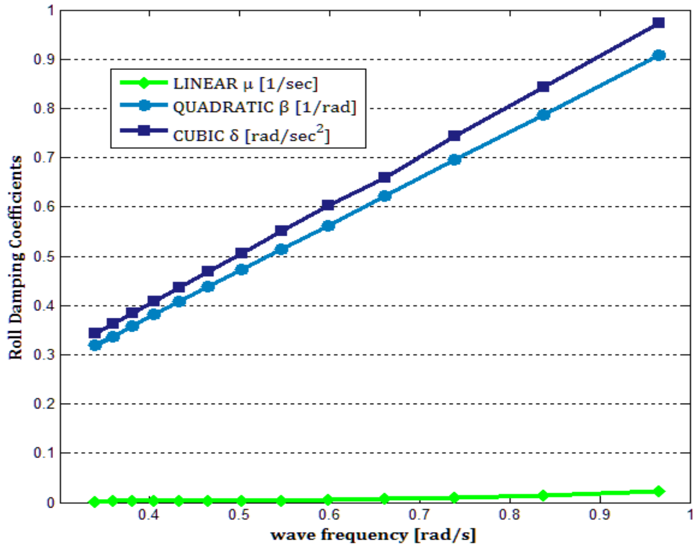



Figure 7.10: RoPax 110, Roll damping coefficients *μ,β,δ* for DP

The value of short-term probability index *Csi* is multiplied with the wave probability *Wi*, for each combination of significant wave height and mean zero crossing wave period

Table 7.9: RoPax110, WiCi for wave periods between 3.5 and 10.5 sec for partial load condition

| Tz / Hs | 3.5 | 4.5 | 5.5 | 6.5 | 7.5 | 8.5 | 9.5 | 10.5 |
|---|---|---|---|---|---|---|---|---|
| **0.5** | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 |
| **1.5** | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 |
| **2.5** | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 |
| **3.5** | 0.0E+00 | 1.9E-20 | 1.2E-19 | 4.6E-16 | 2.1E-12 | 6.5E-11 | 7.7E-11 | 1.3E-11 |
| **4.5** | 0.0E+00 | 0.0E+00 | 8.1E-13 | 2.4E-10 | 3.9E-08 | 3.5E-07 | 3.4E-07 | 8.2E-08 |
| **5.5** | 0.0E+00 | 0.0E+00 | 7.9E-10 | 9.8E-08 | 4.7E-06 | 2.7E-05 | 2.9E-05 | 1.0E-05 |
| **6.5** | 0.0E+00 | 0.0E+00 | 2.2E-08 | 1.8E-06 | 5.2E-05 | 2.7E-04 | 3.6E-04 | 1.8E-04 |
| **7.5** | 0.0E+00 | 0.0E+00 | 0.0E+00 | 5.8E-06 | 1.4E-04 | 7.6E-04 | 1.3E-03 | 8.4E-04 |
| **8.5** | 0.0E+00 | 0.0E+00 | 0.0E+00 | 5.2E-06 | 1.2E-04 | 7.6E-04 | 1.7E-03 | 1.8E-03 |
| **9.5** | 0.0E+00 | 0.0E+00 | 0.0E+00 | 2.0E-06 | 4.3E-05 | 3.3E-04 | 9.9E-04 | 1.5E-03 |
| **10.5** | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 1.2E-05 | 1.1E-04 | 3.8E-04 | 6.7E-04 |
| **11.5** | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 3.0E-06 | 3.3E-05 | 1.3E-04 | 2.7E-04 |
| **12.5** | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 1.0E-06 | 1.0E-05 | 4.4E-05 | 9.9E-05 |
| **13.5** | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 3.0E-06 | 1.4E-05 | 3.5E-05 |
| **14.5** | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 1.0E-06 | 4.0E-06 | 1.2E-05 |
| **15.5** | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 1.0E-06 | 4.0E-06 |
| **16.5** | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 1.0E-06 |

Table 7.10: RoPax 110, WiCi for wave periods between 11.5 and 18.5 sec for partial load condition

| Tz / Hs | 11.5 | 12.5 | 13.5 | 14.5 | 15.5 | 16.5 | 17.5 | 18.5 |
|---|---|---|---|---|---|---|---|---|
| **0.5** | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 |
| **1.5** | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 |
| **2.5** | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 |
| **3.5** | 5.7E-13 | 1.1E-14 | 1.1E-16 | 8.3E-19 | 3.9E-21 | 0.0E+00 | 0.0E+00 | 0.0E+00 |

| **Tz** / **Hs** | **11.5** | **12.5** | **13.5** | **14.5** | **15.5** | **16.5** | **17.5** | **18.5** |
|---|---|---|---|---|---|---|---|---|
| **4.5** | 7.4E-09 | 3.4E-10 | 8.7E-12 | 1.7E-13 | 2.5E-15 | 3.3E-17 | 3.7E-19 | 0.0E+00 |
| **5.5** | 1.6E-06 | 1.3E-07 | 6.7E-09 | 2.5E-10 | 7.3E-12 | 1.9E-13 | 4.5E-15 | 1.5E-16 |
| **6.5** | 4.2E-05 | 5.6E-06 | 4.0E-07 | 3.0E-08 | 1.5E-09 | 6.2E-11 | 2.2E-12 | 8.6E-14 |
| **7.5** | 3.2E-04 | 6.3E-05 | 8.3E-06 | 8.0E-07 | 6.1E-08 | 3.9E-09 | 2.5E-10 | 1.1E-11 |
| **8.5** | 9.6E-04 | 2.9E-04 | 5.7E-05 | 8.0E-06 | 9.1E-07 | 8.7E-08 | 7.2E-09 | 5.3E-10 |
| **9.5** | 1.2E-03 | 5.8E-04 | 1.8E-04 | 3.8E-05 | 6.4E-06 | 8.8E-07 | 1.0E-07 | 1.3E-08 |
| **10.5** | 7.1E-04 | 4.9E-04 | 2.4E-04 | 8.0E-05 | 2.1E-05 | 4.3E-06 | 7.3E-07 | 1.7E-07 |
| **11.5** | 3.1E-04 | 2.5E-04 | 1.4E-04 | 6.3E-05 | 2.3E-05 | 6.4E-06 | 1.7E-06 | 7.8E-07 |
| **12.5** | 1.3E-04 | 1.1E-04 | 6.8E-05 | 3.3E-05 | 1.3E-05 | 4.0E-06 | 1.0E-06 | 0.0E+00 |
| **13.5** | 5.0E-05 | 4.6E-05 | 3.1E-05 | 1.6E-05 | 7.0E-06 | 2.0E-06 | 1.0E-06 | 0.0E+00 |
| **14.5** | 1.8E-05 | 1.8E-05 | 1.3E-05 | 7.0E-06 | 3.0E-06 | 1.0E-06 | 0.0E+00 | 0.0E+00 |
| **15.5** | 6.0E-06 | 7.0E-06 | 5.0E-06 | 3.0E-06 | 1.0E-06 | 1.0E-06 | 0.0E+00 | 0.0E+00 |
| **16.5** | 2.0E-06 | 2.0E-06 | 2.0E-06 | 1.0E-06 | 1.0E-06 | 0.0E+00 | 0.0E+00 | 0.0E+00 |

Summing up all values in Tables 7.9 and 7.10, the long term probability index is obtained as follows

$$C = 0.0197 \; = \; 1.97 \cdot 10^{-2}$$

However, loading condition is not considered vulnerable to dead ship stability failure either $R_{DS}$ is 0.04 or 0.06

Table 7.11: The value of long term probability index *C* for all examined loading conditions

| **Loading Condition** | **Long-term index *C*** | **Status if $R_{DS}$=0.04** | **Status if $R_{DS}$=0.06** |
|---|---|---|---|
| Deepest | 0.0219 | Pass | Pass |
| Partial | 0.0197 | Pass | Pass |
| Lightest | 0.0352 | Pass | Pass |

### 7.4.3 Vessel: RoPax 75 / Loading Condition: Deepest Draft (DS)

***Level 1 Vulnerability Check***

Table 7.12: RoPax 75, Level 1 Parameters for deepest draft

| | | |
|---|---|---|
| 1. | B/d = 3.38 < 3.5 | ok |
| 2. | -0.3 < (KG/d – 1 = 0.49 ) < 0.5 | ok |
| 3. | T = 9.57 < 20 sec | ok |

As long as the above parameters are fulfilled, level 1 check should be actualized

Table 7.13: RoPax 75, Weather criterion particulars for deepest draft

| | | | |
|---|---|---|---|
| A | 940 $m^2$ | OG | 2.10 |
| Z | 6.08 m | r | 1.026 |
| $l_{w1}$ | 0.109 m | C | 0.417 |
| $l_{w2}$ | 0.163 m | T | 9.57 sec |
| $X_1$ | 0.800 | s | 0.0819 |
| $X_2$ | 0.957 m | $\varphi_0$ | 4.0 deg |
| k | 1 | $\varphi_1$ - $\varphi_f$ | 24.2 – 42.3 deg |

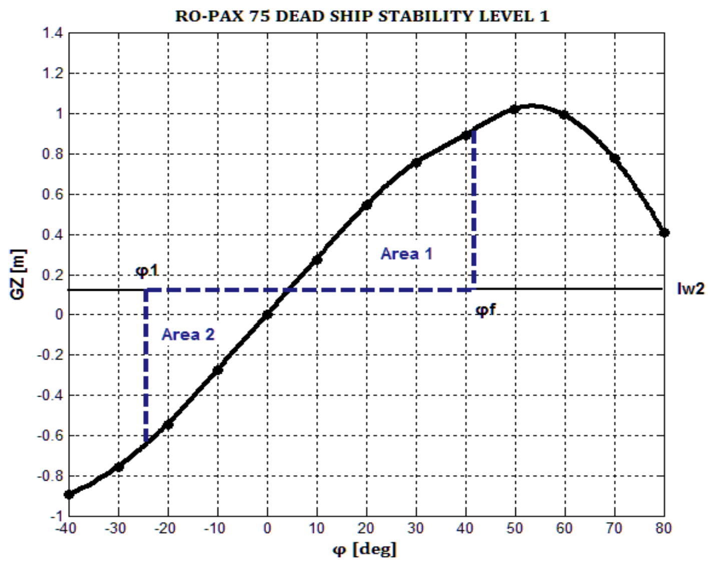



Figure 7.11: RoPax 75 Level 1 Dead ship stability

Table 7.14: RoPax 75, Level 1 Dead ship condition for DS

| Criteria | Value | Units | Actual | Status | Margin % |
|---|---|---|---|---|---|
| Angle of steady heel shall not be greater than (<=) | 16.0 | deg | 3.9 | Pass | +75.26 |
| Area1 / Area2 shall not be less than (>=) | 100.00 | % | 172.45 | Pass | +72.45 |

However, vulnerability is not detected. It is reminded that level 1 is the same regulation with the weather criterion with which the vessel already complies with.

### *Level 2 Vulnerability Check*

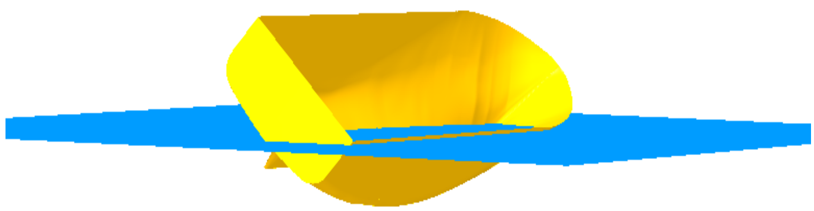


Figure 5.12 RoPax 75 immersion of unprotected openings, critical heel angle of 43 deg that define stability range for DS

Table 7.15: RoPax 75, Level 2 variables criterion related to GZ curve for deepest draft

| Hs | U [m/s] | $l_{WIND}$ [m] | φs [rad] | Ares+ [m·rad] | Ares- [m·rad] | GMres [m] | Δφres,EA- [rad] | Δφres,EA- [rad] |
|---|---|---|---|---|---|---|---|---|
| **0.5** | 3.8124 | 0.003 | 0.0019 | 0.3874 | 0.3919 | 1.5718 | 0.7021 | 0.7062 |
| **1.5** | 7.9301 | 0.0131 | 0.0084 | 0.38 | 0.3994 | 1.5719 | 0.6954 | 0.7129 |
| **2.5** | 11.1475 | 0.0259 | 0.0165 | 0.3707 | 0.409 | 1.5721 | 0.6867 | 0.7213 |

| Hs | U [m/s] | $l_{WIND}$ [m] | φs [rad] | Ares+ [m·rad] | Ares- [m·rad] | GMres [m] | Δφres,EA- [rad] | Δφres,EA- [rad] |
|---|---|---|---|---|---|---|---|---|
| **3.5** | 13.9507 | 0.0406 | 0.0259 | 0.3602 | 0.4202 | 1.5725 | 0.6768 | 0.731 |
| **4.5** | 16.4952 | 0.0568 | 0.0361 | 0.3488 | 0.4326 | 1.5731 | 0.6659 | 0.7416 |
| **5.5** | 18.8564 | 0.0742 | 0.0472 | 0.3366 | 0.4462 | 1.5738 | 0.6541 | 0.753 |
| **6.5** | 21.0778 | 0.0928 | 0.059 | 0.3239 | 0.4609 | 1.5747 | 0.6414 | 0.7651 |
| **7.5** | 23.1877 | 0.1123 | 0.0714 | 0.3108 | 0.4765 | 1.5758 | 0.6281 | 0.7777 |
| **8.5** | 25.2055 | 0.1327 | 0.0843 | 0.2974 | 0.4932 | 1.577 | 0.6141 | 0.7908 |
| **9.5** | 27.1456 | 0.1539 | 0.0978 | 0.2836 | 0.5107 | 1.5782 | 0.5996 | 0.8045 |
| **10.5** | 29.0186 | 0.1758 | 0.1117 | 0.2697 | 0.5292 | 1.5792 | 0.5845 | 0.8187 |
| **11.5** | 30.8329 | 0.1985 | 0.126 | 0.2557 | 0.5487 | 1.5799 | 0.5689 | 0.8334 |
| **12.5** | 32.5954 | 0.2219 | 0.1408 | 0.2416 | 0.569 | 1.5801 | 0.553 | 0.8487 |
| **13.5** | 34.3114 | 0.2458 | 0.156 | 0.2275 | 0.5903 | 1.5795 | 0.5367 | 0.8645 |
| **14.5** | 35.9856 | 0.2704 | 0.1715 | 0.2133 | 0.6124 | 1.5779 | 0.52 | 0.881 |
| **15.5** | 37.6216 | 0.2956 | 0.1875 | 0.1993 | 0.6355 | 1.5749 | 0.5031 | 0.8983 |
| **16.5** | 39.2228 | 0.3212 | 0.2038 | 0.1854 | 0.6595 | 1.5702 | 0.4859 | 0.9165 |

Effective wave slope function r(ω) as obtained by the standard method is shown in the following figure

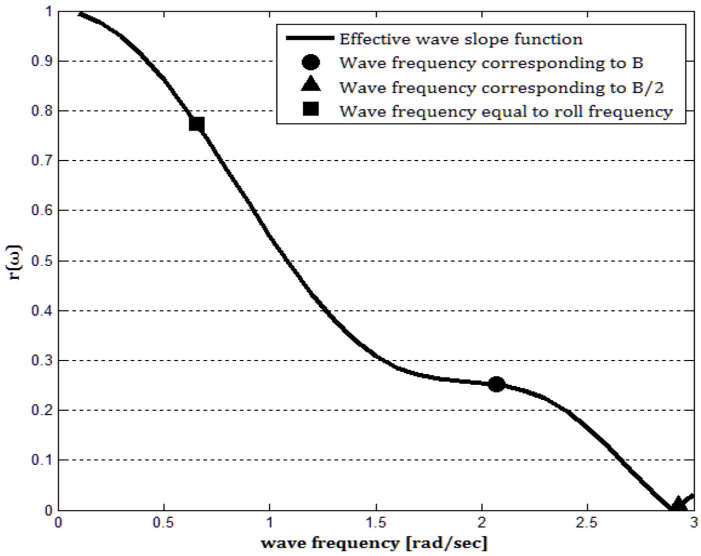



Figure 7.13: RoPax 75 Effective wave slope function for DS

Damping characteristics that are derived from Ikeda simplified method and methodology for estimation roll damping coefficients are shown in the following figures

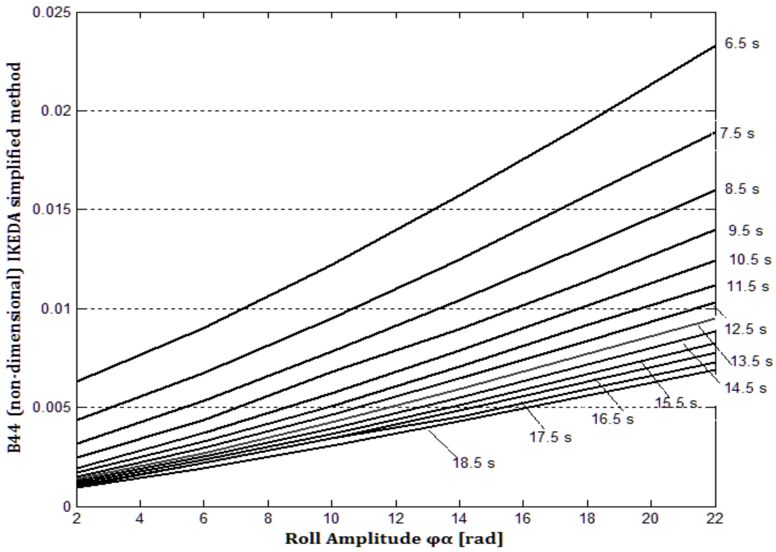



Figure 7.14: RoPax 75, Roll damping coefficient ,$B_{44}$ for DS

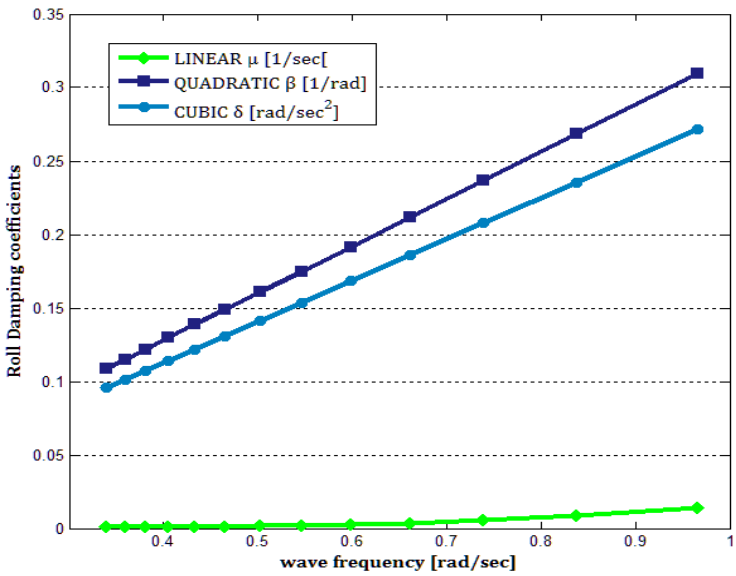



Figure 7.15: RoPax 75, Roll damping coefficients $\mu,\beta,\delta$ for DS

The value of short-term probability index *Csi* is multiplied with the wave probability *Wi* for each combination of significant wave height and mean zero crossing wave period

Table 7.16: RoPax 75, WiCi for wave periods between 3.5 and 10.5 sec for DS

| Tz<br>Hs | 3.5 | 4.5 | 5.5 | 6.5 | 7.5 | 8.5 | 9.5 | 10.5 |
|---|---|---|---|---|---|---|---|---|
| **0.5** | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 |
| **1.5** | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 |
| **2.5** | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 6.7E-15 | 4.3E-12 | 2.2E-11 | 1.2E-11 |
| **3.5** | 0.0E+00 | 9.1E-19 | 2.6E-16 | 6.5E-12 | 1.6E-08 | 4.2E-07 | 8.0E-07 | 3.7E-07 |
| **4.5** | 0.0E+00 | 0.0E+00 | 5.8E-11 | 5.0E-08 | 7.8E-06 | 6.9E-05 | 9.6E-05 | 5.1E-05 |
| **5.5** | 0.0E+00 | 0.0E+00 | 1.1E-08 | 2.8E-06 | 1.4E-04 | 8.5E-04 | 7.0E-04 | 7.3E-04 |

| Hs Tz | 3.5 | 4.5 | 5.5 | 6.5 | 7.5 | 8.5 | 9.5 | 10.5 |
|---|---|---|---|---|---|---|---|---|
| **6.5** | 0.0E+00 | 0.0E+00 | 1.2E-07 | 1.6E-05 | 4.7E-04 | 2.5E-03 | 4.0E-03 | 2.9E-03 |
| **7.5** | 0.0E+00 | 0.0E+00 | 0.0E+00 | 2.0E-05 | 4.3E-04 | 2.3E-03 | 4.7E-03 | 4.6E-03 |
| **8.5** | 0.0E+00 | 0.0E+00 | 0.0E+00 | 6.9E-06 | 1.5E-04 | 9.7E-04 | 2.5E-03 | 3.3E-03 |
| **9.5** | 0.0E+00 | 0.0E+00 | 0.0E+00 | 2.0E-06 | 4.3E-05 | 3.3E-04 | 1.0E-03 | 1.6E-03 |
| **10.5** | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 1.2E-05 | 1.1E-04 | 3.8E-04 | 6.7E-04 |
| **11.5** | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 3.0E-06 | 3.3E-05 | 1.3E-04 | 2.7E-04 |
| **12.5** | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 1.0E-06 | 1.0E-05 | 4.4E-05 | 9.9E-05 |
| **13.5** | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 3.0E-06 | 1.4E-05 | 3.5E-05 |
| **14.5** | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 1.0E-06 | 4.0E-06 | 1.2E-05 |
| **15.5** | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 1.0E-06 | 4.0E-06 |
| **16.5** | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 1.0E-06 |

Table 7.17: RoPax 75, WiCi for wave periods between 11.5 and 18.5 sec for DS

| Tz Hs | 11.5 | 12.5 | 13.5 | 14.5 | 15.5 | 16.5 | 17.5 | 18.5 |
|---|---|---|---|---|---|---|---|---|
| **0.5** | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 |
| **1.5** | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 |
| **2.5** | 1.4E-12 | 7.2E-14 | 1.8E-15 | 2.5E-17 | 2.3E-19 | 1.6E-21 | 0.0E+00 | 0.0E+00 |
| **3.5** | 7.2E-08 | 7.7E-09 | 5.2E-10 | 2.5E-11 | 9.7E-13 | 2.9E-14 | 7.9E-16 | 0.0E+00 |
| **4.5** | 1.3E-05 | 2.2E-06 | 2.5E-07 | 2.3E-08 | 1.7E-09 | 1.1E-10 | 5.4E-12 | 0.0E+00 |
| **5.5** | 2.4E-04 | 5.2E-05 | 8.3E-06 | 1.1E-06 | 1.2E-07 | 1.2E-08 | 1.1E-09 | 1.3E-10 |
| **6.5** | 1.2E-03 | 3.3E-04 | 6.7E-05 | 1.1E-05 | 1.6E-06 | 2.0E-07 | 2.3E-08 | 2.8E-09 |
| **7.5** | 2.5E-03 | 9.0E-04 | 2.3E-04 | 4.6E-05 | 6.9E-06 | 1.2E-06 | 1.9E-07 | 2.1E-08 |
| **8.5** | 2.5E-03 | 1.2E-03 | 4.0E-04 | 9.9E-05 | 2.0E-05 | 3.6E-06 | 5.7E-07 | 8.3E-08 |
| **9.5** | 1.5E-03 | 9.4E-04 | 4.0E-04 | 1.3E-04 | 3.1E-05 | 6.5E-06 | 1.1E-06 | 2.1E-07 |
| **10.5** | 7.2E-04 | 5.1E-04 | 2.7E-04 | 1.0E-04 | 3.2E-05 | 8.0E-06 | 1.6E-06 | 4.2E-07 |
| **11.5** | 3.1E-04 | 2.5E-04 | 1.4E-04 | 6.3E-05 | 2.3E-05 | 6.4E-06 | 1.6E-06 | 7.1E-07 |
| **12.5** | 1.3E-04 | 1.1E-04 | 6.8E-05 | 3.3E-05 | 1.3E-05 | 4.0E-06 | 9.8E-07 | 0.0E+00 |
| **13.5** | 5.0E-05 | 4.6E-05 | 3.1E-05 | 1.6E-05 | 7.0E-06 | 2.0E-06 | 1.0E-06 | 0.0E+00 |
| **14.5** | 1.8E-05 | 1.8E-05 | 1.3E-05 | 7.0E-06 | 3.0E-06 | 1.0E-06 | 0.0E+00 | 0.0E+00 |
| **15.5** | 6.0E-06 | 7.0E-06 | 5.0E-06 | 3.0E-06 | 1.0E-06 | 1.0E-06 | 0.0E+00 | 0.0E+00 |
| **16.5** | 2.0E-06 | 2.0E-06 | 2.0E-06 | 1.0E-06 | 1.0E-06 | 0.0E+00 | 0.0E+00 | 0.0E+00 |

Summing up all values of tables 7.16 and 7.17, the long term probability index is obtained as $C = 0.0714 = 7.14 \cdot 10^{-2}$ However, loading condition is considered vulnerable to dead ship stability failure either $R_{DS}$ is 0.04 or 0.06. In addition an inconsistency between level 1 and 2 arises, because level 1 check does not detect vulnerability, but level 2 detects, something that is unacceptable based on 2nd generation intact stability approaches.

## 7.5 APPLICATION OF DEAD SHIP STABILITY CRITERIA ON RO-RO CARGO SHIPS

### 7.5.1 Vessel: RoRo 180 / Loading Condition: Full Load Arrival

***Level 1 Vulnerability Check***

Table 5.18: RO-RO 180, Level 1 Parameters for full load arrival condition

| | | |
|---|---|---|
| 1. | B/d = 3.726 > 3.5 | Fail |
| 2. | -0.3 < (KG/d – 1 = 0.790 ) > 0.5 | Fail |
| 3. | T = 22.60 > 20 sec | Fail |

As long as the above parameters does not meet limit values, loading condition is proceeded to level 2 vulnerability check

### *Level 2 Vulnerability Check*

Table 7.19: RoRo 180, Level 2 variables criterion related to GZ curve

| Hs | U [m/s] | $l_{WIND}$ [m] | φs [rad] | Ares+ [m·rad] | Ares- [m·rad] | GMres [m] | Δφres,EA+ [rad] | Δφres,EA- [rad] |
|---|---|---|---|---|---|---|---|---|
| **0.5** | 3.8124 | 0.0031 | 0.0047 | 0.1921 | 0.1976 | 0.6596 | 0.7632 | 0.774 |
| **1.5** | 7.9301 | 0.0134 | 0.0204 | 0.1832 | 0.2067 | 0.6575 | 0.7465 | 0.793 |
| **2.5** | 11.148 | 0.0266 | 0.0404 | 0.1722 | 0.2186 | 0.6517 | 0.7269 | 0.819 |
| **3.5** | 13.951 | 0.0416 | 0.0636 | 0.1599 | 0.2325 | 0.6408 | 0.7064 | 0.8518 |
| **4.5** | 16.495 | 0.0581 | 0.0897 | 0.1467 | 0.2482 | 0.6236 | 0.6859 | 0.8921 |
| **5.5** | 18.856 | 0.076 | 0.1188 | 0.133 | 0.2656 | 0.5995 | 0.6661 | 0.9413 |
| **6.5** | 21.078 | 0.0949 | 0.1511 | 0.119 | 0.2847 | 0.5682 | 0.6472 | 1.001 |
| **7.5** | 23.188 | 0.1149 | 0.1872 | 0.105 | 0.3054 | 0.5307 | 0.629 | 1.0729 |
| **8.5** | 25.206 | 0.1358 | 0.228 | 0.0911 | 0.328 | 0.4896 | 0.61 | 1.1575 |
| **9.5** | 27.146 | 0.1575 | 0.274 | 0.0776 | 0.3523 | 0.4513 | 0.5864 | 1.2495 |
| **10.5** | 29.019 | 0.18 | 0.3253 | 0.0647 | 0.3787 | 0.4268 | 0.5507 | 1.3321 |
| **11.5** | 30.833 | 0.2032 | 0.3799 | 0.0527 | 0.4071 | 0.428 | 0.4961 | 1.3792 |
| **12.5** | 32.595 | 0.2271 | 0.4343 | 0.0416 | 0.4377 | 0.4571 | 0.4264 | 1.3838 |
| **13.5** | 34.311 | 0.2516 | 0.4858 | 0.0315 | 0.4704 | 0.5018 | 0.3541 | 1.3692 |
| **14.5** | 35.986 | 0.2767 | 0.534 | 0.0224 | 0.5051 | 0.5434 | 0.2868 | 1.3635 |
| **15.5** | 37.622 | 0.3025 | 0.5804 | 0.0143 | 0.5419 | 0.5633 | 0.2249 | 1.3871 |
| **16.5** | 39.2228 | 0.3288 | 0.6276 | 0.0072 | 0.5807 | 0.539 | 0.1634 | 1.468 |

Effective wave slope function r(ω) as obtained by the standard method is shown in the following figure

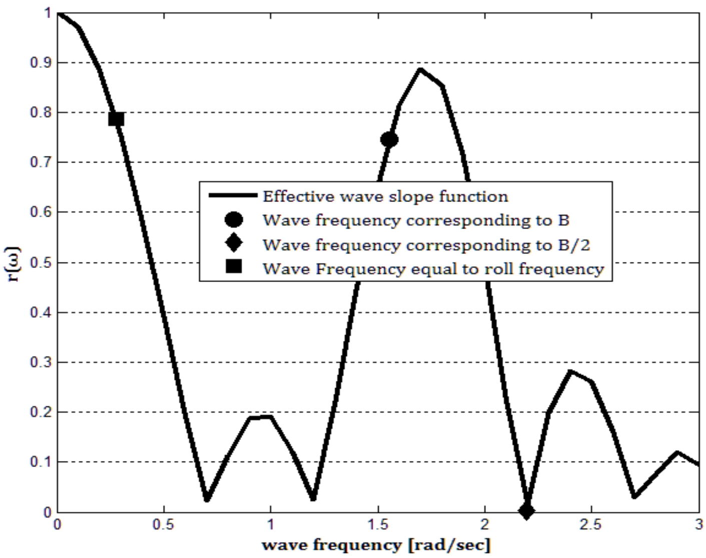



Figure 5.16: RoRo 180 Effective wave slope function for FLA

Damping characteristics that are derived from Ikeda simplified method and methodology for estimation roll damping coefficients are shown in the following figures

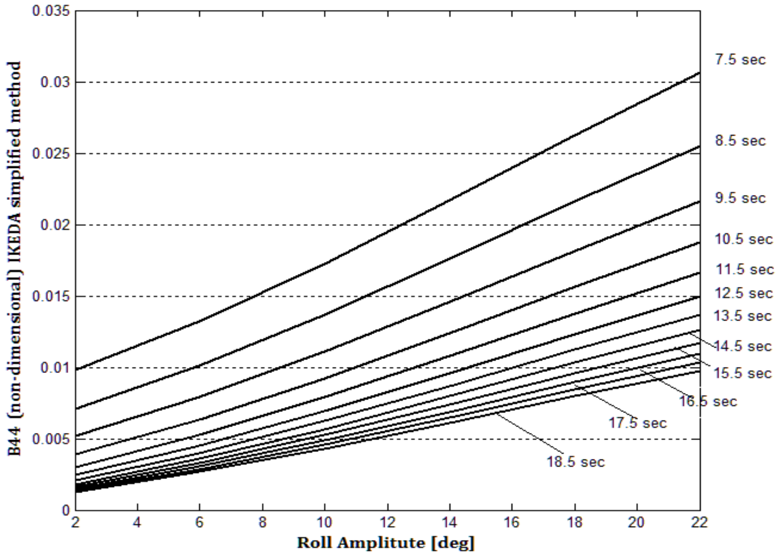



Figure 7.17: RoRo 180, Roll damping coefficient $B_{44}$ for FLA

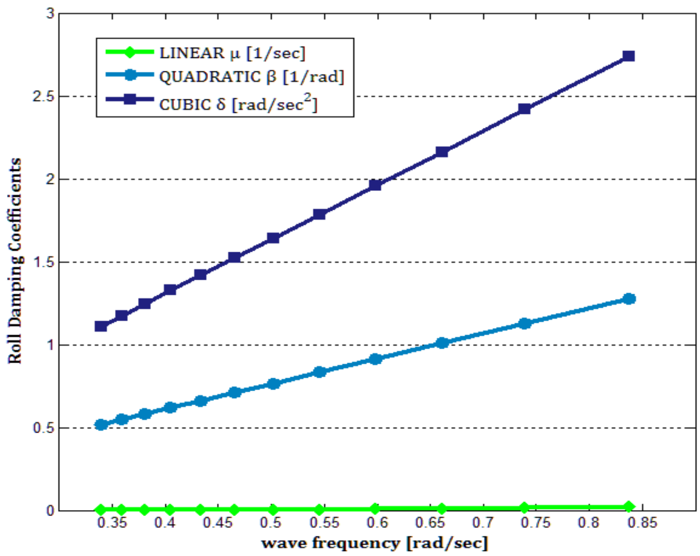



Figure 7.18: RoRo 180, Roll damping coefficients $\mu,\beta,\delta$ for FLA

The value of short-term probability index *Csi* is multiplied with the wave probability *Wi*, for each combination of significant wave height and mean zero crossing wave period

Table 7.20: RoRo 180, WiCi for wave periods between 3.5 and 10.5 sec for FLA condition

| Tz<br>Hs | 3.5 | 4.5 | 5.5 | 6.5 | 7.5 | 8.5 | 9.5 | 10.5 |
|---|---|---|---|---|---|---|---|---|
| **0.5** | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 |
| **1.5** | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 |
| **2.5** | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 |
| **3.5** | 0.0E+00 | 1.2E-16 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 |
| **4.5** | 0.0E+00 | 0.0E+00 | 3.0E-16 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 |

| Hs \ Tz | 3.5 | 4.5 | 5.5 | 6.5 | 7.5 | 8.5 | 9.5 | 10.5 |
|---|---|---|---|---|---|---|---|---|
| **5.5** | 0.0E+00 | 0.0E+00 | 1.3E-11 | 2.1E-15 | 5.5E-19 | 0.0E+00 | 0.0E+00 | 4.5E-18 |
| **6.5** | 0.0E+00 | 0.0E+00 | 2.3E-09 | 4.7E-11 | 9.6E-13 | 4.1E-13 | 2.8E-12 | 4.0E-11 |
| **7.5** | 0.0E+00 | 0.0E+00 | 0.0E+00 | 9.9E-09 | 3.2E-09 | 5.5E-09 | 3.6E-08 | 0.0E+00 |
| **8.5** | 0.0E+00 | 0.0E+00 | 0.0E+00 | 1.7E-07 | 3.1E-07 | 1.2E-06 | 7.4E-06 | 3.2E-05 |
| **9.5** | 0.0E+00 | 0.0E+00 | 0.0E+00 | 7.5E-07 | 3.7E-06 | 2.3E-05 | 1.3E-04 | 3.9E-04 |
| **10.5** | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 8.7E-06 | 7.1E-05 | 3.0E-04 | 6.2E-04 |
| **11.5** | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 3.0E-06 | 3.3E-05 | 1.3E-04 | 2.7E-04 |
| **12.5** | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 1.0E-06 | 1.0E-05 | 4.4E-05 | 9.9E-05 |
| **13.5** | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 3.0E-06 | 1.4E-05 | 3.5E-05 |
| **14.5** | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 1.0E-06 | 4.0E-06 | 1.2E-05 |
| **15.5** | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 1.0E-06 | 4.0E-06 |
| **16.5** | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 1.0E-06 |

Table 7.21: RoRo 180, WiCi for wave periods between 11.5 and 18.5 sec for FLA condition

| Hs \ Tz | 11.5 | 12.5 | 13.5 | 14.5 | 15.5 | 16.5 | 17.5 | 18.5 |
|---|---|---|---|---|---|---|---|---|
| **0.5** | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 |
| **1.5** | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 |
| **2.5** | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 |
| **3.5** | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 |
| **4.5** | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 1.5E-20 | 1.2E-19 | 3.7E-19 | 0.0E+00 |
| **5.5** | 2.0E-16 | 2.9E-15 | 2.2E-14 | 1.1E-13 | 3.2E-13 | 5.7E-13 | 6.0E-13 | 5.9E-13 |
| **6.5** | 3.4E-10 | 1.3E-09 | 2.6E-09 | 3.8E-09 | 4.1E-09 | 3.2E-09 | 1.8E-09 | 7.8E-10 |
| **7.5** | 9.6E-07 | 1.8E-06 | 2.0E-06 | 1.6E-06 | 1.0E-06 | 5.1E-07 | 2.3E-07 | 6.3E-08 |
| **8.5** | 8.0E-05 | 1.0E-04 | 8.3E-05 | 4.8E-05 | 2.2E-05 | 8.3E-06 | 2.5E-06 | 6.1E-07 |
| **9.5** | 6.7E-04 | 6.0E-04 | 3.6E-04 | 1.6E-04 | 5.6E-05 | 1.6E-05 | 3.9E-06 | 9.9E-07 |
| **10.5** | 7.0E-04 | 5.1E-04 | 2.7E-04 | 1.1E-04 | 4.0E-05 | 1.2E-05 | 3.0E-06 | 1.0E-06 |
| **11.5** | 3.1E-04 | 2.5E-04 | 1.4E-04 | 6.4E-05 | 2.4E-05 | 7.0E-06 | 8.5E-11 | 1.0E-06 |
| **12.5** | 1.3E-04 | 1.1E-04 | 6.8E-05 | 3.3E-05 | 1.3E-05 | 4.0E-06 | 1.0E-06 | 0.0E+00 |
| **13.5** | 5.0E-05 | 4.6E-05 | 3.1E-05 | 1.6E-05 | 7.0E-06 | 2.0E-06 | 1.0E-06 | 0.0E+00 |
| **14.5** | 1.8E-05 | 1.8E-05 | 1.3E-05 | 7.0E-06 | 3.0E-06 | 1.0E-06 | 0.0E+00 | 0.0E+00 |
| **15.5** | 6.0E-06 | 7.0E-06 | 5.0E-06 | 3.0E-06 | 1.0E-06 | 1.0E-06 | 0.0E+00 | 0.0E+00 |
| **16.5** | 2.0E-06 | 2.0E-06 | 2.0E-06 | 1.0E-06 | 1.0E-06 | 0.0E+00 | 0.0E+00 | 0.0E+00 |

Summing up all values of tables 7.20 and 7.21 , the long term probability index is obtained as follows

$$C = 0.0075 = 7.5 \cdot 10^{-3}$$

However, loading condition is not consider vulnerable to dead ship stability failure either $R_{DS}$ is 0.04 or 0.06

### 7.5.2 Vessel: RoRo 130 / Loading Condition: Full Load Arrival (FLA)

#### *Level 1 Vulnerability Check*

Table 7.22: RoRo 130, Level 1 Parameters for full load arrival condition

| | | |
|---|---|---|
| 1. | B/d = 3.625 > 3.5 | Fail |
| 2. | -0.3 < (KG/d – 1 = 0.71 ) > 0.5 | Fail |
| 3. | T = 21.14 > 20 sec | Fail |

As long as the above parameters does not meet limit values, loading condition is proceeded to level 2 vulnerability check

### *Level 2 Vulnerability Check*

Table 7.23: RoRo 130, Level 2 variables criterion related to GZ curve

| **Hs** | **U [m/s]** | **$l_{WIND}$ [m]** | **φs [rad]** | **Ares+ [m·rad]** | **Ares- [m·rad]** | **GMres [m]** | **Δφres,EA+ [rad]** | **Δφres,EA- [rad]** |
|---|---|---|---|---|---|---|---|---|
| **0.5** | 3.8124 | 0.0025 | 0.0037 | 0.18 | 0.1838 | 0.6884 | 0.7231 | 0.7308 |
| **1.5** | 7.9301 | 0.011 | 0.0159 | 0.1737 | 0.1903 | 0.6868 | 0.7111 | 0.7444 |
| **2.5** | 11.148 | 0.0217 | 0.0315 | 0.1658 | 0.1987 | 0.6836 | 0.6965 | 0.7624 |
| **3.5** | 13.951 | 0.0339 | 0.0495 | 0.157 | 0.2084 | 0.6782 | 0.6805 | 0.784 |
| **4.5** | 16.495 | 0.0474 | 0.0695 | 0.1476 | 0.2195 | 0.6705 | 0.6636 | 0.8091 |
| **5.5** | 18.856 | 0.062 | 0.0913 | 0.1378 | 0.2316 | 0.6601 | 0.646 | 0.8378 |
| **6.5** | 21.078 | 0.0774 | 0.1149 | 0.1276 | 0.245 | 0.6473 | 0.628 | 0.87 |
| **7.5** | 23.188 | 0.0937 | 0.1403 | 0.1174 | 0.2594 | 0.6323 | 0.6094 | 0.9057 |
| **8.5** | 25.206 | 0.1108 | 0.1675 | 0.1071 | 0.2749 | 0.6159 | 0.5898 | 0.9447 |
| **9.5** | 27.146 | 0.1285 | 0.1966 | 0.097 | 0.2915 | 0.5992 | 0.5689 | 0.9863 |
| **10.5** | 29.019 | 0.1468 | 0.2276 | 0.087 | 0.3093 | 0.5839 | 0.5458 | 1.0292 |
| **11.5** | 30.833 | 0.1657 | 0.2603 | 0.0772 | 0.3282 | 0.5719 | 0.5197 | 1.0713 |
| **12.5** | 32.595 | 0.1852 | 0.2946 | 0.0679 | 0.3484 | 0.5657 | 0.4899 | 1.1098 |
| **13.5** | 34.311 | 0.2052 | 0.33 | 0.059 | 0.3698 | 0.5673 | 0.4561 | 1.1418 |
| **14.5** | 35.986 | 0.2257 | 0.3659 | 0.0506 | 0.3924 | 0.5777 | 0.4186 | 1.1656 |
| **15.5** | 37.622 | 0.2467 | 0.4018 | 0.0428 | 0.4164 | 0.5967 | 0.3786 | 1.1814 |
| **16.5** | 39.2228 | 0.2682 | 0.4371 | 0.0355 | 0.4416 | 0.6225 | 0.3379 | 1.1911 |

Effective wave slope function r(ω) as obtained by the standard method is shown in the following figure

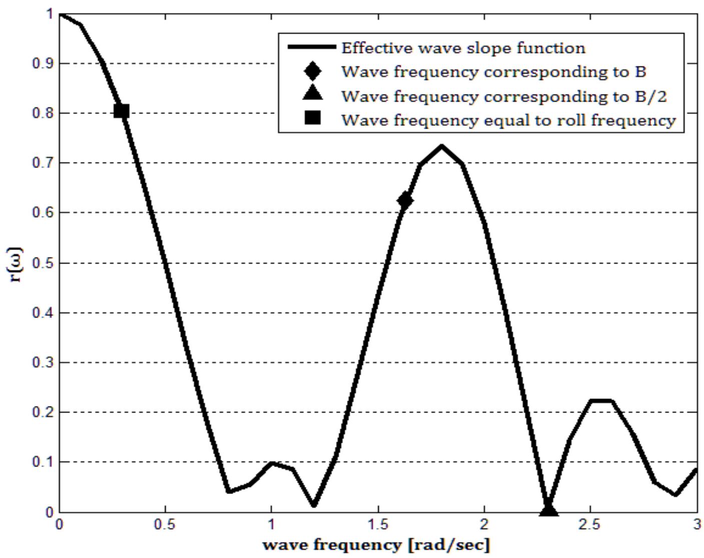



Figure 7.19: RoRo 130 Effective wave slope function for FLA

Damping characteristics as derive from Ikeda simplified method and methodology for estimation roll damping coefficients that is provided on explanatory notes is shown in the following figures

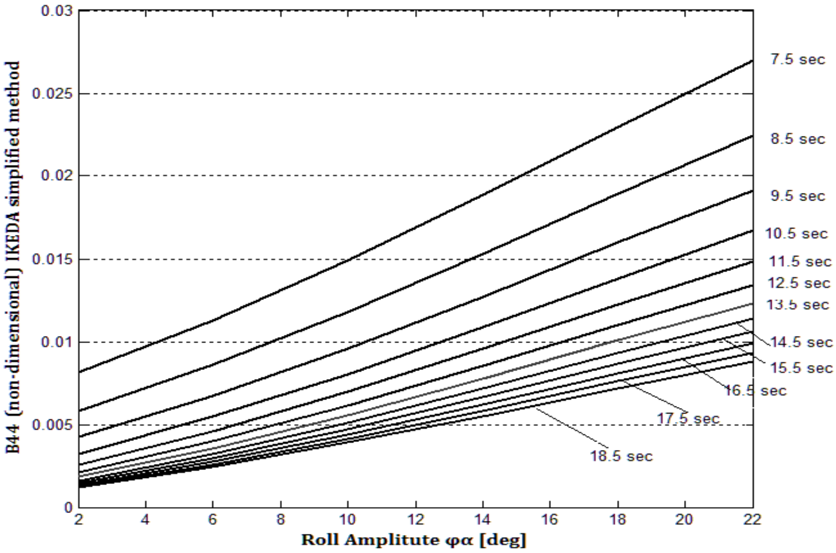



Figure 7.20: RoRo 130, Roll damping coefficient $B_{44}$ for FLA

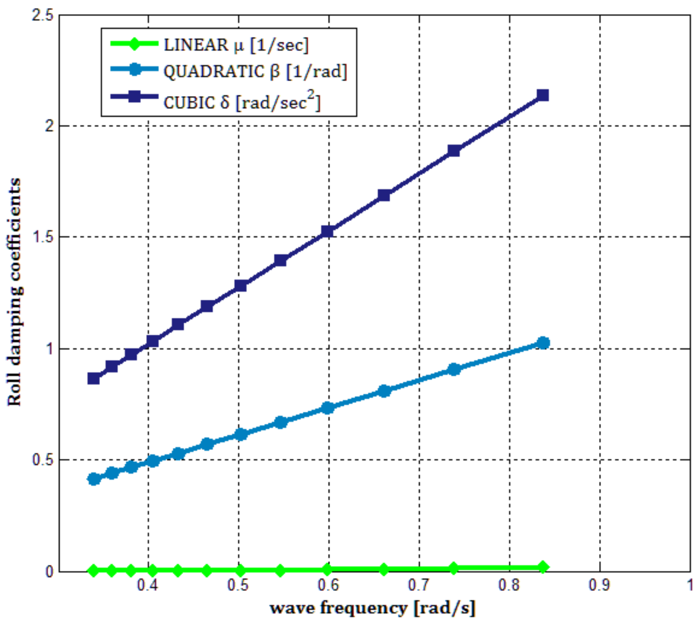



Figure 7.21: RoRo 130, Roll damping coefficients $\mu,\beta,\delta$ for FLA

The value of short-term probability index *Csi* is multiplied with the wave probability *Wi*, for each combination of significant wave height and mean zero crossing wave period.

Table 7.24: RoRo 130, WiCi for wave periods between 3.5 and 10.5 sec for the FLA condition

| Hs \ Tz | 3.5 | 4.5 | 5.5 | 6.5 | 7.5 | 8.5 | 9.5 | 10.5 |
|---|---|---|---|---|---|---|---|---|
| **0.5** | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 |
| **1.5** | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 |
| **2.5** | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 |
| **3.5** | 0.0E+00 | 1.0E-20 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 |
| **4.5** | 0.0E+00 | 0.0E+00 | 6.7E-21 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 |
| **5.5** | 0.0E+00 | 0.0E+00 | 1.1E-14 | 5.7E-20 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 |
| **6.5** | 0.0E+00 | 0.0E+00 | 2.0E-11 | 3.0E-14 | 8.7E-17 | 1.0E-17 | 2.4E-17 | 1.6E-16 |
| **7.5** | 0.0E+00 | 0.0E+00 | 0.0E+00 | 5.1E-11 | 3.3E-12 | 1.7E-12 | 4.5E-12 | 1.8E-11 |
| **8.5** | 0.0E+00 | 0.0E+00 | 0.0E+00 | 3.5E-09 | 1.6E-09 | 2.2E-09 | 6.4E-09 | 2.0E-08 |
| **9.5** | 0.0E+00 | 0.0E+00 | 0.0E+00 | 4.6E-08 | 6.3E-08 | 1.6E-07 | 5.4E-07 | 1.5E-06 |
| **10.5** | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 5.2E-07 | 2.1E-06 | 7.8E-06 | 1.9E-05 |
| **11.5** | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 1.2E-06 | 7.8E-06 | 3.1E-05 | 7.4E-05 |
| **12.5** | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 9.6E-07 | 8.4E-06 | 3.6E-05 | 8.3E-05 |
| **13.5** | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 3.0E-06 | 1.4E-05 | 3.5E-05 |
| **14.5** | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 1.0E-06 | 4.0E-06 | 1.2E-05 |
| **15.5** | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 1.0E-06 | 4.0E-06 |
| **16.5** | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 1.0E-06 |

Table 7.25: RoRo 130, WiCi for wave periods between 11.5 and 18.5 sec for the FLA condition

| Hs \ Tz | 11.5 | 12.5 | 13.5 | 14.5 | 15.5 | 16.5 | 17.5 | 18.5 |
|---|---|---|---|---|---|---|---|---|
| **0.5** | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 |
| **1.5** | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 |
| **2.5** | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 |
| **3.5** | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 |
| **4.5** | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 |
| **5.5** | 0.0E+00 | 0.0E+00 | 0.0E+00 | 4.6E-20 | 1.8E-19 | 3.8E-19 | 4.0E-19 | 3.8E-19 |
| **6.5** | 1.0E-15 | 4.8E-15 | 1.8E-14 | 4.6E-14 | 7.3E-14 | 7.2E-14 | 4.6E-14 | 2.3E-14 |
| **7.5** | 5.3E-11 | 1.1E-10 | 1.9E-10 | 2.2E-10 | 2.2E-10 | 1.5E-10 | 8.0E-11 | 0.0E+00 |
| **8.5** | 3.9E-08 | 5.7E-08 | 6.2E-08 | 5.4E-08 | 3.7E-08 | 1.9E-08 | 8.0E-09 | 2.6E-09 |
| **9.5** | 2.5E-06 | 2.8E-06 | 2.4E-06 | 1.7E-06 | 9.6E-07 | 4.4E-07 | 1.6E-07 | 5.7E-08 |
| **10.5** | 3.0E-05 | 3.0E-05 | 2.3E-05 | 1.4E-05 | 6.9E-06 | 2.8E-06 | 7.7E-07 | 3.8E-07 |
| **11.5** | 1.0E-04 | 9.8E-05 | 6.7E-05 | 3.6E-05 | 1.6E-05 | 5.2E-06 | 1.6E-06 | 8.7E-07 |
| **12.5** | 1.1E-04 | 9.9E-05 | 6.3E-05 | 3.1E-05 | 1.3E-05 | 3.9E-06 | 9.9E-07 | 0.0E+00 |
| **13.5** | 5.0E-05 | 4.6E-05 | 3.1E-05 | 1.6E-05 | 7.0E-06 | 2.0E-06 | 1.0E-06 | 0.0E+00 |
| **14.5** | 1.8E-05 | 1.8E-05 | 1.3E-05 | 7.0E-06 | 3.0E-06 | 1.0E-06 | 0.0E+00 | 0.0E+00 |
| **15.5** | 6.0E-06 | 7.0E-06 | 5.0E-06 | 3.0E-06 | 1.0E-06 | 1.0E-06 | 0.0E+00 | 0.0E+00 |
| **16.5** | 2.0E-06 | 2.0E-06 | 2.0E-06 | 1.0E-06 | 1.0E-06 | 0.0E+00 | 0.0E+00 | 0.0E+00 |

Summing up all values of tables 7.24 and 7.25, the long term probability index is obtained as follows

$$C = 0.0014 = 1.4 \cdot 10^{-3}$$

However, loading condition is not consider vulnerable to dead ship stability failure either $R_{DS}$ is 0.04 or 0.06

## 7.6 EVALUATION OF DEAD SHIP STABILITY CRITERIA

### 7.6.1 Relationship of Level 2 with Level 1 and Weather Criterion

In the current draft regulation a ship in the specified loading condition is considered not to be vulnerable in dead ship condition failure mode on Level 1, when fulfilling the requirements of severe wind and rolling criterion (weather criterion) as defined in [14]. However, a new table has been introduced for the calculation of wave steepness factor *s*, that includes rolling periods higher than 20 sec. In [14] is indicated that all tables and formulas required for the calculation of the angle of roll $\varphi_1$ are based on ships having the following parameters

1. B/d < 3.5
2. -0.3<(KG/d-1)<0.5
3. T<20 sec

For ships with parameters outside the above limits the angle of roll $\varphi_1$ may be determined with model experiments with the procedure described in MSC.1/Circ.1200 as an alternative. On Level 1 check for dead ship condition, according to draft regulation, a ship with parameters outside the above limits should either follow the procedure of MSC.1/Circ.1200 with model experiments or to be subjected directly to Level 2 vulnerability check.

Based on the above, it is obviously understood, based on statistical analysis of modern ship characteristics, that the majority of RoPax and RoRo Cargo vessels will procced directly to Level 2 check, because their design is completely outside of the above limits on every loading condition, especially for B/d ratio, as one can observe in figure 7.22 which comprises an analysis for B/d ratio of 62 RoPax ships, where draft corresponds to maximum load condition, that means that in lighter conditions B/d ratio will be higher. Even the fast type ferries with Froude numbers above 0.35, which perform limited breadth and correspond to the lower points of figure 1.25, perform a B/d ratio higher than 3.5

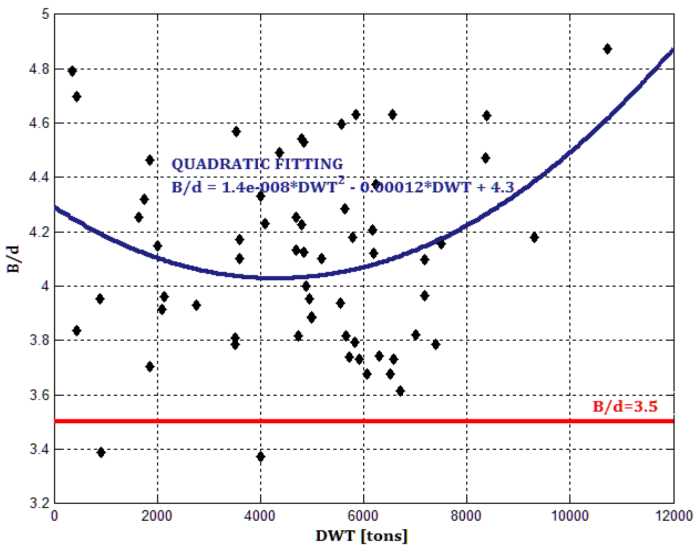



Figure 7.22: B/d ratio on deepest draft for 62 RoPax Ships of various sizes built between 1995 and 2010

Only 2 out of 62 ships in figure 5.22 have a B/d ratio less than 3.5. However, the majority of RoRo ships will require a Level 2 analysis or will follow the procedure of MSC.1/Circ.1200 for determining $\varphi_1$ angle, namely draft regulation considers level 2 criterion for dead ship condition and MSC.1/Circ.1200 as equivalent. However, in the current thesis we put forward an effort in order to examine if the two options are indeed equivalent, using the GM required curves of Level 2, MSC.1/Circ.1200, and weather criterion as formulated in [14]. It should be mentioned that there is little experience on the implementation of MSC.1/Circ.1200 as an alternative to the weather criterion, and the majority of designers of RoRo ships prefer to follow the weather criterion. However relative results were not available, for this reason a procedure was followed in order to estimate the value that $\varphi_1$ angle could have according to MSC.1/Circ.1200, on the sample ships of this thesis. This procedure is based on the alternative procedure 2 that one can find in Explanatory notes of alternative assessment of the weather criterion [15] and is based on the numerical solving of beam-sea roll motion differential equation, which has the following form in case of using only quadratic damping

$$\ddot{\varphi}+\beta\cdot\dot{\varphi}\cdot\left|\dot{\varphi}\right|+\omega_0{}^2\cdot\varphi=\omega_0{}^2\cdot\varphi\cdot\pi\cdot s\cdot a_0\cdot\cos\left(\omega\cdot t\right) \tag{7.15}$$

Where: $\beta$ the quadratic damping coefficient , $\omega_0$ the natural roll frequency, $\omega$ the wave frequency, $s$ the steepness factor, $a_0$ the effective wave slope coefficient

The RoPax ship in [15] that is used as an example for the application of MSC.1/Circ.1200 has the characteristics reported on the following table, for the condition in which roll equation is solved on page 17

Table.7.26 Characteristics of the vessel [15]

| | | | |
|---|---|---|---|
| $L_{BP}$ [m] | 170 | Bilge keels area[m$^2$] | 61.32 |
| B [m] | 25 | KG [m] | 10.63 |
| D [m] | 14.8 | GM [m] | 1.41 |
| d [m] | 6.6 | Flooding angle [deg] | 39.5 |
| Displacement[tons] | 14983 | Roll Period [sec] | 17.9 (according to $T_R$=0.85B/GM$^{0.5}$) |
| $C_B$ | 0.52 | $A_{LATERAL}$ [m$^2$] | 3432 |
| B/d | 3.79 | $Z_{LATERAL}$ [m] | 9.71 |

By solving numerically the roll equation with the parameters $\beta$=0.52 1/rad, $a_0$=0.873, $s$=0.0383, $\omega_0$=0.3344 rad/sec and $\omega$=0.325 rad/sec ($\omega/\omega_0$=0.972) where the maximum amplitude is occurred, the value $\varphi_1$=28.3 deg is arisen as one can verify on page 17 of [15]. The value $\varphi_1$ corresponding to random sea state is $\varphi_1$'=0.7$\varphi_1$=19.8 deg, according to the procedure of [MSC.1/Circ.1200]. The experimentally determined value is $\varphi_1$=19.3 deg. Moreover, it is worth mentioning that $\varphi_1$ angle determined by the formulas of the weather criterion is 15.4 deg namely that on this ship the alternative experimental procedure leads to a more strict weather criterion. The roll equation is again solved but this time with the quadratic coefficient $\beta$=0.5016, calculated according to the fitting procedure on level 2 dead ship condition draft regulation where damping is estimated via Ikeda simplified method. In addition $s$ is derived from the steepness table of MSC.Circ.1200 as s=0.0357, so a steady angle $\varphi_1$=27.776 deg is arisen corresponding to an angle $\varphi_1$=19.44 deg for random waves

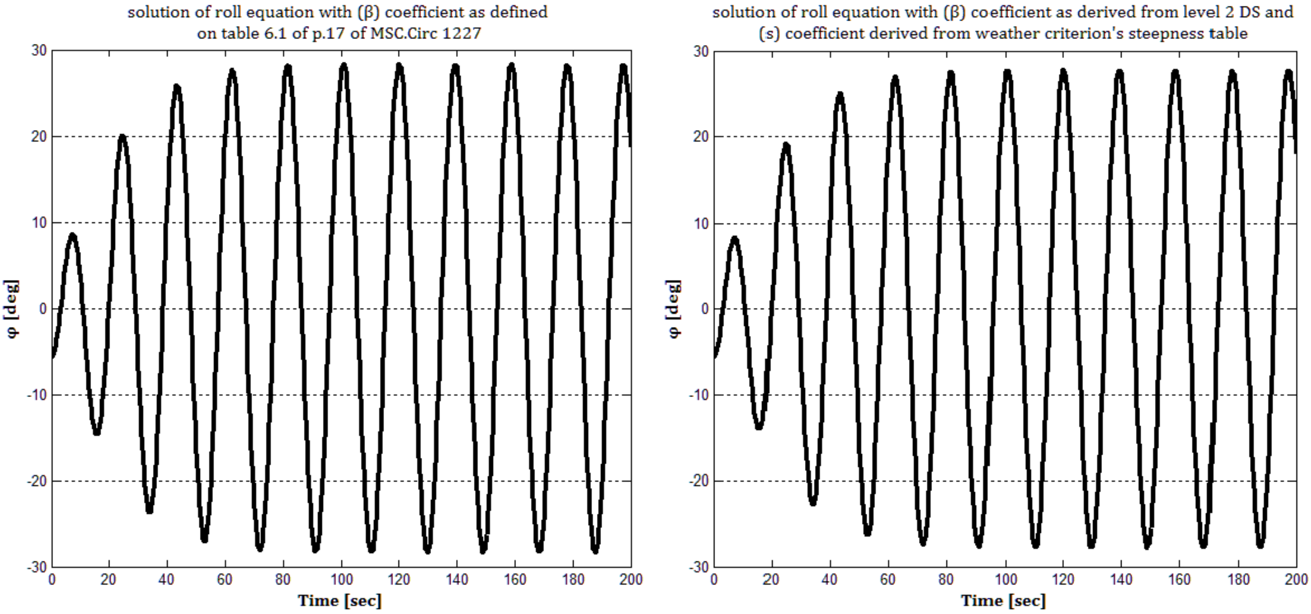



Figure 7.23 Numerical solution of differential equation (7.15) for beam-sea rolling

As long as the two solutions are very close we can conclude that the solution of differential equation of roll using the $\beta$ damping coefficient from fitting procedure and $s$ from the table of the weather criterion can give a reliable estimation for the value of which $\varphi_1$ angle will approximately have according to experimental procedure. However in order to finally examine the relationship between Level 2 dead ship stability and MSC.Circ.1200, the steady roll amplitude $\varphi_1$ is calculated based on the above procedure for RoPax 160 and RoPax 110, effective wave slope coefficient $\alpha_0$ having no other choice is considered as the value that 'standard methodology' of level 2 for effective wave slope function gives for the certain wave period.

Table 7.27 Comparison of $\varphi_1$ angle obtained from weather criterion formulas and MSC.Circ.1200

| | **RoPax 160** | | **RoPax 110** | |
|---|---|---|---|---|
| | **MSC.Circ. 1200 (Estimate)** | **Weather criterion formulas** | **MSC.Circ. 1200 (Estimate)** | **Weather criterion formulas** |
| Deepest draft | | | | |
| Steepness *(s)* | 0.0550 | 0.0550 | 0.0734 | 0.0734 |
| Effective wave slope coefficient $(a_0)$ | 0.7883 | 1.1907 | 0.8082 | 1.1589 |
| Quadratic damping coefficient $(\beta)$ | 0.4283 | - | 0.4813 | - |
| $\varphi_1$ angle | **24.684** | **19.742** | **27.685** | **23.470** |
| Partial draft | | | | |
| Steepness *(s)* | 0.0449 | 0.0449 | 0.0712 | 0.0712 |
| Effective wave slope coefficient $(a_0)$ | 0.8027 | 1.3325 | 0.8349 | 1.2057 |
| Quadratic damping coefficient $(\beta)$ | 0.5410 | - | 0.5414 | - |
| $\varphi_1$ angle | **20.065** | **18.610** | **25.638** | **23.303** |
| Lightest draft | | | | |
| Steepness *(s)* | 0.0623 | 0.0623 | 0.0781 | 0.0781 |
| Effective wave slope coefficient $(a_0)$ | 0.8012 | 1.4256 | 0.8297 | 1.2044 |
| Quadratic damping coefficient $(\beta)$ | 0.5341 | - | 0.4871 | - |
| $\varphi_1$ angle | **24.064** | **21.572** | **28.149** | **23.886** |

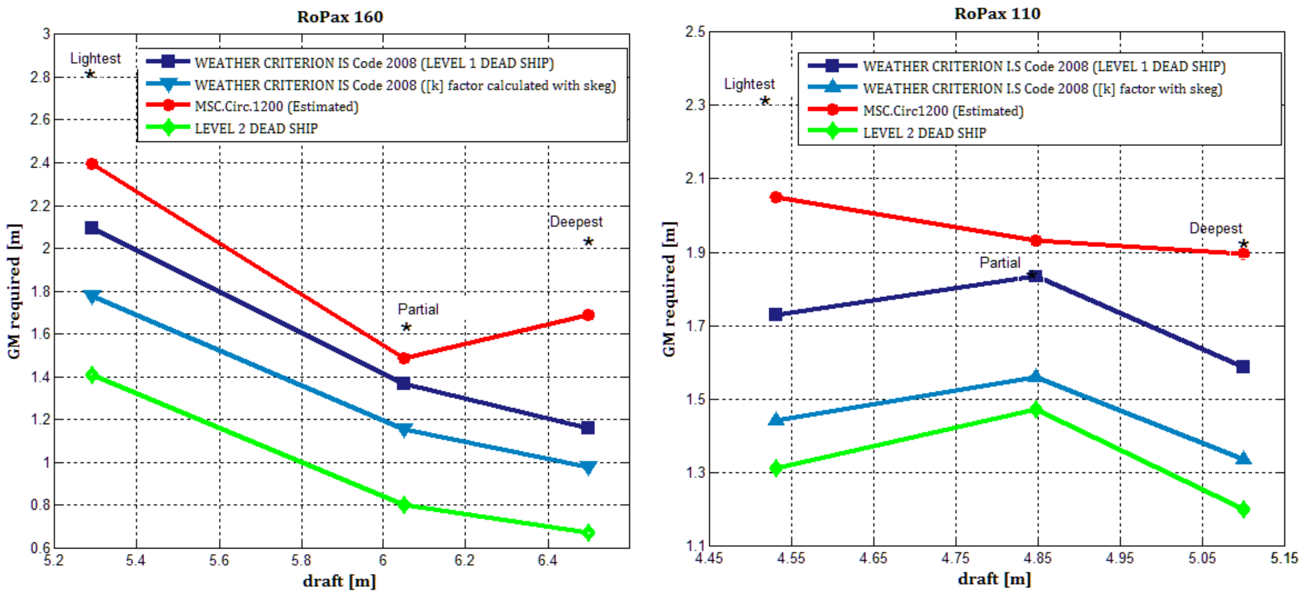



Figure 7.24: RoPax 160, GM required curves related to weather criterion and dead ship stability

### 7.6.2 Inconsistency between Level 1 and Level 2 in case of Small Vessels with Parameters inside the Weather Criterion

RoPax 75 is a vessel that have characteristics inside the boundaries of the formulas of the weather criterion and level 1 draft regulation consequently. The ship performs the following characteristics on her FLD condition

1. B/d=3.38<3.5
2. -0.3<KG/d-1=0.49<0.5
3. T=9.57 <20 sec

Calculations of Level 1 and Level 2 for this vessel was presented in previous paragraphs. After calculations vulnerability on Level 1 stage was not detected. Nevertheless, we proceeded to Level 2 check in order to investigate the consistency between level 1 and level 2. As expected vulnerability on level 2 stage was detected, because *Cs* index is higher than 0.04 or 0.06. Undoubtedly, the fact that level 1 and level 2 is inconsistent in case of vessels with parameters inside boundaries of weather criterion formulas is revealed.

### 7.6.3 Effective Wave Slope Function

#### *7.6.3.1 Effect of GM on effective wave slope function of 'standard methodology'*

The effect of GM value on effective wave slope function's shape that is obtained by the standard methodology of draft regulation, is shown in the figure 7.25 which is referred to RoRo 180 and RoPax 75, two ships with significant different geometry. As one can observe, effective wave slope function is stretched from a descended harmonic function to a more linear shaped one, as GM obtains a higher value.

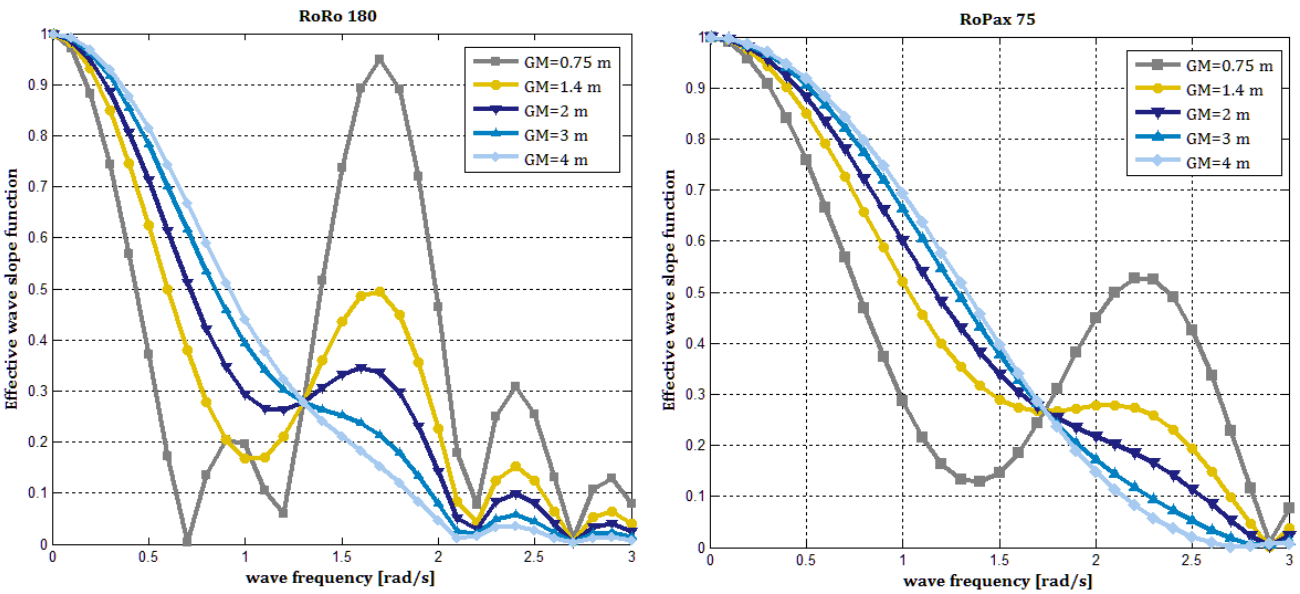



Figure 7.25: Effect of GM value on effective wave slope function

### *7.6.3.2 Effect of draft on effective wave slope function of 'standard methodology'*

The effect of draft on effective wave slope function is indicated on the following figure. For the RoPax 160, effective wave slope function have not significant difference as the draft increases from a light loading condition with 5 m draft to the heaviest loading condition with 6.5 draft.

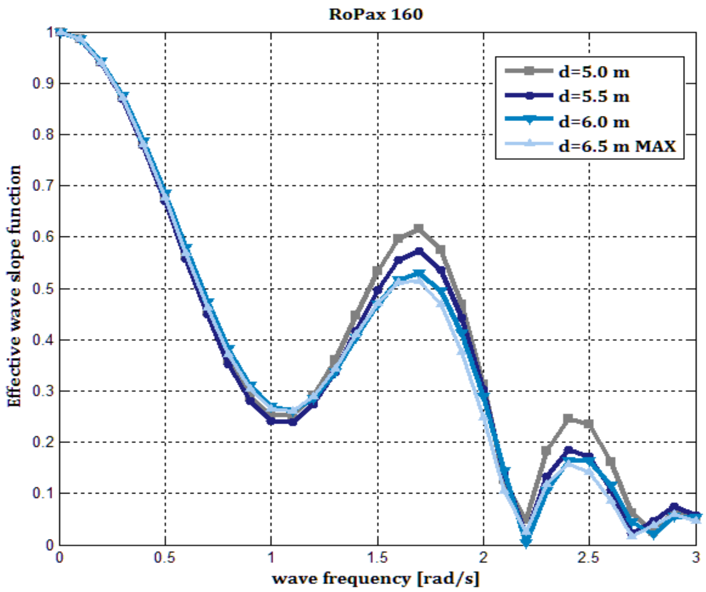



Figure 7.26: RoPax 160-Effect of draft changes on effective wave slope function

### *7.6.3.3 Effect of effective wave slope function form on long-term probability index C*

In general in the current form of draft regulation, effective wave slope function that is arisen from the standard methodology have specific characteristics. The basic concept is that that waves with length smaller than vessel's breadth *B* will have a significant influence and will lead to a high value of effective wave slope coefficient and waves with length larger than *B* will have a negligible influence and the corresponding slope coefficient will be close to zero. For all the examined vessels effective wave slope function is (0) for a wave with length equal to vessel's *B/2*. For a wave length equal to vessel's B the value depends on *GM* and is on the space from (0.2 to 0.7) with smaller values corresponding to higher *GM* values. For a wave with frequency equal to roll frequency a coefficient around to 0.8 was arise for all vessels, something that seems to be in the right way based on experiments. For frequencies above $\omega_0$ and smaller than $\omega(B/2)$ the results are questionable, especially due to the fact that they affect a lot the total long-term index *C* However, the most significant fact is the connection of the function with the loading condition and GM, that plays a very important role on the function shape as one can observe on figure 7.25.

In the first stage of regulation's development effective wave slope function had proposed to be a step function with the form of figure 7.27 and to be independent from *GM* value, there, waves smaller than *B/2* corresponds to a specific constant effective wave slope coefficient and wave larger than *B/2* to a zero coefficient. This assumption seems to be consistent with model experiments

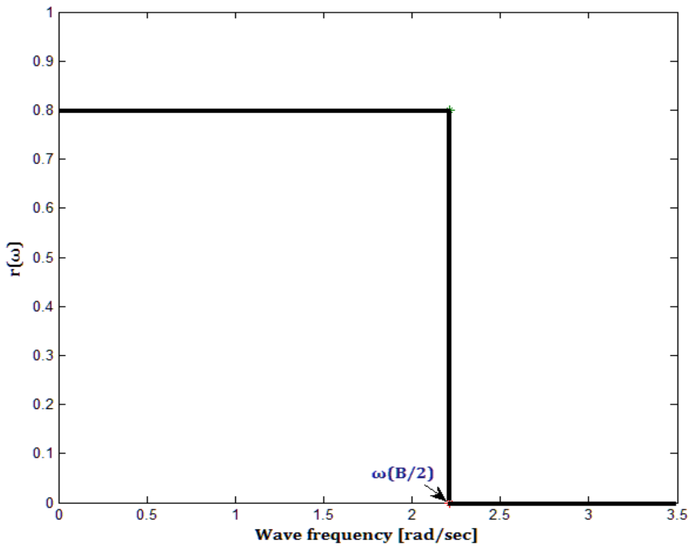



Figure 7.27: Constant slope function

In order to be investigated the effect of function's shape on *C* index *C*, was recomputed for the three loading conditions of the RoPax 160 and the RoPax 110, assuming that effective wave slope function has the form of figure 7.27 with the constant value corresponding to the value, that standard methodology's function gives for the natural roll frequency, and is about 0.7 to 0.8 . The results are shown in table 7.28

Table 7.28: Effect of effective wave slope function's shape on *C* index

| Vessel | Loading condition | [C] Index E.W.S.F Standard | Status if $R_{DS}$=0.04 | Status if $R_{DS}$=0.06 | [C] Index E.W.S.F Constant | Status if $R_{DS}$=0.04 | Status if $R_{DS}$=0.06 |
|---|---|---|---|---|---|---|---|
| **RoPax 160** | Deepest | 0.0052 | Pass | Pass | 0.0255 | Pass | Pass |
| | Partial | 0.0138 | Pass | Pass | 0.0347 | Pass | Pass |
| | Lightest | 0.0055 | Pass | Pass | 0.0268 | Pass | Pass |
| **RoPax 110** | Deepest | 0.0219 | Pass | Pass | 0.0588 | **Fail** | Pass |
| | Partial | 0.0197 | Pass | Pass | 0.0589 | **Fail** | Pass |
| | Lightest | 0.0352 | Pass | Pass | 0.0608 | **Fail** | **Fail** |

However a large difference arose indicating the large impact of effective wave function's form on *C* dead ship vulnerability index, while vulnerability is detected for RoPax 110 in all examined loading condition, if $R_{DS}$=0.04. Moreover GM-required curve for level 2 recomputed for the RoPax 160 with characteristic results, due to the fact that higher GM close to those of the weather criterion, are required, in contrast with the extremely low GM values required from level 2 with the effective wave slope function of the 'standard methodology'.

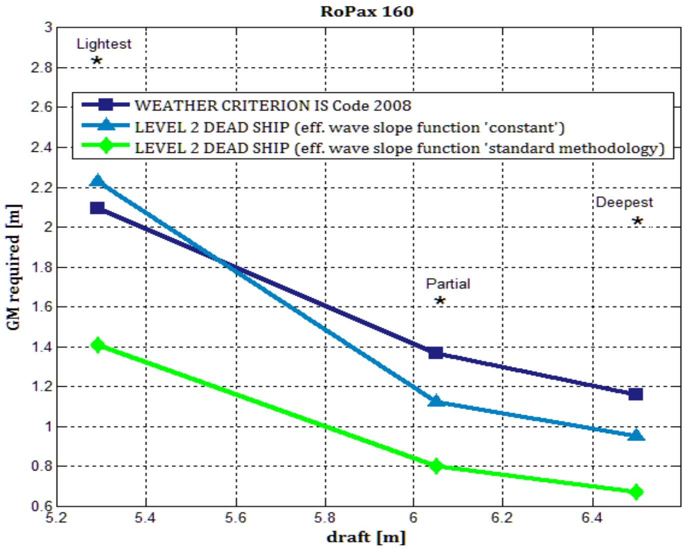



Figure 7.28: Updated *GM* required curve for level 2 for the RoPax 160

### 7.6.4 Effect of *GM* on Long-term Probability Index *C*

Figure 7.29 shows the long term probability index *C* as a function of *GM* for the RoPax 160 and the RoPax 110. As one can observe, *C* is quite high when *GM* is low, as *GM* is increasing *C* is steeply dropped to its minimum observed value, consequently as GM is further increasing *C* is increasing too. This behavior has already been reported in [9] by the delegation of France. However, this behavior may be a source of confusion when a GM-required curve is computed because a loading condition with high *GM* value may be considered vulnerable, when at the same time the minimum GM, required in the same draft, in order *C* index to be less or equal to 0.04 could lower.

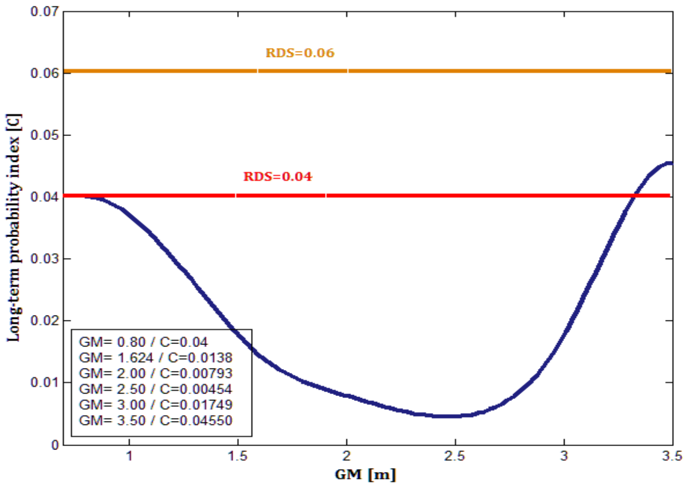



Figure 7.29: RoPax 160, Long-term index *C* versus *GM* for d=6.05

### 7.6.5 General Comments about Dead Ship Stability Criteria

The current Level 2 draft regulation for dead ship stability failure mode seems somehow problematic and requires some further development before it evaluates a ship's vulnerability adequately. A principal issue is effective wave slope function, and the fact that it is connected to vessel's loading condition. It should be mentioned that effective wave slope function plays an important role as roll excitation is multiplied with it and as a consequence the final result is strongly affected.

Another important issue is the procedure based on which the standard deviation of roll velocity $\sigma x'$ and as a consequence the equivalent linear roll damping coefficient $\mu e(\sigma_{x'})$ is calculated. The deriving of $\sigma_{x'}$ by numerically solving the integral equation $F(\sigma_{x'})$ is not straightforward and seems inconsistent with level 2 approaches. As an alternative the above integral equation could be systematically solved for a large number of sample ships in order to be derived from a simplified formula as a function of the involved parameters.

$$F(\sigma_{\dot{x}})=\sigma_{\dot{x}}^2-\int_0^\infty \frac{\omega^2\cdot\omega_0^4}{\left(\omega_{0,e}^2(\phi_S)-\omega^2\right)^2+\left(2\cdot\left(\mu+\sqrt{\frac{2}{\pi}}\cdot\beta\cdot\sigma_{\dot{x}}+\frac{3}{2}\cdot\delta\cdot\sigma_{\dot{x}}^2\right)\cdot\omega\right)^2}\cdot\frac{\left(r(\omega)\cdot\Delta\cdot GM_{res}(\varphi_S)\right)^2\cdot S_{aa}(\omega)+S_{\delta M_{wind,tot}}(\omega)}{\left(\Delta\cdot\overline{GM}\right)^2}d\omega$$

Moreover the equivalent linear roll damping coefficient $\mu e(\sigma_{x'})$ is connected to linear, quadratic and cubic roll damping coefficients $\mu$, $\beta$, $\delta$ respectively which are calculated based on a square fitting procedure which is a function of displacement $\Delta$, roll natural frequency $\omega_0$, GM, rolling amplitude $\varphi_\alpha$ and dimensional roll damping coefficient $B_{44}$ derived from Ikeda's simplified method. The fitting procedure requires $B_{44}$ coefficient in a range of $\varphi_\alpha$ amplitudes which is as large as possible. However, is not specified what value of amplitude is considered as large something leading to misunderstandings. In addition it should be clearly mentioned on explanatory notes that $B_{44}$ is a function of wave period and roll amplitude, in that way a different fitting should be calculated as wave period change. Furthermore, Ikeda simplified has a limit value for wave period around 6.5 sec under of which roll damping coefficient cannot be calculated.

Last but not least the inconsistency between level 1 and 2 which may arise, in case of a vessel with parameters inside limits of the weather criterion formulas, should be carefully examined.

## 7.7 CONCLUSIONS AND POSSIBILITIES FOR IMPROVEMENT ON DEAD SHIP STABILITY CRITERIA

It is believed that effective wave slope function is the key factor for all the structure of level 2 dead ship stability regulation, and further study is necessary before the finalization of regulation. The delegation of Italy that inserts level 2, had considered the effective wave slope function with the constant shape for wave frequencies lower than *B/2*. Calculations with this form of the function shows that the *GM* values required from the criterion are comparable with the *GM* values required by the weather criterion, in contrast to results with the function of standard methodology's that leads to totally unacceptable results. The fact that large ships such as cruise vessels, can pass level 2 with a *GM* value below 1 m is at least questionable. Nevertheless, If the standard methodology will be adopted, it is believed that the value 0.04 for $R_{DS}$ is very high and has to be decreased.

# CHAPTER 8 - PURE LOSS OF STABILITY

## 8.1 PHYSICAL BACKGROUND

Stability reduction in waves is a phenomenon known to naval architects since 19th century when researchers like Froude and Reed in the U.K had observed that a ship's GZ curve could experience a significant change when the ship is sailing to large waves. In 1938 in Germany, Kompf made the significant observation that the stability of a ship could be reduced in following seas when the wave crest is located amidships. Stability failure related to stability reduction on or near the wave crest is entitled 'Pure Loss of Stability' and its nature was identified by model tests which were conducted in the San Francisco bay in the 1970s [Pauling et al. 1972].

Pure loss of stability is clearly a phenomenon of hydrostatic nature, during which the value of initial metacentric height *GM* turns negative, due to the small waterplane area on the wave crest. The hull of modern RoPax ferries, Ro-Ro Cargo ships and Containerships are characterized by wall-sided mid ship sections fore sections with wide flare and barge type sterns. Considering the above, when the ship is on the wave crest draft at midship is increased and a part of the hull on fore and aft sections is emerged. This leads to a reduction of waterplane area. Under this circumstances, the moment of inertia of the waterplane area is being decreased, as a result *GM* may obtain a negative value, for a loading condition of specified *KG*. Capsize depends on the time during which the ship will remain in the condition of negative *GM* value, so vessel has the ability to develop heel angle and finally capsize. Pure loss of stability phenomenon is considered to be more critical when the wave length is comparable with the vessel's length. However, it can also occur for smaller than vessel wave lengths.

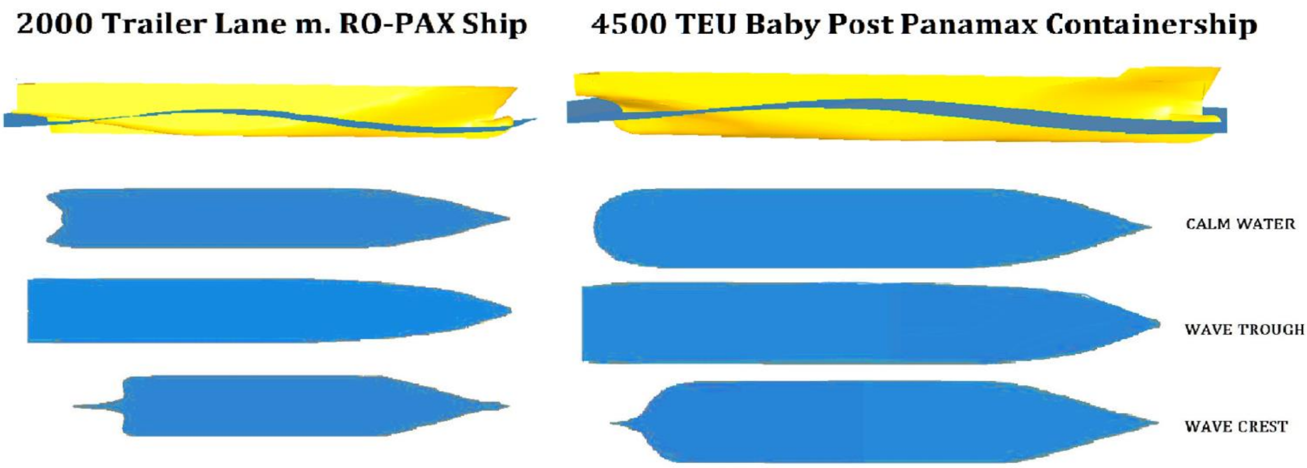



Figure 8.1 Waterplane area alternations of a RoPax and a Containership

## 8.2 LEVEL 1 VULNERABILITY CRITERION FOR PURE LOSS OF STABILITY

Level 1 vulnerability check requires the calculation of $GM$ as a wave equal to $L_{WL}$ passes along the ship. Therefore, if the wave crest can be located in different positions along the vessel's length using a stability software, the minimum value of $GM$ is easily calculated. In the majority of modern ships like RoRo, RoPax and Containerships the minimum $GM$ value arises when the wave crest is located on or near amidships. If the above minimum value is smaller than 0.05 m, the ship is considered vulnerable to pure loss of stability and more detail check on Level 2 must be conducted.

## 8.3 LEVEL 2 VULNERABILITY CRITERION FOR PURE LOSS OF STABILITY

Level 2 check is based on the form of the GZ curve on the wave and requires stability calculations, considering the ship to balance in sinkage and trim on a series of waves with characteristics identified in two different options the first one Option A comes from delegation of Italy and the other one, Option B from delegation of Japan. In order to extract the required values, wave crest centered at different positions along vessel's length

Option A provides 16 wave cases with specified probability, length and height, in which stability calculations have to be conducted.

Option B requires stability calculations on 10 wave that are characterized by $\lambda_i=L_{WL}$ and height according to the equation h=0.01J·L, j=1,2,.....10. The probability of each wave case is extracted from full wave scatter diagram, according to a procedure

For each case, as the wave passes along the ship, the minimum obtained value of angle of vanishing stability $\varphi_v$, taking into account the unprotected openings on vessel's superstructure, the minimum obtained value of angle of heel $\varphi_s$ under the action of heeling level specified by $RPL_3=8(H/\lambda)\cdot d\cdot Fn^2$ ,the maximum obtained value of loll angle $\varphi_{loll}$ and the minimum obtained value of $GZ_{MAX}$ are being calculated. $C1_i$ takes the value 1, when $\varphi_v<30^0$, $C2_i$ when $\varphi_s>15^0$ or $\varphi_{loll}>25^0$ and $C3_i$ when $GZ_{MAX}<RPL_3$. The final being used to judge the vessel's vulnerability or not, is taken as the largest value of three criteria $CR_1$, $CR_2$, $CR_3$ which represent a weighted sum, concerning the violation of the criterion for $\varphi_v$, $\varphi_s$-$\varphi_{loll}$, $GZ_{max}$, respectively. For option A the loading condition is not considered vulnerable to if Max($C1i,C2i,C3i$) $\leq$ 0.06 and for option B if Max($C1i,C2i,C3i$) $\leq$ 0.15

## 8.4 APPLICATION OF PURE LOSS OF STABILITY CRITERIA ON RO-RO PASSENGER SHIPS

### 8.4.1 Vessel: RoPax 160 / Loading Condition: Partial Draft (DP)

***Level 1 Vulnerability Check***

The Froude numbers that correspond to the operational speeds from 20 to 26 kn are 0.256 to 0.32. Therefore Level 1 vulnerability check has to be applied

- Wave Length: $\lambda=L_{WL}$=162 m
- Steepness: $Sw$=0.0334
- Wave Height: $H$=5.41 m

The minimum value of $GM$ is $GM_{MIN}$ = 0.464 m and is arisen when the wave of the above height is located at midship. Therefore $GM_{MIN}$>0.05 and the ship is not considered vulnerable to the phenomenon of pure loss of stability

Figure 8.2: RoPax 160 on the wave crest of a wave with $\lambda$=162 m and $Sw$ = 0.0334

For all loading conditions the results are summarized on the following table

Table 8.1 RoPax 160, Results for Level 1 check for pure loss of stability

| **Loading condition** | | **GM [m]** | **$GM_{MIN}$ [m]** | **Status** |
|---|---|---|---|---|
| DS | Deepest subdivision draft | 2.027 | 0.719 | Pass |
| DP | Partial draft | 1.624 | 0.464 | Pass |
| DL | Lightest service draft | 2.802 | 1.522 | Pass |

### 8.4.2 Vessel: RoPax 110 / Loading Condition: Partial Draft (DP)

***Level 1 Vulnerability Check***

The Froude numbers that correspond to the operational speeds from 20 to 23 kn are 0.30 to 0.34. Therefore Level 1 vulnerability check has to be applied

- Wave Length: $\lambda$=$L_{WL}$=119 m
- Steepness: $Sw$=0.0334
- Wave Height: $H$=3.97 m

The minimum value of GM is $GM_{MIN}$ = 0.275 m and is obtained when the wave of the above height and length is located at midship. Therefore $GM_{MIN}$>0.05 m and the ship is not considered vulnerable to the phenomenon of pure loss of stability.

Figure 8.3: RoPax 110 on the wave crest of a wave crest with $\lambda$=119 m and $Sw$ =0.0334

For all loading conditions the results are summarized on the following table

Table 8.2 RoPax 110, Results for Level 1 check for pure loss of stability

| **Loading condition** | | **GM [m]** | **$GM_{MIN}$ [m]** | **Status** |
|---|---|---|---|---|
| DS | Deepest subdivision draft | 1.904 | 0.423 | Pass |
| DP | Partial draft | 1.834 | 0.275 | Pass |
| DL | Lightest service draft | 2.304 | 1.022 | Pass |

### 8.4.3 Vessel: RoPax 75 / Loading Condition: Deepest Draft (DP)

***Level 1 Vulnerability Check***

The Froude number that corresponds to the usual operational speed is 0.25 for 20 Kn. Therefore Level 1 vulnerability check has to be applied

- Wave Length: $\lambda = L_{WL} = 78$ m
- Steepness: $Sw = 0.0334$
- Wave Height: $H = 2.605$ m

The minimum value of GM is $GM_{MIN} = 0.833$ m and is obtained when the wave of the above height is located at midship. Therefore $GM_{MIN} > 0.05$ and the ship is not considered vulnerable to the phenomenon of pure loss of stability.

Figure 8.4: RoPax 75 on the wave crest of a wave with $\lambda = 78$ m and $Sw = 0.0334$

## 8.5 APPLICATION OF PURE LOSS OF STABILITY CRITERIA ON RO-RO CARGO SHIPS

### 8.5.1 Vessel: RoRo 180 / Loading Condition: Full Load Arrival (FLA)

***Level 1 Vulnerability Check***

The Froude number that corresponds to the usual operational speed of 21 kn is 0.257. Therefore Level 1 vulnerability check has to be applied

- Wave Length: $\lambda = L_{WL} = 181$ m
- Steepness: $Sw = 0.0334$
- Wave Height: $H = 6.045$ m

The minimum value of GM is $GM_{MIN} = -0.34$ m and is obtained when the wave of the above height is located at midship. Therefore $GM_{MIN} < 0.05$ and the loading condition is considered vulnerable to the phenomenon of pure loss of stability. However, Level 2 Vulnerability Check is required.

***Level 2 Vulnerability Check***

OPTION A

Table 8.3 Results for RoRo 180 for option A of Level 2 Check

| Case No. | Weight Wi | Wave Length $\lambda_t$ [m] | Wave Height $H_i$ [m] | $RPL_3$ | $\varphi_v$ [deg] | $\varphi_s$ [deg] | $\varphi_{loll}$ [deg] | $GZ_{MAX}$ MIN | C1i | C2i | C3i |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **1** | 0.000013 | 22.574 | 0.7 | 0.1119 | 52 | 10 | 0 | 0.375 | 0 | 0 | 0 |
| **2** | 0.001654 | 37.316 | 0.99 | 0.0958 | 49.8 | 7 | 0 | 0.368 | 0 | 0 | 0 |
| **3** | 0.020912 | 55.743 | 1.715 | 0.1111 | 49.7 | 6 | 0 | 0.364 | 0 | 0 | 0 |
| **4** | 0.092799 | 77.857 | 2.589 | 0.12 | 42.7 | 6 | 0 | 0.301 | 0 | 0 | 0 |
| **5** | 0.199218 | 103.655 | 3.464 | 0.1206 | 44.5 | 5 | 19 | 0.252 | 0 | 0 | 0 |
| **6** | 0.248788 | 133.139 | 4.41 | 0.1196 | 47.9 | 5 | 32 | 0.067 | 0 | 1 | 1 |
| **7** | 0.208699 | 166.309 | 5.393 | 0.1171 | 46.3 | 4 | 35 | 0.052 | 0 | 1 | 1 |
| **8** | 0.128984 | 203.164 | 6.351 | 0.116 | 46.9 | 4 | 32 | 0.085 | 0 | 1 | 1 |
| **9** | 0.062446 | 243.705 | 7.25 | 0.1074 | 47.6 | 5 | 30.5 | 0.126 | 0 | 1 | 0 |
| **10** | 0.024790 | 287.931 | 8.08 | 0.1013 | 48.6 | 5 | 27 | 0.174 | 0 | 1 | 0 |
| **11** | 0.008367 | 335.843 | 8.841 | 0.095 | 49.1 | 5 | 22 | 0.208 | 0 | 0 | 0 |
| **12** | 0.002473 | 387.44 | 9.539 | 0.0889 | 49.6 | 3 | 17 | 0.236 | 0 | 0 | 0 |
| **13** | 0.000658 | 442.723 | 10.194 | 0.0831 | 50 | 4 | 5 | 0.257 | 0 | 0 | 0 |
| **14** | 0.000158 | 501.691 | 10.739 | 0.0773 | 50.4 | 5 | 0 | 0.279 | 0 | 0 | 0 |
| **15** | 0.000034 | 564.345 | 12.241 | 0.0719 | 51 | 10 | 0 | 0.293 | 0 | 0 | 0 |
| **16** | 0.000007 | 630.684 | 11.9 | 0.0681 | 50.8 | 4 | 0 | 0.305 | 0 | 0 | 0 |

Finally, for option A the total value for all indexes $CR_1$, $CR_2$, $CR_3$ are :

$$CR_1 = \sum_{i=1}^{N} W_i C1_i = 0, \quad CR_2 = \sum_{i=1}^{N} W_i C2_i = 0.6737, \quad CR_3 = \sum_{i=1}^{N} W_i C3_i = 0.5865$$

Therefore the largest value among *CR1*, $CR_2$, $CR_3$ is *CR2*=0.6737>0.06, and the ship fails to pass Level 2 Check, so as far as option A is considered vulnerable to pure loss of stability for the examined loading condition

OPTION B

Table 8.4 Results for RoRo 180 for option B of Level 2 Check

| Case No. | Weight Wi | Wave Length $\lambda_t$ [m] | Wave Height $H_i$ [m] | $RPL_3$ | $\varphi_v$ [deg] | $\varphi_s$ [deg] | $\varphi_{loll}$ [deg] | $GZ_{MAX}$ MIN | C1i | C2i | C3i |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **1** | 0.2296 | 181 | 1.81 | 0.0361 | 50.3 | 1 | **0** | 0.281 | 0 | 0 | 0 |
| **2** | 0.1843 | 181 | 3.62 | 0.0722 | 48.8 | 1 | 25 | 0.179 | 0 | 0 | 0 |
| **3** | 0.0868 | 181 | 5.43 | 0.1083 | 47.8 | 4 | 31 | 0.079 | 0 | 1 | 1 |
| **4** | 0.0316 | 181 | 7.24 | 0.1444 | 0 | - | - | 0 | 1 | 1 | 1 |
| **5** | 0.0093 | 181 | 9.05 | 0.1805 | 0 | - | - | 0 | 1 | 1 | 1 |
| **6** | 0.0023 | 181 | 10.86 | 0.2166 | 0 | - | - | 0 | 1 | 1 | 1 |
| **7** | 0.0005 | 181 | 12.67 | 0.2527 | 0 | - | - | 0 | 1 | 1 | 1 |
| **8** | 0.0001 | 181 | 14.48 | 0.2888 | 0 | - | - | 0 | 1 | 1 | 1 |
| **9** | 0 | 181 | 16.29 | 0.3249 | 0 | - | - | 0 | 1 | 1 | 1 |
| **10** | 0 | 181 | 18.1 | 0.361 | 0 | - | - | 0 | 1 | 1 | 1 |

For option B the total values for all indexes *CR1*, $CR_2$, $CR_3$ are :

$$CR_1 = \sum_{i=1}^{N} W_i C1_i = 0.0438 \ , \ CR_2 = \sum_{i=1}^{N} W_i C2_i = 0.1305 \ , \ CR_3 = \sum_{i=1}^{N} W_i C3_i = 0.1305$$

Therefore the largest value among *CR1*, $CR_2$, $CR_3$ is $CR_2$=0.1305<0.15, and vulnerability is not being detected with option B on level 2 Check , so as far as Option B is not considered vulnerable, to pure loss of stability for the examined loading condition

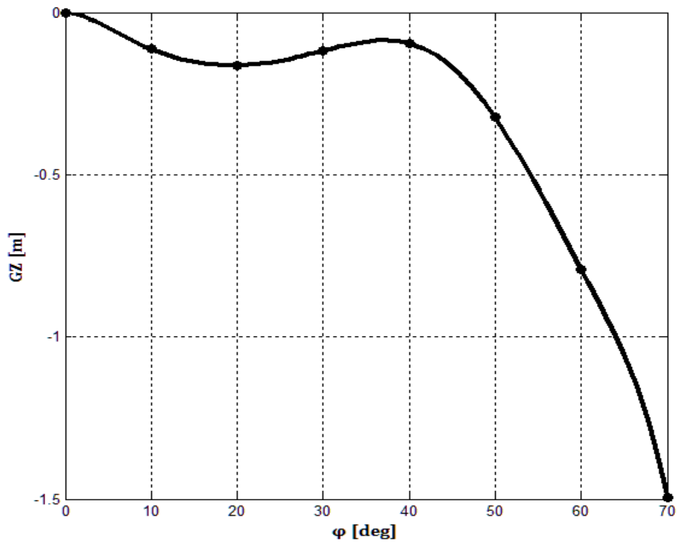



Figure 8.5: RoRo 180 GZ curve on a wave where hydrostatic capsize occurs when initial GM is 0.746 m (wave case 4-option B)

### 8.5.2 Vessel: RoRo 130 / Loading Condition: Full Load Arrival (FLA)

***Level 1 Vulnerability Check***

The Froude number that corresponds to the usual operational speed of 19 kn is 0.27. Therefore Level 1 vulnerability check has to be applied

- Wave Length: $\lambda = L_{WL}$=135 m
- Steepness: $Sw$=0.0334
- Wave Height: $H$=4.509 m

The minimum value of GM is $GM_{MIN}$ = - 0.247 m and is obtained when the wave of the above height is located at midship. Therefore $GM_{MIN}$ < 0.05 and the ship is considered vulnerable to the phenomenon of pure loss of stability. However, Level 2 Vulnerability Check is required.

**Level 2 Vulnerability Check**

OPTION A

Table 8.5 Results for RoRo 130 for option A of Level 2 Check

| Case No. | Weight Wi | Wave Length $\lambda_i$ [m] | Wave Height $H_i$ [m] | $RPL_3$ | $\varphi_v$ [deg] | $\varphi_s$ [deg] | $\varphi_{loll}$ [deg] | $GZ_{MAX}$ MIN | C1i | C2i | C3i |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **1** | 0.000013 | 22.574 | 0.7 | 0.1145 | 41.7 | 8 | 0 | 0.515 | 0 | 0 | 0 |
| **2** | 0.001654 | 37.316 | 0.99 | 0.098 | 40.8 | 6 | 0 | 0.497 | 0 | 0 | 0 |
| **3** | 0.020912 | 55.743 | 1.715 | 0.1136 | 39.6 | 7 | 0 | 0.446 | 0 | 0 | 0 |
| **4** | 0.092799 | 77.857 | 2.589 | 0.1228 | 38 | 5 | 5 | 0.429 | 0 | 0 | 0 |
| **5** | 0.199218 | 103.655 | 3.464 | 0.1234 | 37.5 | 5 | 23 | 0.294 | 0 | 0 | 0 |
| **6** | 0.248788 | 133.139 | 4.41 | 0.1223 | 38.7 | 5 | 22 | 0.259 | 0 | 0 | 0 |
| **7** | 0.208699 | 166.309 | 5.393 | 0.1198 | 40 | 5 | 20 | 0.288 | 0 | 0 | 0 |
| **8** | 0.128984 | 203.164 | 6.351 | 0.1187 | 41.7 | 5 | 16 | 0.328 | 0 | 0 | 0 |
| **9** | 0.062446 | 243.705 | 7.25 | 0.1099 | 41.8 | 5 | 10 | 0.363 | 0 | 0 | 0 |
| **10** | 0.02479 | 287.931 | 8.08 | 0.1036 | 42.7 | 5 | 0 | 0.385 | 0 | 0 | 0 |
| **11** | 0.008367 | 335.843 | 8.841 | 0.0972 | 42.6 | 5 | 0 | 0.410 | 0 | 0 | 0 |
| **12** | 0.002473 | 387.44 | 9.539 | 0.0909 | 43 | 4 | 0 | 0.428 | 0 | 0 | 0 |
| **13** | 0.000658 | 442.723 | 10.194 | 0.085 | 43 | 5 | 0 | 0.441 | 0 | 0 | 0 |
| **14** | 0.000158 | 501.691 | 10.739 | 0.0791 | 43.3 | 4 | 0 | 0.454 | 0 | 0 | 0 |
| **15** | 0.000034 | 564.345 | 12.241 | 0.0736 | 43.3 | 4 | 0 | 0.465 | 0 | 0 | 0 |
| **16** | 0.000007 | 630.684 | 11.9 | 0.0697 | 43.2 | 4 | 0 | 0.474 | 0 | 0 | 0 |

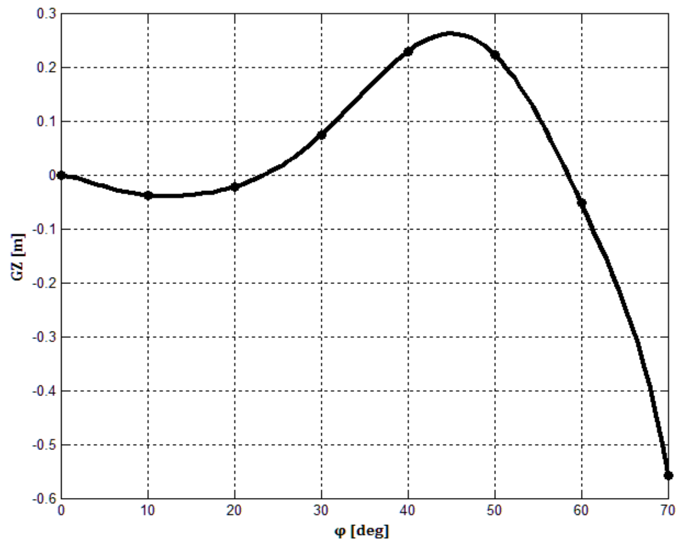



Figure 8.6: GZ curve on a wave where loll angle occurs when initial GM is 0.78 m (wave case 6-option A)

Finally, for option A the total value for all indexes $CR_1$, $CR_2$, $CR_3$ are :

$$CR_1 = \sum_{i=1}^{N} W_i C1_i = CR_2 = \sum_{i=1}^{N} W_i C2_i = CR_3 = \sum_{i=1}^{N} W_i C3_i = 0$$

Therefore by the application of option A the ship passes level 2 Check and is not considered vulnerable to pure loss of stability for the examined loading condition

OPTION B

Table 8.6 Results for RoRo 130 for option B of Level 2 Check

| Case No. | Weight Wi | Wave Length $\lambda_i$ [m] | Wave Height $H_i$ [m] | $RPL_3$ | $\varphi_v$ [deg] | $\varphi_s$ [deg] | $\varphi_{loll}$ [deg] | $GZ_{MAX}$ MIN | C1i | C2i | C3i |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **1** | 0.1963 | 134.9 | 1.349 | 0.0369 | 42 | 1.5 | 0 | 0.448 | 0 | 0 | 0 |
| **2** | 0.2288 | 134.9 | 2.698 | 0.0739 | 40.6 | 3 | 0 | 0.366 | 0 | 0 | 0 |
| **3** | 0.1593 | 134.9 | 4.047 | 0.1108 | 39.3 | 5 | 20 | 0.285 | 0 | 0 | 0 |
| **4** | 0.0884 | 134.9 | 5.396 | 0.1477 | 37.9 | 5 | 29 | 0.206 | 0 | 1 | 0 |
| **5** | 0.0426 | 134.9 | 6.745 | 0.1847 | 36.6 | 6 | 30 | 0.138 | 0 | 1 | 1 |
| **6** | 0.0183 | 134.9 | 8.094 | 0.2216 | 35.3 | 6 | 30 | 0.085 | 0 | 1 | 1 |
| **7** | 0.0067 | 134.9 | 9.443 | 0.2585 | 34.0 | 7 | 32 | 0.040 | 0 | 1 | 1 |
| **8** | 0.0024 | 134.9 | 10.792 | 0.2955 | 0 | 0 | - | 0 | 1 | 1 | 1 |
| **9** | 0.0008 | 134.9 | 12.141 | 0.3324 | 0 | 0 | - | 0 | 1 | 1 | 1 |
| **10** | 0.0002 | 134.9 | 13.49 | 0.3693 | 0 | 0 | - | 0 | 1 | 1 | 1 |

For option B the total values for all indexes $CR_1$, $CR_2$, $CR_3$ are :

$$CR_1 = \sum_{i=1}^{N} W_i C1_i = 0.0034 \ , \ CR_2 = \sum_{i=1}^{N} W_i C2_i = 0.1593 \ , \ CR_3 = \sum_{i=1}^{N} W_i C3_i = 0.0709$$

Therefore the largest value among $CR_1$, $CR_2$, $CR_3$ is $CR_2$=0.1593>0.15, and the ship fails to level 2 Check, so by option B is considered vulnerable to pure loss of stability for the examined loading condition

## 8.6 EVALUATION OF PURE LOSS OF STABILITY CRITERIA

### 8.6.1 Inconsistency between Level 1 and Level 2 on Partial Draft Loading Conditions

The GM-required curves for level 1 and level 2 pure loss of stability criteria computed for the vessel RoRo 180 and an important issue arose which has to do with an inconsistency between level 1 and 2 on low drafts. In general according to 2nd generation intact stability criteria concept GM-required curve of level 1 should be higher than level 2.

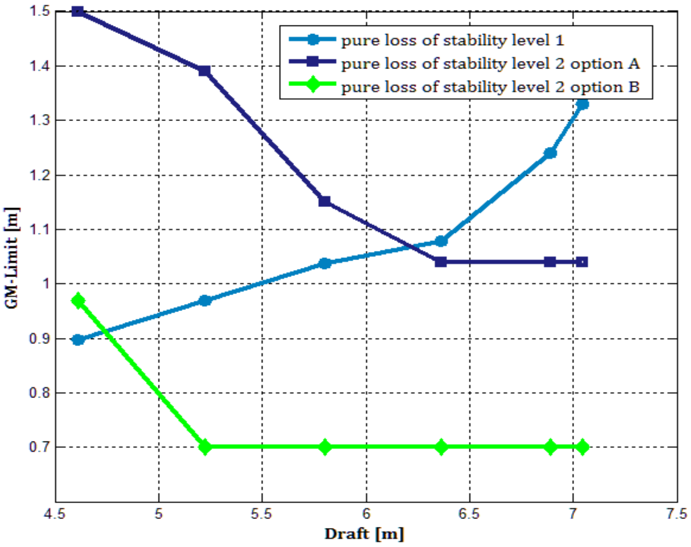



Figure 8.7: GM-required curves for pure loss of stability level 1 and 2

However, as one can observe on figure 8.7 level 1 curve is below level 2 option A curve, for draft lower than around 6.25 m, and below level 2 option B, for draft lower than around 4.7 m. The above inconsistency has already been reported and an explanation can be found in [19] and is related to the fact that level 1 is based on the minimum GM value calculated on a wave when its crest is located near amidships, and this value does not characterize the stability of the ship in large heel angles. In many cases of light loading condition the minimum GM value is near 0.05 which is level 1 limit, but at the same time GZ curve at large heel angles corresponds to hydrostatic capsize of the ship. According to [19] this inconsistency has been observed to some ships in loading conditions where B/d ratio is near 4.75.

Based on the above observation GZ curve on the wave with the crest in the position where the minimum GM value arises, computed for the RoRo 180 for two drafts (4.6 and 5.2 m) where level 1 GM-limit curve is below level 2 (option A) and for two drafts (6.36 and 6.89 m) where level 1 GM-limit curve is under level 2 (option A) for the *KG* required of level 1. Indeed as one can observe in figure 8.8, when the inconsistency occurs, GZ curve on the wave has negative values on some heel angles and stability at large angles corresponds to hydrostatic capsize after a specific value of heel even though level 1 check does not detect vulnerability. Moreover the angle above in which capsize occurs becomes smaller as draft is decreasing (B/d ratio is increasing). On the other hand when inconsistency does not occur GZ curve has the same form as in calm water. However, it is believed that the limit value of 0.05 m for the minimum *GM* on level 1 is not enough and a criteria for GZ curve should be introduced, after the verification of the above observations in a number of sample ships, in order the inconsistency between level 1 and 2 to be overcome.

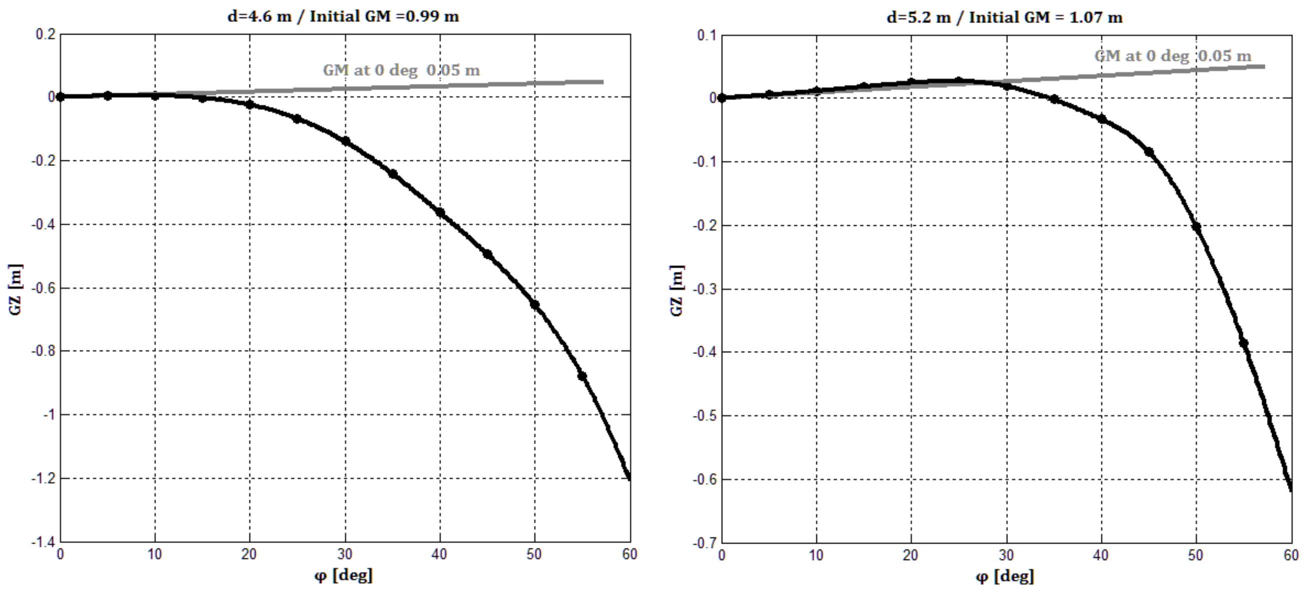



Figure 8.8: RoRo 180-GZ curve on a wave of H/λ=0.0334 for light drafts

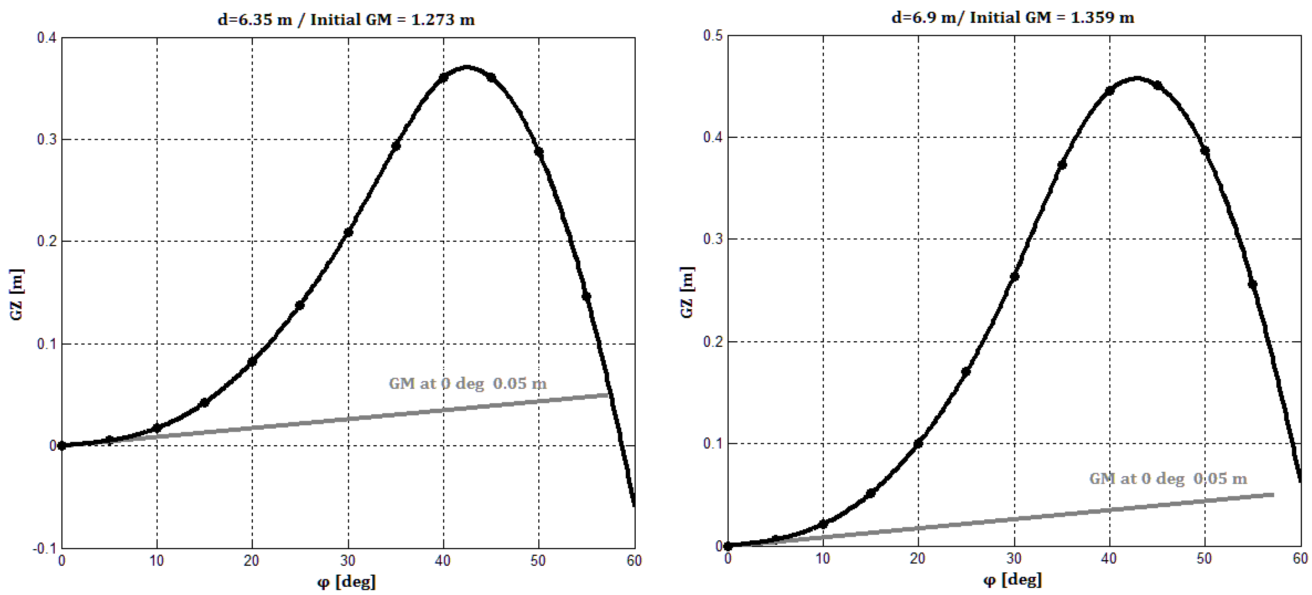



Figure 8.9: RoRo 180-GZ curve on a wave of H/λ=0.0334 for deep drafts

### 8.6.2 Inconsistency between options A and B

The fact that the two options A and B of Level 2 are inconsistent should be underlined. RoRo 130 ($L_{BP}$=132.6 m) was found vulnerable on Level 2 with option B while with option A it was not, and RoRo 180 ($L_{BP}$=179.4 m) was found vulnerable with option A while with option B it was not. Option A is based on 16 wave cases of certain wave length, wave height and probability of occurrence. Pure loss of stability phenomenon is strongly related to the wave length, the most critical case is being when wave length is close to ship length. Nevertheless capsize could be occurred on smaller than ship length waves.

An analysis for accidents due to pure loss of stability on table 8.7 show that in all cases the wave length/$L_{BP}$ ratio was near to 0.7. For the above reason option A seems more appropriate than B. On the other hand with option B, high waves arise for large ships like post-panamax containerships and large RoRo ships, that have probability of occurrence close to zero, whereas vessels do not meet the requirements of draft regulation in the majority of those waves, the total vulnerability index $C_R$ performs very low values and vulnerability is not being detected. On the other hand for smaller ships the arisen wave heights have significant value of probability and as a result vulnerability is detected easily.

Based on the above observations, it is evident that the overcome of the above inconsistencies between two options is of the utmost importance, if not, one can obviously understand that a safety issue emerges. If the designer has the freedom to choose between the two options as equivalent, then all the concept of 2nd generation intact stability is being posed under question, due to the fact that loading conditions with evident characteristics of vulnerability are considered non-vulnerable, especially those with low initial GM values below 1 m, which are undoubtedly vulnerable. A step towards dealing with the problem is margin setting and connection of the two options with the ship's length, after careful examination. For instance if the length of the vessel is $40 < L_{BP} < 150$ m vulnerability check should be carry out with option B, and if $150 < L_{BP} < 300$ m it has to be performed with option A.

### 8.6.3 Time period below negative GM

Another very important issue not included in the current form of draft regulation is the amount of time, spent on a wave under negative GM value. Pure loss of stability is a failure of hydrostatic nature but whether the ship will finally capsize or not depends heavily on the time spending below negative GM. According to [7] time below 'critical' GM can be modelled as:

$$tbc = \frac{|x_2 - x_1|}{c - V_S} \quad [s]$$

Where

- *x1, x2* : are the longitudinal positions on the wave between which GM has negative value
- *c* : is the wave group celerity which in deep water depends only from wave length as

  $$c = \sqrt{\frac{g \cdot \lambda}{2 \cdot \pi}} \quad [m/s]$$
- *Vs* : is vessel's speed [m/s]

*tbc* time interval may be correlated with the period of roll in calm water and a criterion for each wave case could be

$$Cti = \frac{tbc}{T_R}$$

If the above ratio is small or close to zero it means that the ship remains under negative *GM* only for a short period of time and possibly cannot capsize. On the other hand if the ratio approaches 1 or even higher values the ship may cannot return in the upright position, in case of a developed large loll angle and the capsize probability is very high. The minimum value of $tbc/T_R$ should be defined by an analysis of accidents.

Furthermore, the relationship between wave celerity and vessel's speed in which capsize can occur. In table is shown an analysis for 3 accidents related to pure loss of stability on following seas. The data have been derived from the investigation report of each accident, [20], [22], [36]

Table 8.7: wave celerity and ship's speed at major pure loss of stability accidents

| **SHIP** | **$L_{BP}$** | **Vs (kn)** | **Vs (m/s)** | **λ** | **$\lambda/L_{BP}$** | **Cw** | **$\omega_e$ [rad/s]** | **Te [sec]** | **Cw/Vs** |
|---|---|---|---|---|---|---|---|---|---|
| FINNBIRCH | 132 | 18 | 9.27 | 80 | 0.600 | 11.17 | 0.15 | 41.90 | 1.205 |
| COUGAR ACE | 190 | 18.6 | 9.579 | 129 | 0.678 | 14.192 | 0.225 | 27.94 | 1.482 |
| RIVERDANCE | 103.4 | 14.5 | 7.467 | 76.5 | 0.739 | 10.92 | 0.284 | 28.95 | 1.462 |

The above calculations indicate that pure loss of stability in both three cases occurred when the wave had a celerity slightly bigger than the vessel's speed. However after further investigation additional criteria should be introduced. In the current thesis two new criteria are being introduced the first one for the C/V ratio under negative GM as

$$C_{SPEEDi} = \begin{cases} 1 & \text{if } 1.2 < C/V < 1.5 > \text{ and } GM_{MIN} < 0.05 \\ 0 & \text{otherwise} \end{cases}$$

The other one for $tbc/T_R$ as

$$Ct_i = \begin{cases} 1 & \text{if } tcb/T_R > 0.5 \\ 0 & \text{otherwise} \end{cases}$$

The value 0.5 has been introduced based on the assumption that the vessel is travelling on longitudinal waves where negative *GM* can occur, she cannot return upright if a heel has been developed when the time interval spending along negative *GM* is higher than the half roll period . An analysis for the above accidents was not feasible as lines drawings of vessels are not available.

**Vessel: RoRo 180 / Loading Condition: FLA / Roll Period $T_R$=22.65 sec**

***Level 2 Option A wave cases***

| Case No. | Weight Wi | Wave Length $\lambda_i$ [m] | Wave Height $H_i$ [m] | min GM | Wave Frequency $\omega_0$[rad/s] | Wave Celerity C [m/s] | C/Vs (21 kn) | C/Vs (24 kn) |
|---|---|---|---|---|---|---|---|---|
| 1 | 0.000013 | 22.574 | 0.7 | 0.672 | 1.652 | 5.9368 | 0.5489 | 0.4803 |
| 2 | 0.001654 | 37.316 | 0.99 | 0.540 | 1.2849 | 7.6329 | 0.7058 | 0.6176 |
| 3 | 0.020912 | 55.743 | 1.715 | 0.274 | 1.0513 | 9.3291 | 0.8626 | 0.7548 |
| 4 | 0.092799 | 77.857 | 2.589 | 0.144 | 0.8895 | 11.0254 | 1.0195 | 0.892 |
| 5 | 0.199218 | 103.655 | 3.464 | 0.032 | 0.7709 | 12.7215 | 1.1763 | 1.0293 |
| 6 | 0.248788 | 133.139 | 4.41 | -0.152 | 0.6802 | 14.4177 | **1.3331** | 1.1665 |
| 7 | 0.208699 | 166.309 | 5.393 | -0.576 | 0.6086 | 16.114 | **1.49** | **1.3037** |
| 8 | 0.128984 | 203.164 | 6.351 | -0.512 | 0.5507 | 17.8102 | 1.6468 | **1.441** |
| 9 | 0.062446 | 243.705 | 7.25 | -0.435 | 0.5028 | 19.5064 | 1.8036 | 1.5782 |
| 10 | 0.024790 | 287.931 | 8.08 | -0.341 | 0.4626 | 21.2026 | 1.9605 | 1.7154 |
| 11 | 0.008367 | 335.843 | 8.841 | -0.210 | 0.4283 | 22.8988 | 2.1173 | 1.8527 |
| 12 | 0.002473 | 387.44 | 9.539 | -0.164 | 0.3988 | 24.595 | 2.2742 | 1.9899 |
| 13 | 0.000658 | 442.723 | 10.194 | -0.082 | 0.373 | 26.2912 | 2.431 | 2.1271 |
| 14 | 0.000158 | 501.691 | 10.739 | -0.008 | 0.3504 | 27.9874 | 2.5878 | 2.2644 |
| 15 | 0.000034 | 564.345 | 12.241 | 0.033 | 0.3304 | 29.6836 | 2.7447 | 2.4016 |
| 16 | 0.000007 | 630.684 | 11.9 | 0.115 | 0.3125 | 31.3798 | 2.9015 | 2.5388 |

$$CR_{SPEED-21\ kn} = \sum_{i=1}^{N} W_i C_{SPEEDi} = 0.4575 > 0.06 \ , \ CR_{SPEED-24\ kn} = \sum_{i=1}^{N} W_i C_{SPEEDi} = 0.3380 > 0.06$$

| | | $V_S$=21 kn = 10.81 m/s (Fn=0.2567) | | | $V_S$=24 kn = 12.36 m/s (Fn=0.2933) | | |
|---|---|---|---|---|---|---|---|
| Case No. | X2-X1 [m] | Time below Negative GM TBC [sec] | Period of Encounter 0 deg [sec] | TBC/$T_R$ | Time below Negative GM TBC [sec] | Period of Encounter [sec] | TBC/$T_R$ |
| 1 | 0 | 0 | - | 0 | 0 | -3.5152 | 0 |
| 2 | 0 | 0 | - | 0 | 0 | -7.8974 | 0 |
| 3 | 0 | 0 | - | 0 | 0 | -18.4059 | 0 |
| 4 | 0 | 0 | 365.2316 | 0 | 0 | -58.4587 | 0 |
| 5 | 0 | 0 | 54.2763 | 0 | 0 | 284.1684 | 0 |
| 6 | 44.85 | 12.4488 | 36.9175 | **0.5495** | 21.7957 | 64.5868 | **0.9621** |
| 7 | 64.59 | 12.1892 | 31.361 | **0.5381** | 17.2058 | 44.254 | **0.7595** |
| 8 | 53.82 | 7.6939 | 29.0247 | 0.3396 | 9.8749 | 37.2458 | 0.4359 |
| 9 | 53.82 | 6.1923 | 28.0239 | 0.2733 | 7.5311 | 34.0783 | 0.3324 |
| 10 | 44.85 | 4.3177 | 27.7044 | 0.1906 | 5.072 | 32.5421 | 0.2239 |
| 11 | 44.85 | 3.7116 | 27.7795 | 0.1638 | 4.2557 | 31.8497 | 0.1879 |
| 12 | 35.88 | 2.6038 | 28.1034 | 0.1149 | 2.9326 | 31.6504 | 0.1295 |
| 13 | 26.91 | 1.7388 | 28.5944 | 0.0768 | 1.9316 | 31.764 | 0.0853 |
| 14 | 0 | 0 | 29.2029 | 0 | 0 | 32.0887 | 0 |
| 15 | 0 | 0 | 29.8973 | 0 | 0 | 32.5625 | 0 |
| 16 | 0 | 0 | 30.6562 | 0 | 0 | 33.1454 | 0 |

$$CR_{TIME-21\ kn} = \sum_{i=1}^{N} W_i C_{TIMEi} = 0.4575 > 0.06 \ , \ CR_{TIME-24\ kn} = \sum_{i=1}^{N} W_i C_{TIMEi} = 0.4575 > 0.06$$

### *Level 2 Option B wave cases*

| Case No. | Weight Wi | Wave Length $\lambda_i$ [m] | Wave Height $H_i$ [m] | min GM | Wave Frequency $\omega_0$[rad/s] | Wave Celerity C [m/s] | C/Vs (21 kn) | C/Vs (24 kn) |
|---|---|---|---|---|---|---|---|---|
| **1** | 0.2296 | 181 | 1.81 | 0.05 | 0.5834 | 16.81 | 1.554 | **1.36** |
| **2** | 0.1843 | 181 | 3.62 | -0.087 | 0.5834 | 16.81 | 1.554 | **1.36** |
| **3** | 0.0868 | 181 | 5.43 | -0.521 | 0.5834 | 16.81 | 1.554 | **1.36** |
| **4** | 0.0316 | 181 | 7.24 | -0.676 | 0.5834 | 16.81 | 1.554 | **1.36** |
| **5** | 0.0093 | 181 | 9.05 | -0.787 | 0.5834 | 16.81 | 1.554 | **1.36** |
| **6** | 0.0023 | 181 | 10.86 | -0.871 | 0.5834 | 16.81 | 1.554 | **1.36** |
| **7** | 0.0005 | 181 | 12.67 | -0.941 | 0.5834 | 16.81 | 1.554 | **1.36** |
| **8** | 0.0001 | 181 | 14.48 | -0.990 | 0.5834 | 16.81 | 1.554 | **1.36** |
| **9** | 0 | 181 | 16.29 | -1.045 | 0.5834 | 16.81 | 1.554 | **1.36** |
| **10** | 0 | 181 | 18.1 | -1.079 | 0.5834 | 16.81 | 1.554 | **1.36** |

$$CR_{SPEED-21\ kn} = \sum_{i=1}^{N} W_i C_{SPEEDi} = 0 < 0.15 \ , \ CR_{SPEED-24\ kn} = \sum_{i=1}^{N} W_i C_{SPEEDi} = 0.3149 > 0.15$$

| | | $V_S$=21 kn = 10.81 m/s (Fn=0.2567) | | | $V_S$=24 kn = 12.10 m/s (Fn=0.2933) | | |
|---|---|---|---|---|---|---|---|
| **Case No.** | **X2-X1 [m]** | **Time below Negative GM TBC [sec]** | **Period of Encounter 0 deg [sec]** | **$TBC/T_R$** | **Time below Negative GM TBC [sec]** | **Period of Encounter 0 deg [sec]** | **$TBC/T_R$** |
| **1** | 0 | 0 | 30.18 | 0 | 0 | 40.63 | 0 |
| **2** | 44.95 | 7.4971 | 30.18 | 0.3309 | 10.0997 | 40.63 | 0.4458 |
| **3** | 53.82 | 8.9765 | 30.18 | 0.3963 | 12.0927 | 40.63 | **0.5338** |
| **4** | 62.79 | 10.4726 | 30.18 | 0.4623 | 14.1081 | 40.63 | **0.6228** |
| **5** | 62.79 | 10.4726 | 30.18 | 0.4623 | 14.1081 | 40.63 | **0.6228** |
| **6** | 53.82 | 8.9765 | 30.18 | 0.3963 | 12.0927 | 40.63 | **0.5338** |
| **7** | 53.82 | 8.9765 | 30.18 | 0.3963 | 12.0927 | 40.63 | **0.5338** |
| **8** | 53.82 | 8.9765 | 30.18 | 0.3963 | 12.0927 | 40.63 | **0.5338** |
| **9** | 53.82 | 8.9765 | 30.18 | 0.3963 | 12.0927 | 40.63 | **0.5338** |
| **10** | 53.82 | 8.9765 | 30.18 | 0.3963 | 12.0927 | 40.63 | **0.5338** |

$$CR_{TIME-21\ kn} = \sum_{i=1}^{N} W_i C_{TIMEi} = 0.00 < 0.15 \ , \ CR_{TIME-24\ kn} = \sum_{i=1}^{N} W_i C_{TIMEi} = 0.1305 < 0.15$$

**Vessel: RoRo 130 / Loading Condition: FLA / Roll Period $T_R$=21.17sec**

**Level 2 Option A wave cases**

| Case No. | Weight Wi | Wave Length $\lambda_i$ [m] | Wave Height $H_i$ [m] | min GM | Wave Frequency $\omega_0$[rad/s] | Wave Celerity C [m/s] | C/Vs (19 kn) | C/Vs (22.5 kn) |
|---|---|---|---|---|---|---|---|---|
| **1** | 0.000013 | 22.574 | 0.7 | 0.640 | 1.652 | 5.9368 | 0.6067 | 0.5123 |
| **2** | 0.001654 | 37.316 | 0.99 | 0.620 | 1.2849 | 7.6329 | 0.7801 | 0.6587 |
| **3** | 0.020912 | 55.743 | 1.715 | 0.350 | 1.0513 | 9.3291 | 0.9534 | 0.8051 |
| **4** | 0.092799 | 77.857 | 2.589 | -0.429 | 0.8895 | 11.0254 | 1.1268 | 0.9515 |
| **5** | 0.199218 | 103.655 | 3.464 | -0.273 | 0.7709 | 12.7215 | **1.3001** | 1.0979 |
| **6** | 0.248788 | 133.139 | 4.41 | -0.280 | 0.6802 | 14.4177 | **1.4735** | **1.2443** |
| **7** | 0.208699 | 166.309 | 5.393 | -0.226 | 0.6086 | 16.114 | 1.6468 | **1.3906** |
| **8** | 0.128984 | 203.164 | 6.351 | -0.146 | 0.5507 | 17.8102 | 1.8202 | 1.537 |
| **9** | 0.062446 | 243.705 | 7.25 | -0.073 | 0.5028 | 19.5064 | 1.9935 | 1.6834 |
| **10** | 0.024790 | 287.931 | 8.08 | 0.004 | 0.4626 | 21.2026 | 2.1668 | 1.8298 |
| **11** | 0.008367 | 335.843 | 8.841 | 0.080 | 0.4283 | 22.8988 | 2.3402 | 1.9762 |
| **12** | 0.002473 | 387.44 | 9.539 | 0.144 | 0.3988 | 24.595 | 2.5135 | 2.1225 |
| **13** | 0.000658 | 442.723 | 10.194 | 0.201 | 0.373 | 26.2912 | 2.6869 | 2.2689 |
| **14** | 0.000158 | 501.691 | 10.739 | 0.257 | 0.3504 | 27.9874 | 2.8602 | 2.4153 |
| **15** | 0.000034 | 564.345 | 12.241 | 0.284 | 0.3304 | 29.6836 | 3.0336 | 2.5617 |
| **16** | 0.000007 | 630.684 | 11.9 | 0.347 | 0.3125 | 31.3798 | 3.2069 | 2.7081 |

$$CR_{SPEED-19\ kn} = \sum_{i=1}^{N} W_i C_{SPEEDi} = 0.4480 > 0.06 \ , \ CR_{SPEED-22.5\ kn} = \sum_{i=1}^{N} W_i C_{SPEEDi} = 0.4574 > 0.06$$

| | | $V_S$=19 kn = 9.78 m/s (Fn=0.269) | | | $V_S$=22.5kn = 12.10 m/s (Fn=0.2872) | | |
|---|---|---|---|---|---|---|---|
| **Case No.** | **X2-X1 [m]** | **Time below Negative GM TBC [sec]** | **Period of Encounter 0 deg [sec]** | **TBC/$T_R$** | **Time below Negative GM TBC [sec]** | **Period of Encounter [sec]** | **TBC/$T_R$** |
| **1** | 0 | 0 | - | 0 | 0 | - | 0 |
| **2** | 0 | 0 | - | 0 | 0 | - | 0 |
| **3** | 0 | 0 | - | 0 | 0 | - | 0 |
| **4** | 25.19 | 20.31 | 62.628 | **0.959** | 44.819 | - | 2.1187 |
| **5** | 26.52 | 9.031 | 35.2596 | 0.4265 | 23.3853 | 91.144 | **1.1044** |
| **6** | 33.15 | 7.1556 | 28.716 | 0.3379 | 11.7128 | 46.9809 | **0.5532** |
| **7** | 26.52 | 4.1903 | 26.2605 | 0.1979 | 5.8589 | 36.7083 | 0.2767 |
| **8** | 26.52 | 3.3046 | 25.3016 | 0.1561 | 4.2618 | 32.6254 | 0.2013 |
| **9** | 19.89 | 2.046 | 25.0562 | 0.0966 | 2.5117 | 30.756 | 0.1186 |
| **10** | 0 | 0 | 25.2063 | 0 | 0 | 29.929 | 0 |
| **11** | 0 | 0 | 25.5986 | 0 | 0 | 29.6757 | 0 |
| **12** | 0 | 0 | 26.1497 | 0 | 0 | 29.7716 | 0 |
| **13** | 0 | 0 | 26.8108 | 0 | 0 | 30.096 | 0 |
| **14** | 0 | 0 | 27.551 | 0 | 0 | 30.5778 | 0 |
| **15** | 0 | 0 | 28.3503 | 0 | 0 | 31.173 | 0 |
| **16** | 0 | 0 | 29.1946 | 0 | 0 | 31.8523 | 0 |

$$CR_{TIME-19\ kn} = \sum_{i=1}^{N} W_i C_{TIMEi} = 0.0928 > 0.06 \ , \ CR_{TIME-22.5\ kn} = \sum_{i=1}^{N} W_i C_{TIMEi} = 0.448 > 0.06$$

*Level 2 Option B wave cases*

| Case No. | Weight Wi | Wave Length $\lambda_i$ [m] | Wave Height $H_i$ [m] | min GM | Wave Frequency $\omega_0$[rad/s] | Wave Celerity C [m/s] | C/Vs (19 kn) | C/Vs (22.5 kn) |
|---|---|---|---|---|---|---|---|---|
| **1** | 0.1963 | 134.9 | 1.349 | 0.230 | 0.6758 | 14.51 | **1.483** | **1.25** |
| **2** | 0.2288 | 134.9 | 2.698 | -0.038 | 0.6758 | 14.51 | **1.483** | **1.25** |
| **3** | 0.1593 | 134.9 | 4.047 | -0.230 | 0.6758 | 14.51 | **1.483** | **1.25** |
| **4** | 0.0884 | 134.9 | 5.396 | -0.366 | 0.6758 | 14.51 | **1.483** | **1.25** |
| **5** | 0.0426 | 134.9 | 6.745 | -0.471 | 0.6758 | 14.51 | **1.483** | **1.25** |
| **6** | 0.0183 | 134.9 | 8.094 | -0.554 | 0.6758 | 14.51 | **1.483** | **1.25** |
| **7** | 0.0067 | 134.9 | 9.443 | -0.622 | 0.6758 | 14.51 | **1.483** | **1.25** |
| **8** | 0.0024 | 134.9 | 10.792 | -0.630 | 0.6758 | 14.51 | **1.483** | **1.25** |
| **9** | 0.0008 | 134.9 | 12.141 | -0.732 | 0.6758 | 14.51 | **1.483** | **1.25** |
| **10** | 0.0002 | 134.9 | 13.49 | -0.777 | 0.6758 | 14.51 | **1.483** | **1.25** |

$$CR_{SPEED-21\ kn} = \sum_{i=1}^{N} W_i C_{SPEEDi} = 0.5475 > 0.15 \ , \ CR_{SPEED-24\ kn} = \sum_{i=1}^{N} W_i C_{SPEEDi} = 0.5475 > 0.15$$

| | | $V_S$=19 kn = 9.78 m/s (Fn=0.269) | | | $V_S$=22.5kn = 11.56 m/s (Fn=0.3185) | | |
|---|---|---|---|---|---|---|---|
| **Case No.** | **X2-X1 [m]** | **Time below Negative GM TBC [sec]** | **Period of Encounter 0 deg [sec]** | **TBC/$T_R$** | **Time below Negative GM TBC [sec]** | **Period of Encounter 0 deg [sec]** | **TBC/$T_R$** |
| **1** | 0 | 0 | 28.53 | 0 | 0 | 46.05 | 0 |
| **2** | 6.630 | 1.4023 | 28.53 | 0.0662 | 2.2664 | 46.05 | 0.1070 |
| **3** | 33.15 | 7.0117 | 28.53 | 0.3311 | 11.3322 | 46.05 | **0.5352** |
| **4** | 33.15 | 7.0117 | 28.53 | 0.3311 | 11.3322 | 46.05 | **0.5352** |
| **5** | 39.78 | 8.4141 | 28.53 | 0.3974 | 13.5987 | 46.05 | **0.6422** |
| **6** | 39.78 | 8.4141 | 28.53 | 0.3974 | 13.5987 | 46.05 | **0.6422** |
| **7** | 39.78 | 8.4141 | 28.53 | 0.3974 | 13.5987 | 46.05 | **0.6422** |
| **8** | 39.78 | 8.4141 | 28.53 | 0.3974 | 13.5987 | 46.05 | **0.6422** |
| **9** | 39.78 | 8.4141 | 28.53 | 0.3974 | 13.5987 | 46.05 | **0.6422** |
| **10** | 39.78 | 8.4141 | 28.53 | 0.3974 | 13.5987 | 46.05 | **0.6422** |

$$CR_{TIME-21\ kn} = \sum_{i=1}^{N} W_i C_{TIMEi} = 0.00 < 0.15 \ , \ CR_{TIME-24\ kn} = \sum_{i=1}^{N} W_i C_{TIMEi} = 0.3187 > 0.15$$

## 8.7 CONCLUSION - POSSIBILITIES FOR IMPROVEMENT OF PURE LOSS OF STABILITY CRITERIA

Pure loss of stability is a stability failure on waves that is strongly connected with the safety of RoRo vessels especially RoRo cargo vessels and probably pure car carrier vessels and not so much for the RoPax vessels that operate in higher GM values. Major accidents on RoRo cargo vessels due to pure loss of stability, such as the capsize of 'Finnbirch' or 'Riverdance' were not luckily connected with many fatalities, even though more attention was required. In [9], is recognized that the critical condition for capsize is when the wave celerity is slightly above the ship's speed. As one can observe in table 8.7 this condition was fulfilled in the three pure loss of stability accidents. Although, pure loss of stability regulation has been finalized, an analysis for the relationship between vessel's speed and wave's celerity similar to that carried out on previous paragraphs is of the utmost importance. The inconsistency between option A and B should be also carefully examined. Another important aspect which may be included in the regulation is the separation of passenger from cargo ships. Pure loss of stability is a dangerous phenomenon and its appearance to a passenger ship may have tremendous consequences. If we take into account the risk-based character of the 2nd generation intact stability, the probability should be close to zero for the minimization of risk. For this reason it seems that level 1 check should be more conservative for a passenger ship and the calculation of the minimum GM on the wave is preferable to be carried out based on a higher wave and not those with $s$=0.0344. In general passenger ships operate in higher *GM* values today, due to damage stability. However a good margin on level 1 check is observed in contrast to RoRo Cargo ships. In addition the wave height on which the negative *GM* occurs seems not to be dependent on vessel's size but on the hull form and the initial *GM*. As is shown on figure 8.10 there are loading conditions where negative GM never occurs, while when it occurs, it corresponds to a higher than level 1 wave height. Based on that it is proposed that the wave height for level 1 check on a passenger ship should be set between 6 to 8 metres

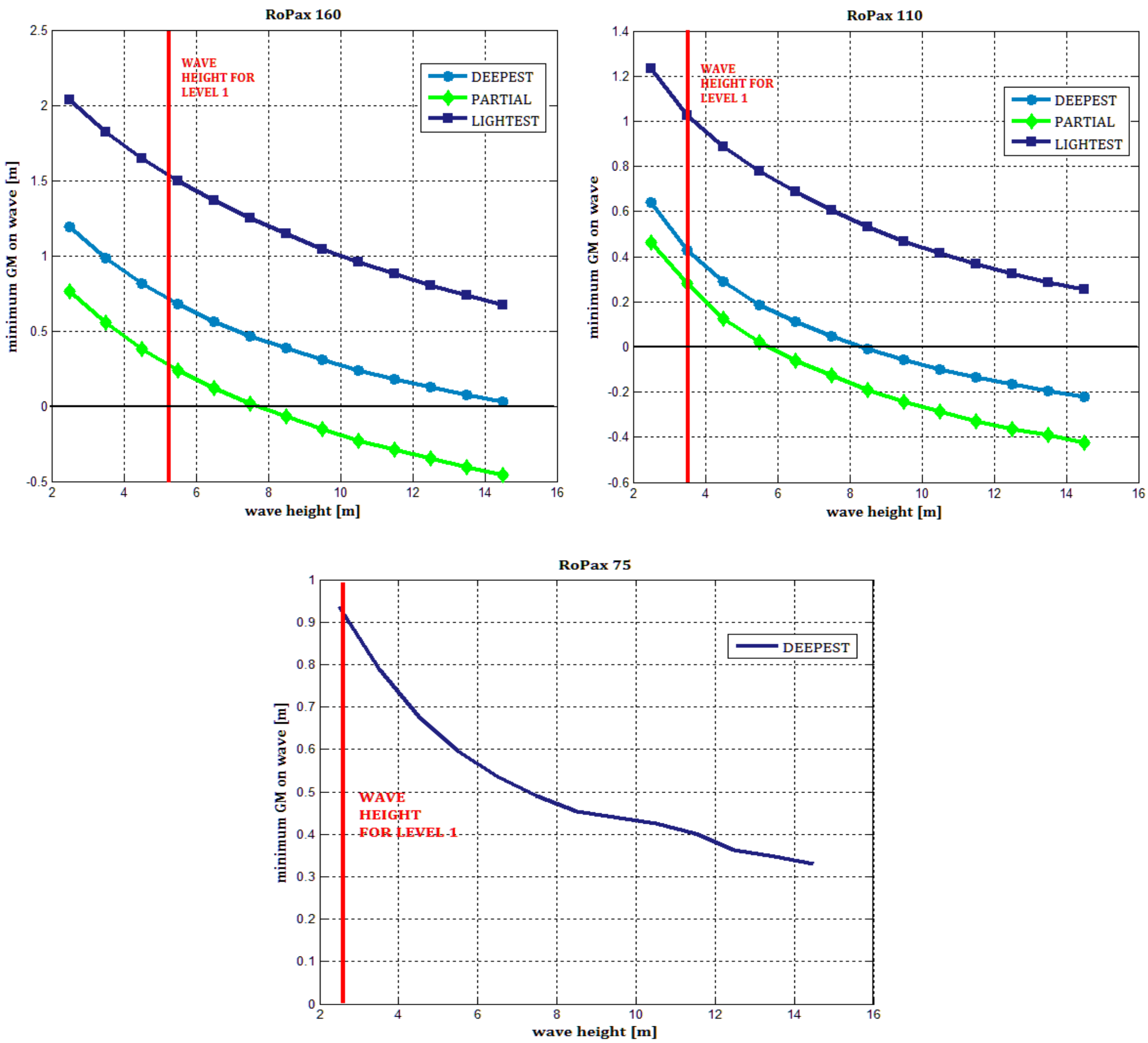



Figure 8.10 wave height on which negative GM is occurred for RoPax ships

# CHAPTER 9 – PARAMETRIC ROLL

## 9.1 PHYSICAL BACKGROUND

Parametric roll is a form of instability in waves during which large roll angles are being observed despite the absence of beam sea excitation. The phenomenon is triggered by the alternations of transverse stability on longitudinal waves that are observed on ships with fine hull forms and large flares such as containerships and modern RoRo vessels. However, the alternation of GZ curve as the wave passes along the ship is not enough. A certain relationship between the natural roll frequency $\omega_f$ and encounter frequency $\omega_e$ between ship and wave should exist. That means that parametric roll resonance occures when $\omega_e/\omega_f = 1$ or $\omega_e/\omega_f = 2$. As stability alternations are becoming more pronounced, the phenomenon expands and appears in frequencies where $\omega_e/\omega_f$ is near but not equal to 1 or 2. On large ships the probability of capsizing from parametric roll is not significant, although loss of containers on containerships or cargo shifting on RoRo ships is very probable. The first verified parametric roll accident is 'APL China's' in 1998. 'Nedlloyd Genova's' in 2006 is also a widely known accident, as well as the incident with the cruise ship 'Pacific Sun' in 2008.

If we assume that under harmonic waves the variation of GM as a function of time will also be harmonic. As a result the function is

$$GM(t) = GM + \Delta GM \cdot \cos(\omega_e t) \tag{9.1}$$

Where $GM$ is approximately the value of metacentric height in calm water , and $\Delta GM$ is amplitude of harmonic variation of GM expressed as $\Delta GM = GM_{trough} - GM_{crest}$

The linear roll equation without external excitation as is well-known is the following

$$(I_{XX} + \delta I) \cdot \ddot{\varphi} + B \cdot \dot{\varphi} + mg \cdot GM \cdot \varphi = 0 \tag{9.2}$$

By introducing the time-dependent GM the roll equation is:

$$(I_{XX} + \delta I) \cdot \ddot{\varphi} + B \cdot \dot{\varphi} + mg(GM + \Delta GM \cdot \cos(\omega_e t)) \cdot \varphi = 0 \tag{9.3}$$

Or

$$\ddot{\varphi} + b \cdot \dot{\varphi} + \omega_0^2 \cdot (1 + h \cdot \cos(\omega_e t)) \cdot \varphi = 0 \tag{9.4}$$

where $h = \dfrac{\Delta GM}{GM}$ and $b = \dfrac{B}{(I + \Delta I)}$

In eq 7.4 when the damping term *b,* is neglected the Mathieu equation is obtained as follows

$$\ddot{\varphi} + \omega_0^2 \cdot (1 + h \cdot \cos(\omega_e t)) \cdot \varphi = 0 \tag{9.5}$$

Mathieu equation is a linear differential equation in which the restoring coefficient is time dependent. The Mathieu equation seems simple but a closed-form solution does not exist. Studies based on the numerically solution of Mathieu equation for multiple pairs of ($\omega_0^2/\omega_e^2$, h) showed that certain values give stable while others give unstable solutions. So the Ince-Strutt diagram shown in figure 9.1 can be constructed where $\delta=\omega_0^2/\omega_e^2$, $\varepsilon=h(\omega_0^2/\omega_e^2)$. The shaded areas represent the stable pairs of $(\delta,\varepsilon)$ for which roll motion cannot take place, while the non-shaded area represents the unstable pairs, where roll motion exists. The basic characteristic of Mathieu equation is the fact that unstable solutions exist for any h, when $4\omega_0^2/\omega_e^2 \cong n^2$ where n is any positive integer n=1,2,3,4… n=1 corresponds to 'principal' resonance ($\omega_0=\omega_e/2$) and n=2 corresponds to 'fundamental' resonance ($\omega_0=\omega_e$)

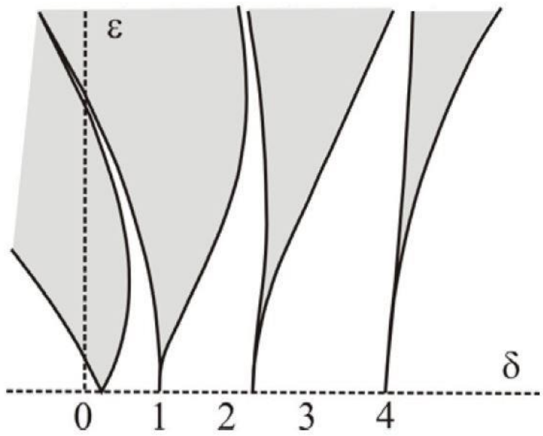



Figure 9.1 Ince-Strutt diagram(taken from [2])

The damping term is not included on Mathieu equation. However damping plays a significant role in the onset of parametric roll resonance. When the damping is introduced, the unstable regions are shifted upwards as one can see on figure 9.2. For this reason ships with small waterplane area alternations in waves that corresponds to small values of h are safe against parametric roll, even though the relationship of $\omega_0$ and $\omega_e$ corresponds to principal or fundamental resonance. The roll damping increases when bilge keels, stabilizer fins are used.

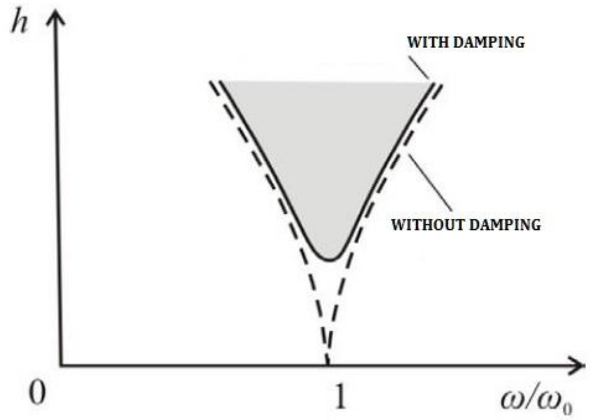



Figure 9.2 Effect of damping (taken from [2])

## 9.2 LEVEL 1 VULNERABILITY CRITERION FOR PARAMETRIC ROLL

According to level 1 draft regulation the value of GM variation ΔGM can be computed as

$$\Delta GM = \frac{I_H - I_L}{2V}, \ \sin ce \ \frac{V_D - V}{A_W \cdot \left(D - d\right)} \geq 1.00$$

An alternative approach for the calculation of *ΔGM* is to be computed as one half the difference between the maximum and minimum GM value, considering the ship to be balanced on ten different points along a wave with the above characteristics

$$\lambda = L\, m \quad H = 0.0167 \cdot L$$

The ratio *ΔGM/GM* has to be compared with the value of $R_{PR,}$ where

$$R_{PR} = 0.17 + 0.425 \cdot \left(\frac{100 \cdot A_K}{L \cdot B}\right) \quad if \ \ C_M > 0.96$$

$$R_{PR} = 0.17 + \left(10.625 \cdot C_M - 9.775\right) \cdot \left(\frac{100 \cdot A_K}{L \cdot B}\right) \quad if \ \ 0.94 < C_M < 0.96$$

$$R_{PR} = 0.17 + 0.2125 \cdot \left(\frac{100 \cdot A_K}{L \cdot B}\right) \quad if \ \ C_M < 0.96$$

Where $\left(\frac{100 \cdot A_K}{L \cdot B}\right)$ should not exceed 4;

If $\frac{\Delta GM}{GM} \leq R_{PR}$ the examined loading condition is not considered vulnerable to parametric rolling stability failure

## 9.3 LEVEL 2A VULNERABILITY CRITERION FOR PARAMETRIC ROLL

Level 2A vulnerability check requires the calculation of the ratio *ΔGM/GM* for 16 wave case and its comparison with the value of $R_{PR}$ according to the following relationship

$$GM(H_i, \lambda_i) > 0 \quad and \quad \frac{\Delta GM\left(H_i, \lambda_i\right)}{GM(H_i, \lambda_i)} < R_{PR} \tag{9.6}$$

In addition the comparison of vessels speed with the reference speed that corresponds to Mathieu resonance for each wave case is required, according to the following relationship

$$V_{PR,i} = \left| \frac{2\lambda_i}{T_\varphi} \cdot \sqrt{\frac{GM\left(H_i, \lambda_i\right)}{GM}} - \sqrt{g \frac{\lambda_i}{2\pi}} \right| > V_s \tag{9.7}$$

Where:

*ΔGM(H$_i$,λ$_i$)* is defined as one half the difference between the maximum and minimum GM values calculating as a wave characterized by (H$_i$,λ$_i$) passes the ship, *GM(H$_i$,λ$_i$)* is the average value of GM calculating as a wave characterized by (H$_i$,λ$_i$) passes the ship, $T_\varphi$ is the natural roll period $g$ is gravitational acceleration and *GM* the metacentric height in calm water

The total C1 vulnerability index is calculated as $C1=\sum_{i=1}^{N} W_i C_i$, where *Ci* is taking the value 1 when the two relationships 9.6 and 9.7 are not simultaneously satisfying. The loading condition is not considered vulnerable to parametric rolling if $C1 \leq 0.06$

### 9.4 LEVEL 2B VULNERABILITY CRITERION FOR PARAMETRIC ROLL

Level 2B vulnerability check requires the calculation of maximum parametric roll amplitude for 10 wave cases seven different wave direction $\beta$ (0$^o$,30$^o$,60$^o$,120$^o$,150$^o$,180$^o$ and 180$^o$ at zero speed) as follows

$$C2=\left[\sum_{i=1}^{3} C2\left(Fn_i,\beta_h\right)+C2\left(0,\beta_h\right)+\sum_{i=1}^{3} C2\left(Fn_i,\beta_f\right)\right]/7 \qquad (9.8)$$

Where $C2\left(Fn,\beta\right)=\sum_{i=1}^{N} W_i C_i$, where N is the number of waves and *Ci* takes the value 1 when the maximum parametric roll amplitude is larger than 25 deg, and the value 0 when parametric roll amplitude is smaller than 25 deg. The loading condition is not considered vulnerable to parametric rolling if $C2 \leq 0.15$

Each wave case is characterized by $\lambda_t$=$L_{WL}$ and height according to the equation h=0.01J·L, j=1,2,.....10. The probability of each wave case *Wi* is extracted from full wave scatter diagram, according to a procedure.

Parametric roll amplitude can be calculated either by solving numerically the averaged equation of 9.10 or by numerically solving the one-degree-of freedom parametric roll differential equation of 9.12 as a time domain approach. The time domain approach is considered to be more accurate for the prediction of parametric roll angle, notwithstanding the averaging method approach is less complex and more consistent with second generation intact stability approaches, so it will probably be completely adopted in the final form of regulation.

$$\begin{aligned}&\left\{\frac{\pi^2\left(\omega_e/2\right)\left(3A^2\left(\omega_e/2\right)^2\gamma+8\alpha\right)}{\left(2\pi^2-A^2\right)\omega_f^2}\right\}^2+\left\{\frac{6A^2\omega_f^2-8\pi^2\omega_f^2}{4\left(\pi^2-A^2\right)\omega_f^2}\frac{GM_{mean}}{GM}+\right.\\&\left.\frac{-5\pi^2A^4l_5\omega_f^2-6\pi^2A^2l_3\omega_f^2+8\pi^2\left(\omega_e/2\right)^2-8\pi^2\omega_f^2}{4\left(\pi^2-A^2\right)\omega_f^2}\right\}^2=\left(\frac{GM_{amp}}{GM}\right)^2\end{aligned} \qquad (9.9)$$

Whatever solution is obtained from the equation 7.9, amplitude *A=0* should be used if the following relationship of eq. 7.10 is satisfied.

$$\frac{GM_{amp}}{GM} < 2 \cdot \sqrt{\left\{ \left(1 + \frac{GM_{mean}}{GM}\right) - \frac{1}{4}\left(\frac{\omega_e}{\omega_f}\right)^2 \right\}^2 + \left(\frac{a}{\omega_f}\right)^2 \left(\frac{\omega_e}{\omega_f}\right)^2} \qquad (9.10)$$

$$\ddot{\varphi} + 2\alpha\dot{\varphi} + \gamma\dot{\varphi}^3 + \omega_f^2\varphi + \omega_f^2 I_3\varphi^3 + \omega_f^2 I_5\varphi^5 + \omega_f^2\left(GM_{mean} + GM_{amp}\ \cos(\omega_e t)\right)\cdot\left(1 - \left(\frac{\varphi}{\pi}\right)^2\right)\frac{\varphi}{GM} = 0 \qquad (9.11)$$

Where

$A$ the parametric roll amplitude, $\omega_f$ the natural roll frequency, $\omega_e$ the encounter frequency, $GM_{mean}$ the mean of metacentric height variations, $GM_{amp}$ the amplitude of metacentric height variations ,$I_3$ and $I_5$ the restoring coefficients determined with a least square fit to the GZ curve in calm water, $\alpha$ and $\gamma$ linear and cubic damping coefficients determined using a procedure

### 9.5 APPLICATION OF PARAMETRIC ROLL CRITERIA ON RO-RO PASSENGER SHIPS

#### 9.5.1 Vessel: RoPax 160 / Loading Condition: Partial Draft (DP)

***Level 1 Vulnerability Check***

For partial loading condition we have :

$L = 162\ m$

$V = 13305\ m^3$

$d = 6.05\ m$

$d_{FULL} = 6.5\ m$

$V_D = 44708\ m^3$

$dH = d + \min(D-d, L\cdot S_W/2) = 7.403\ m$

$dL = d + \min(d - 0.25\cdot d_{FULL}, L\cdot S_W/2) = 4.697\ m$

$I_H = 1.610\cdot 10^5\ m^4$

$I_L = 1.106\cdot 10^5\ m^4$

$A_W = 3105.6\ m^2$

However, $\frac{V_D - V}{A_W\cdot(D-d)} = 1.182 > 1$

And $\Delta GM = 1.894$

Whereas the ratio is $\Delta GM / GM = 1.166$

For the alternative approach ΔGM is to be computed as one half the difference between the maximum and minimum GM value, considering the ship to be balance on ten different points along a wave with the above characteristics

$$\lambda = 162\ m \quad H = 0.0167 \cdot \lambda = 2.705\ m$$

Then ΔGM value is $\Delta GM = 1.256$

and the ratio $\Delta GM / GM = 0.774$

The ratio *ΔGM/GM* has to be compared with the value of $R_{PR}$, since $C_M$=0.94

$$R_{PR} = 0.17 + (10.625 \cdot C_M - 9.775) \cdot \left( \frac{100 \cdot A_K}{L \cdot B} \right) \Rightarrow R_{PR} = 0.3670 \text{ Or}$$

$$R_{PR} = 0.17 + 0.2125 \cdot \left( \frac{100 \cdot A_K}{L \cdot B} \right) \Rightarrow R_{PR} = 0.3670$$

However, with both options $\Delta GM/GM > R_{PR}$ and the loading condition is considered vulnerable to parametric roll. However, Level 2A check is required.

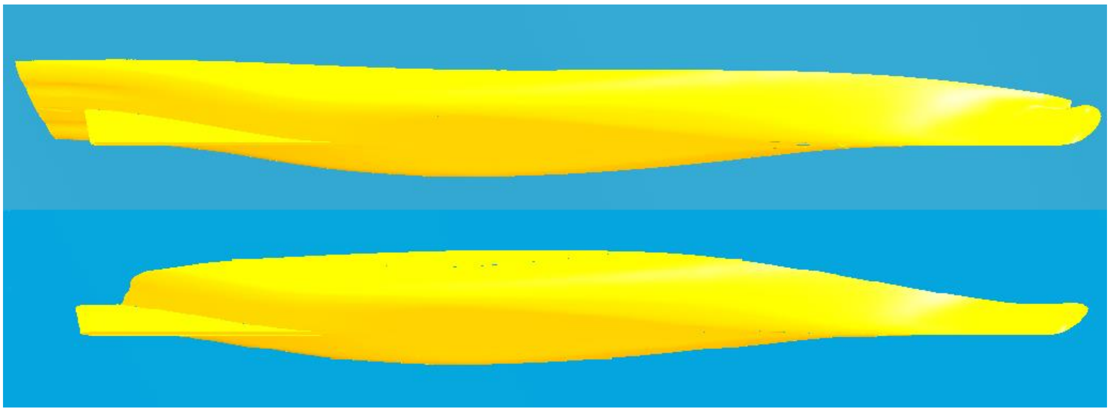


Figure 9.3 RoPax 160 on wave trough and wave crest for a wave with λ=162 m/H=2.705 m

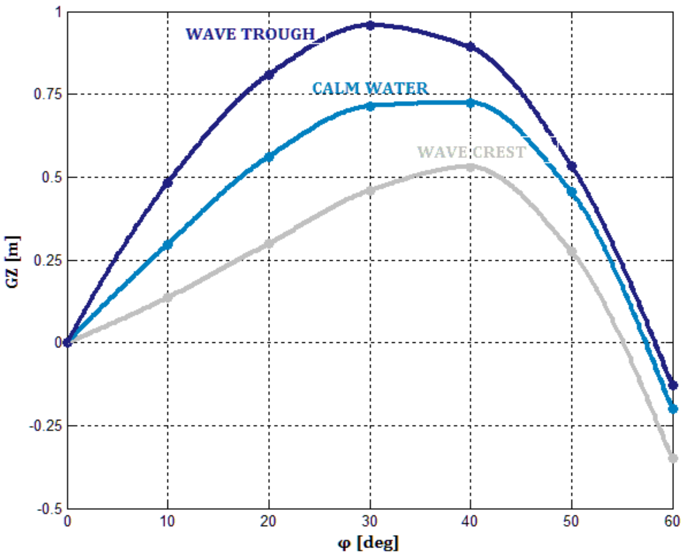



Figure 9.4 RoPax 160 GZ variations for a wave with λ=162 m/H=2.705 m

Results for level 1 vulnerability check for the other two examined loading conditions are shown in the following table

Table 9.1: RoPax 160, Results for level 1 check for parametric roll

| Loading Condition | ΔGM/GM | $R_{PR}$ | Status |
|---|---|---|---|
| Deepest subdivision draft | 0.8459 with Option A | 0.3619 | Fail |
| | 0.5676 with Option B | 0.3619 | Fail |
| Partial draft | 1.1660 with Option A | 0.3670 | Fail |
| | 0.7740 with Option B | 0.3670 | Fail |
| Lightest service draft | 0.7848 with Option A | 0.3682 | Fail |
| | 0.5023 with Option B | 0.3682 | Fail |

***Level 2A Vulnerability Check***

Table 9.2 RoPax 160 Results for level 2A check for parametric roll for DP

| Case No. | Weight Wi | Wave Length $\lambda_i$ [m] | Wave Height $H_i$ [m] | ΔGM/GM | $R_{PR}$ | $V_S$ (kn) | VPR (kn) | Ci |
|---|---|---|---|---|---|---|---|---|
| 1 | 0.000013 | 22.574 | 0.35 | 0.0397 | 0.367 | 21 | 5.9849 | 0 |
| 2 | 0.001654 | 37.316 | 0.495 | 0.0642 | 0.367 | 21 | 5.625 | 0 |
| 3 | 0.020912 | 55.743 | 0.8575 | 0.174 | 0.367 | 21 | 4.2489 | 0 |
| 4 | 0.092799 | 77.857 | 1.2945 | 0.2127 | 0.367 | 21 | 1.6888 | 0 |
| 5 | 0.199218 | 103.655 | 1.732 | 0.5443 | 0.367 | 21 | 1.9946 | 1 |
| 6 | 0.248788 | 133.139 | 2.205 | 0.6531 | 0.367 | 21 | 7.0599 | 1 |
| 7 | 0.208699 | 166.309 | 2.6965 | 0.6512 | 0.367 | 21 | 12.7521 | 1 |
| 8 | 0.128984 | 203.164 | 3.1755 | 0.609 | 0.367 | 21 | 19.2019 | 1 |
| 9 | 0.062446 | 243.705 | 3.625 | 0.5612 | 0.367 | 21 | 26.3352 | 0 |
| 10 | 0.024790 | 287.931 | 4.04 | 0.5147 | 0.367 | 21 | 34.2414 | 0 |
| 11 | 0.008367 | 335.843 | 4.4205 | 0.4632 | 0.367 | 21 | 42.8645 | 0 |
| 12 | 0.002473 | 387.44 | 4.7695 | 0.4164 | 0.367 | 21 | 52.3151 | 0 |
| 13 | 0.000658 | 442.723 | 5.097 | 0.3686 | 0.367 | 21 | 62.5548 | 0 |
| 14 | 0.000158 | 501.691 | 5.3695 | 0.3334 | 0.367 | 21 | 73.5188 | 0 |
| 15 | 0.000034 | 564.345 | 5.621 | 0.2904 | 0.367 | 21 | 85.1128 | 0 |
| 16 | 0.000007 | 630.684 | 5.95 | 0.2474 | 0.367 | 21 | 97.2971 | 0 |

The total $C_1$ index for level 2A in partial loading condition is

$$C_1 = \sum_{i=1}^{16} W_i \cdot C_i = 0.786 > 0.06 = R_{PR0}$$

That means that loading condition is considered vulnerable to parametric roll at the usual operational speed of 21 kn, corresponding to slow steaming, so a level 2B check is required. C1 index is also calculated for the other two examined loading conditions (Deepest and Lightest) the results for all loading conditions for the speed of 21 kn, are summarized in table 9.3

Table 9.3 : RoPax 160, Results for level 2A check for parametric roll

| Loading condition | | V (kn) | C1 Index | Status |
|---|---|---|---|---|
| DS | Deepest subdivision draft | 21 | 0.0657 | Fail |
| | | 26 | 0.7850 | Fail |
| DP | Partial draft | 21 | 0.7850 | Fail |
| | | 26 | 0.7850 | Fail |
| DL | Lightest service draft | 21 | 0.2480 | Fail |
| | | 26 | 0.4650 | Fail |

*C1* index is also calculated for different speeds, from the extra slow steaming speed of 13 kn to the speed of 28 kn the results are presented in figure 9.5. Only on lightest loading condition at the speed of 15 kn the ship could pass level 2A check

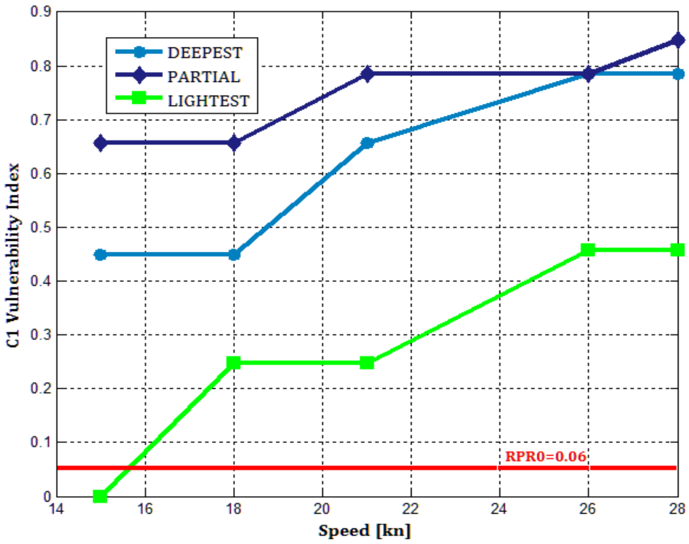



Figure 9.5 *C1* parametric roll vulnerability index at various speeds

### *Level 2B Vulnerability Check*

For the examined loading condition the procedure of Appendix 2 (method for determining linear and cubic roll damping coefficients using the equivalent linear roll damping coefficients in Ikeda's simplified formula) at explanatory notes for parametric roll yields the following

Ikeda's dimensionless damping coefficients for roll angle of 1 and 20 degrees including bilge keel's and lift component for the speed of 21 kn are respectively

$$\hat{B}_{44,1} = 0.0051 \qquad \hat{B}_{44,20} = 0.0189$$

And by using Ikeda's normalizing

$$B_{44,1} = 3.9098 \cdot 10^7 \qquad B_{44,20} = 1.4425 \cdot 10^8$$

The procedure of deriving linear *(α)* and cubic *(γ)* roll damping coefficients yields:

$$a = \frac{B_{44,1}}{2 \cdot (I_{XX} + J_{XX})} \frac{\pi}{\omega_f} = 0.0897 \qquad a_e = \frac{B_{44,20}}{2 \cdot (I_{XX} + J_{XX})} \frac{\pi}{\omega_f} = 0.3311$$

Where $I_{XX}$ is the moment of inertia calculated as $I_{XX} = \rho \cdot V \cdot (0.4B)^2 = 1.3797 \cdot 10^9$ and $J_{XX}$ is the added mass in roll calculated as $J_{XX} = 0.25 \cdot I_{XX} = 0.3449$ in the absence of specific data for the ship

$$c = \frac{a - a_e}{\varphi_m^2} = 1.2676$$ ,where $\varphi_m$=25 deg=0.436 rad

However, $\alpha = \frac{\omega_f}{\pi} \cdot a = 0.0113 \qquad \gamma = \frac{4c}{3\pi^2}\left(\frac{2\pi}{\omega_f}\right) = 2.7115$

The quantic fit of GZ curve in calm water from which 5th and 3rd order restoring coefficients are calculated is shown on figure 9.6

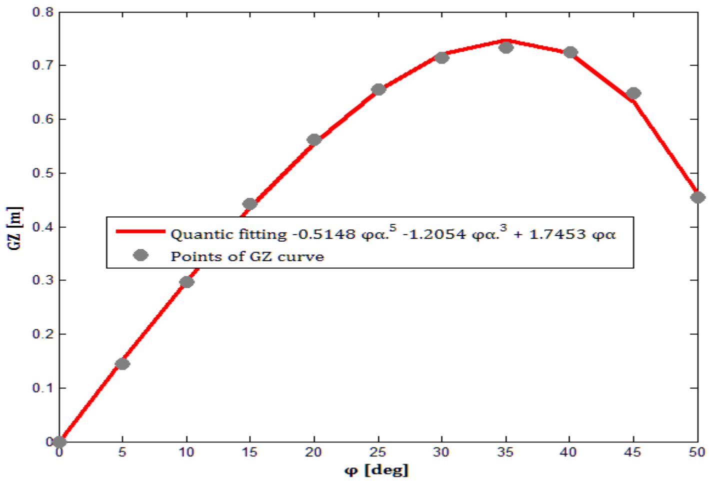



Figure 9.6 RoPax 160, L.C Partial, Quantic fitting of GZ curve

As long as GZ curve in calm water is modelled as $GZ = \varphi + I_3\varphi^3 + I_5\varphi^5$, The restoring coefficients are

$$I_5 = \frac{-0.5148}{1.7453} = -0.2950 \qquad I_3 = \frac{-1.2054}{1.7453} = -0.6906$$

On level 2B check wave frequency is fixed to a specific value due to the fact that only wave height is varied and not wave length. However, for the waterline length of 162 m the following result yields for wave frequency

$$\omega_0 = \sqrt{\frac{2 \cdot \pi \cdot g}{L}} \Rightarrow \omega_0 = 0.6168 \text{ rad/sec}$$

The calculation of parametric roll amplitude for seven different direction (0°,30°,60° for following seas, 120°,150°,180° for head seas and 0° for zero speed). The encounter frequencies for the usual operational speed of 21 kn and for each wave direction are shown in table 9.4

Table 9.4: RoPax 160 encounter frequencies for 21 kn

| **Wave direction** | **Encounter frequency** |
|---|---|
| 0 | 0.1974 |
| 30 | 0.2536 |
| 60 | 0.4071 |
| 120 | 0.8266 |
| 150 | 0.9801 |
| 180 | 1.0363 |

The wave characteristics of level 2B check and the values of $GM_{mean}$, defined as $GM_{mean} = 0.5(GM_{MAX} + GM_{MIN})$ and $GM_{amp}$ defined as $GM_{amp} = 0.5(GM_{MAX} - GM_{MIN})$ are shown in table 9.5

Table 9.5: RoPax 160 wave characteristic for level 2B check for DP

| Case No. | Weight Wi | Wave Length $\lambda_i$ [m] | Wave Height $H_i$ [m] | Steepness $s_i=H_i/\lambda_i$ | $GM_{mean}$ | $GM_{amp}$ |
|---|---|---|---|---|---|---|
| **1** | 0.2272 | 162 | 1.62 | 0.01 | 1.8865 | 0.8825 |
| **2** | 0.2035 | 162 | 3.24 | 0.02 | 2.0195 | 1.4005 |
| **3** | 0.115 | 162 | 4.86 | 0.03 | 2.103 | 1.76 |
| **4** | 0.0488 | 162 | 6.48 | 0.04 | 2.178 | 2.043 |
| **5** | 0.0182 | 162 | 8.1 | 0.05 | 2.2115 | 2.2355 |
| **6** | 0.0055 | 162 | 9.72 | 0.06 | 2.2265 | 2.3855 |
| **7** | 0.0015 | 162 | 11.34 | 0.07 | 2.215 | 2.492 |
| **8** | 0.0004 | 162 | 12.96 | 0.08 | 2.139 | 2.528 |
| **9** | 0.0001 | 162 | 14.58 | 0.09 | 1.9095 | 2.4025 |
| **10** | 0 | 162 | 16.2 | 0.1 | 1.6345 | 2.2295 |

C2 index calculating with the two available options for calculation of parametric roll amplitude *(A)* is

$C2$=0.000<0.15=$R_{PR1}$: *(A)* calculated with averaging method

$C2$=0.000291<0.15=$R_{PR1}$: *(A)* calculated with time domain method

However, in both methods vulnerability index is smaller than 0.15 and vulnerability is not detected. However, significant steady parametric roll amplitudes occurs when differential equation 9.11 is solved numerically for a time period 500 sec, only in case of head seas. This amplitudes that correspond to parametric roll resonance occurs only on high waves above 6 m and are larger as vessel's speed is increasing. On the other hand parametric roll amplitudes did not detect on following seas at any speed

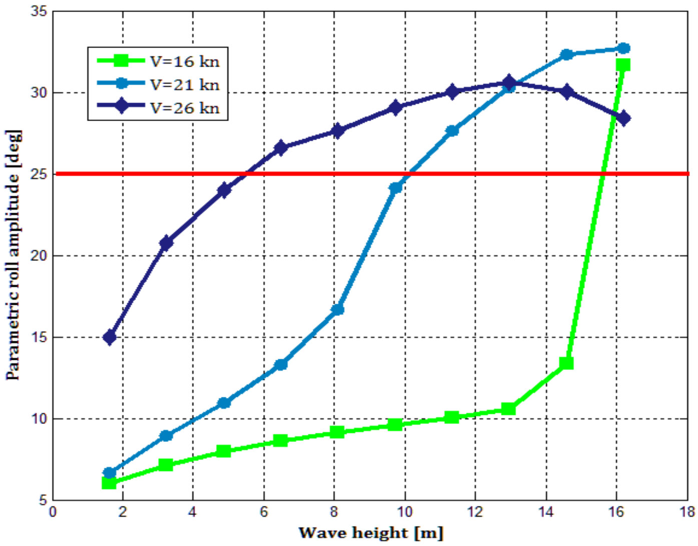



Figure 9.7: RoPax 160 parametric roll amplitudes obtained by TDM as a function of wave height in pure head seas for DP

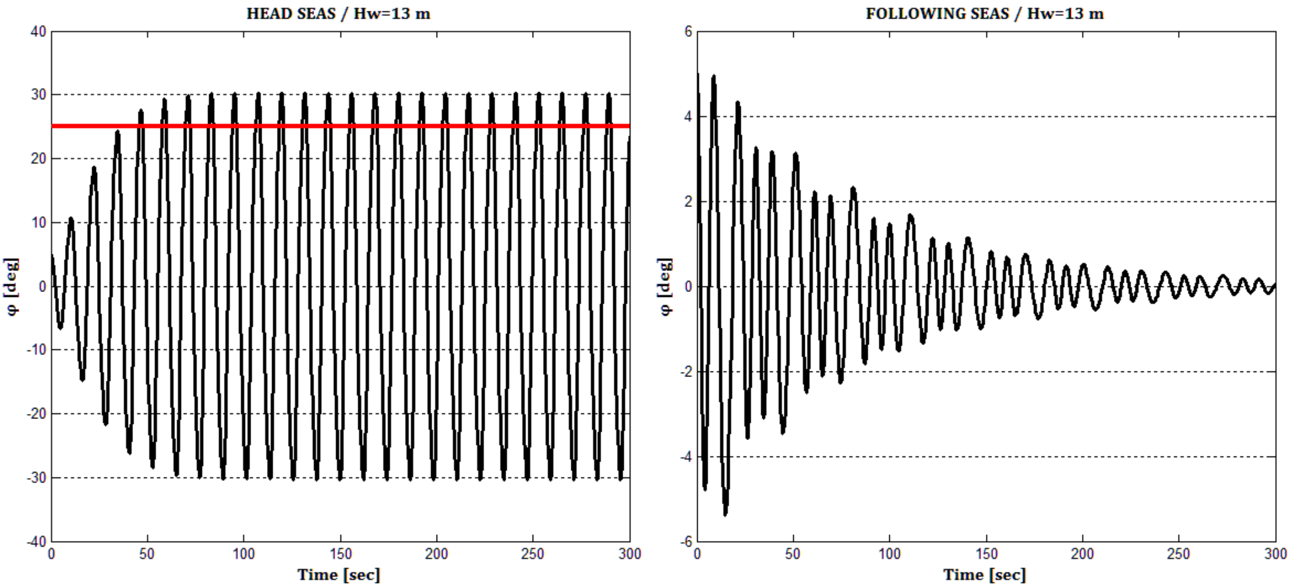



Figure 9.8 RoPax 160, Loading case DP, 21 kn, $H_w$=13 m / In head seas parametric roll occurs, in following seas parametric roll does not occur

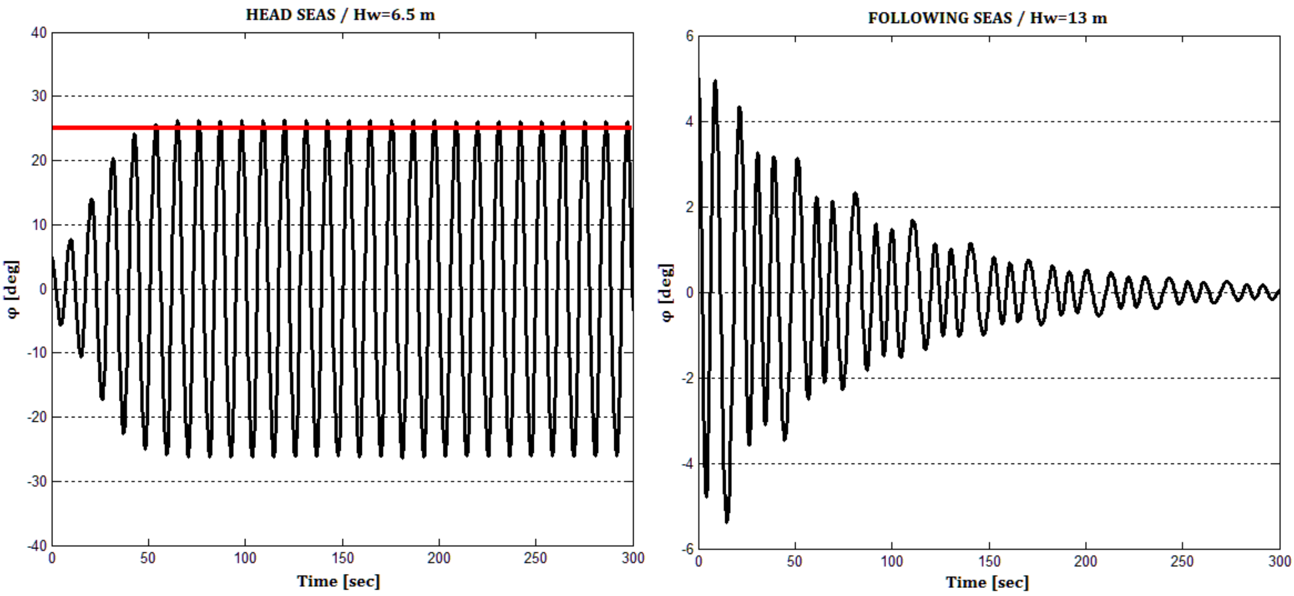



Figure 9.9 RoPax 160, Loading case DP, 26 kn, $H_w$=6.5 m / In head seas parametric roll occurs, in following seas parametric roll does not occur

*C2* index is also calculated for the other two examined loading conditions (DS and DL) the results for all loading conditions for the speed of 21 kn, are summarized in table 7.6. For DS and DL parametric roll amplitudes in pure or quarter head seas and pure or quarter following seas and did not detected neither for 21 kn nor for any other speed from 16 to 28 kn

Table 9.6 : RoPax 160, Results for level 2B check for parametric roll

| **Loading condition** | | **V (kn)** | **C2 SDC** | **C2 Averaging** | **Status TDM** | **Status Averaging** |
|---|---|---|---|---|---|---|
| DS | Deepest subdivision draft | 21 | 0.000 | 0.000 | Pass | Pass |
| | | 26 | 0.000 | 0.000 | Pass | Pass |
| DP | Partial draft | 21 | 0.000291 | 0.000 | Pass | Pass |
| | | 26 | 0.0143 | 0.000 | Pass | Pass |
| DL | Lightest service draft | 21 | 0.000 | 0.000 | Pass | Pass |
| | | 26 | 0.000 | 0.000 | Pass | Pass |

### 9.5.2 Vessel: RoPax 110 / Loading Condition: Partial Draft (DP)

***Level 1 Vulnerability Check***

For partial loading condition we have :

$V = 5809\ m^3$
$d = 4.86\ m$
$d_{FULL} = 5.1\ m$
$V_D = 19720\ m^3$
$dH = d + \min(D - d, L \cdot S_W / 2) = 5.857\ m$
$dL = d + \min(d - 0.25 \cdot d_{FULL}, L \cdot S_W / 2) = 3.863\ m$
$I_H = 4.735 \cdot 10^4\ m^4$
$I_L = 3.432 \cdot 10^4\ m^4$
$A_W = 1671\ m^2$

However, $\dfrac{V_D - V}{A_W \cdot (D - d)} = 1.158 > 1$

And $\Delta GM = 1.122$

Whereas the ratio is $\Delta GM / GM = 0.612$

For the alternative approach ΔGM is to be computed as one half the difference between the maximum and minimum GM value, considering the ship to be balance on ten different points along a wave with the above characteristics

$$\lambda = 119.4\ m \quad H = 0.0167 \cdot \lambda = 1.9\ m$$

Then ΔGM value is $\Delta GM = 0.8155$

and the ratio $\Delta GM / GM = 0.444$

The ratio ΔGM/GM has to be compared with the value of RPR, since $C_M$=0.96

$$R_{PR} = 0.17 + \left(10.625 \cdot C_M - 9.775\right) \cdot \left(\frac{100 \cdot A_K}{L \cdot B}\right) \Rightarrow R_{PR} = 0.5894$$

However, with the first option $\Delta GM/GM > R_{PR}$ and the loading condition is considered vulnerable to parametric roll, while with the second option $\Delta GM/GM < R_{PR}$ and the loading condition is not considered vulnerable to parametric roll, and there is an inconsistency between the two options, so a level 2A check is required.

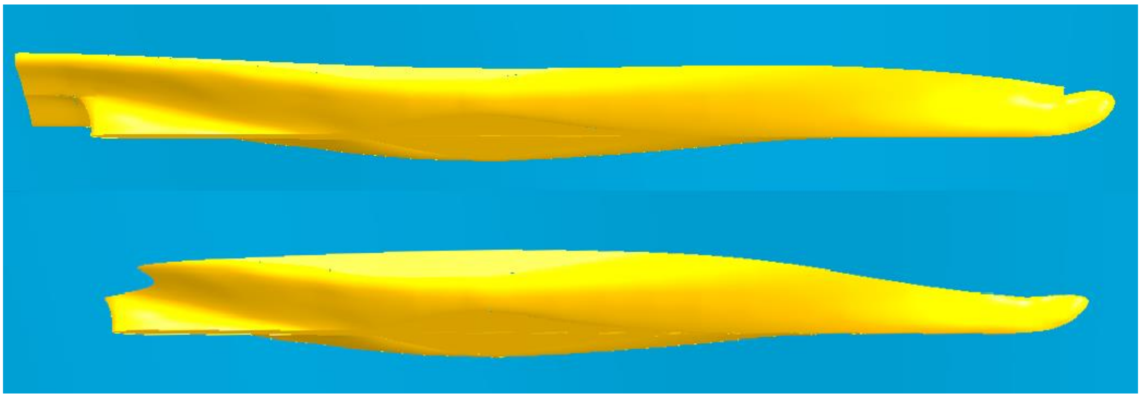


Figure 9.10 RoPax 110 on wave trough and wave crest for a wave with λ=119.4 m/H=1.900 m

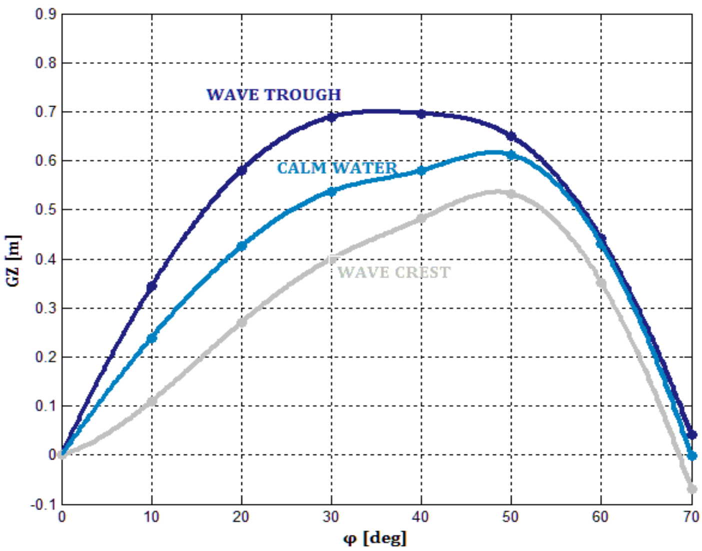



Figure 9.12 RoPax 110 GZ variations for a wave with λ=119.4 m/H=1.900 m

Results for level 1 vulnerability check for the other two examined loading conditions are shown on the following table 9.7

Table 9.7 RoPax 110, Results for level 1 check for parametric roll

| Loading condition | ΔGM/GM | $R_{PR}$ | Status |
|---|---|---|---|
| Deepest subdivision draft | 0.4834 with Option A | 0.5908 | Pass |
| | 0.3900 with Option B | 0.5908 | Pass |
| Partial draft | 0.6120 with Option A | 0.5894 | **Fail** |
| | 0.4470 with Option B | 0.5894 | Pass |
| Lightest service draft | 0.6032 with Option A | 0.6090 | Pass |
| | 0.4442 with Option B | 0.6090 | Pass |

### *Level 2A Vulnerability Check*

Table 9.8 RoPax 110, Results for level 2A check for parametric roll

| Case No. | Weight Wi | Wave Length $\lambda_i$ [m] | Wave Height $H_i$ [m] | ΔGM/GM | $R_{PR}$ | $V_S$ (kn) | $V_{PR}$ (kn) | Ci |
|---|---|---|---|---|---|---|---|---|
| **1** | 0.000013 | 22.574 | 0.35 | 0.0916 | 0.5894 | 21 | 3.8004 | 0 |
| **2** | 0.001654 | 37.316 | 0.495 | 0.1568 | 0.5894 | 21 | 2.1387 | 0 |
| **3** | 0.020912 | 55.743 | 0.8575 | 0.2054 | 0.5894 | 21 | 0.4383 | 0 |
| **4** | 0.092799 | 77.857 | 1.2945 | 0.4642 | 0.5894 | 21 | 3.6274 | 0 |
| **5** | 0.199218 | 103.655 | 1.732 | 0.5544 | 0.5894 | 21 | 7.826 | 0 |
| **6** | 0.248788 | 133.139 | 2.205 | 0.535 | 0.5894 | 21 | 13.715 | 0 |
| **7** | 0.208699 | 166.309 | 2.6965 | 0.483 | 0.5894 | 21 | 21.3155 | 0 |
| **8** | 0.128984 | 203.164 | 3.1755 | 0.4426 | 0.5894 | 21 | 30.243 | 0 |
| **9** | 0.062446 | 243.705 | 3.625 | 0.4033 | 0.5894 | 21 | 40.958 | 0 |
| **10** | 0.024790 | 287.931 | 4.04 | 0.5798 | 0.5894 | 21 | 46.0958 | 0 |
| **11** | 0.008367 | 335.843 | 4.4205 | 0.3204 | 0.5894 | 21 | 66.1702 | 0 |
| **12** | 0.002473 | 387.44 | 4.7695 | 0.2836 | 0.5894 | 21 | 80.8218 | 0 |
| **13** | 0.000658 | 442.723 | 5.097 | 0.2556 | 0.5894 | 21 | 96.7719 | 0 |
| **14** | 0.000158 | 501.691 | 5.3695 | 0.2306 | 0.5894 | 21 | 113.977 | 0 |
| **15** | 0.000034 | 564.345 | 5.621 | 0.2164 | 0.5894 | 21 | 132.3576 | 0 |
| **16** | 0.000007 | 630.684 | 5.95 | 0.1736 | 0.5894 | 21 | 153.2457 | 0 |

The total $C_1$ index for level 2A in partial loading condition is

$$C_1 = \sum_{i=1}^{16} W_i \cdot C_i = 0.00 < 0.06 = R_{PR0}$$

That means that loading condition is not considered vulnerable to parametric roll at the speed of 21 kn, C1 index is also 0.00 for different speeds from the extra slow steaming speed of 15 to 24 kn due to fact that $\Delta GM/GM < R_{PR}$ in all wave cases.

### 9.5.3 Vessel: RoPax 75 / Loading Condition: Deepest Subdivision Draft (DS)

***Level 1 Vulnerability Check***

For partial loading condition we have :

$L = 78.12\ m$
$V = 2629\ m^3$
$d = 4.25\ m$
$d_{FULL} = 4.25\ m$
$V_D = 9273\ m^3$
$dH = d + \min(D - d, L \cdot S_W / 2) = 4.904\ m$
$dL = d + \min(d - 0.25 \cdot d_{FULL}, L \cdot S_W / 2) = 3.598\ m$
$I_H = 1.514 \cdot 10^4\ m^4$
$I_L = 1.285 \cdot 10^4\ m^4$
$A_W = 941.5\ m^2$

However, $\dfrac{V_D - V}{A_W \cdot (D - d)} = 1.077 > 1$

and $\Delta GM = 0.4346$,

Whereas the ratio is $\Delta GM / GM = 0.276$

An alternative approach for the calculation of ΔGM is to be computed as one half the difference between the maximum and minimum GM value, considering the ship to be balance on ten different points along a wave with the above characteristics

$$\lambda = 78.12\ m \quad H = 0.0167 \cdot \lambda = 1.305\ m$$

then ΔGM value is $\Delta GM = 0.3535$

and the ratio is $\Delta GM / GM = 0.2252$

The ratio $\Delta GM/GM$ has to be compared with the value of $R_{PR}$, since $C_M<0.94$

$$R_{PR} = 0.17 + 0.2125\left(\frac{100 \cdot A_K}{L \cdot B}\right) \Rightarrow R_{PR} = 0.5054$$

However, with the both option $\Delta GM/GM<R_{PR}$ and the loading condition is not considered vulnerable to parametric roll.

Table 9.9 RoPax 75, Results for level 1 check for parametric roll

| Loading condition | ΔGM/GM | $R_{PR}$ | Status |
|---|---|---|---|
| Deepest subdivision draft | 0.2768 with Option A | 0.5054 | Pass |
| | 0.2252 with Option B | 0.5054 | Pass |

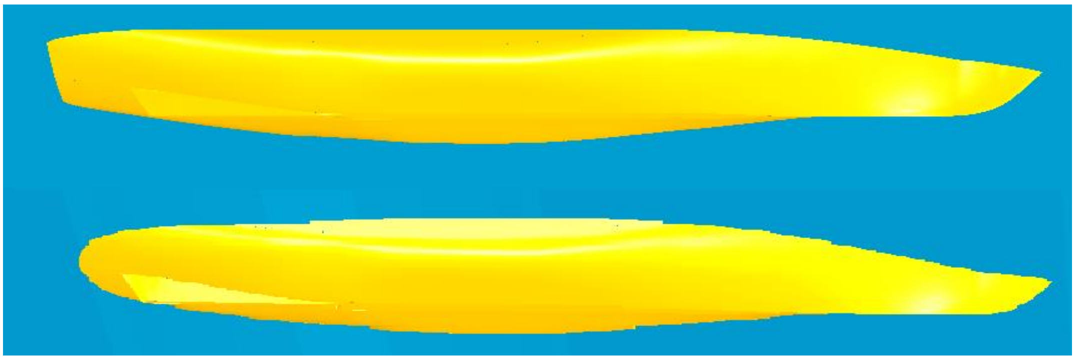


Figure 7.13 RoPax 75 on wave trough and wave crest for a wave with λ=78.12 m/H=1.305 m

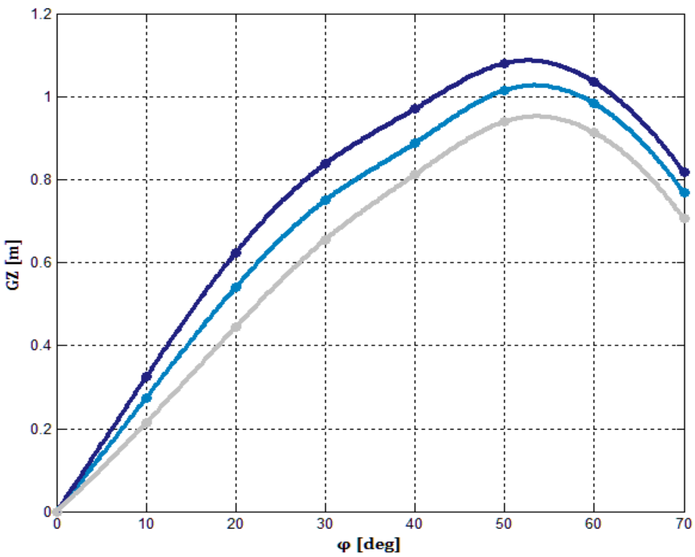



Figure 9.14 RoPax 75 GZ variations for a wave with λ=78.12 m/H=1.305 m

## 9.6 APPLICATION OF PARAMETRIC ROLL CRITERIA ON RO-RO CARGO SHIPS

### 9.6.1 Vessel: RoRo 180 / Loading Condition: Full Load Arrival (FLA)

***Level 1 Vulnerability Check***

For FLA condition we have :

$L = 181.2\ m$

$V = 18790\ m^3$

$d = 6.87\ m$

$d_{FULL} = 7.00\ m$

$V_D = 61733\ m^3$

$d_H = d + \min(D-d, L \cdot S_W / 2) = 8.388\ m$

$d_L = d + \min(d - 0.25 \cdot d_{FULL}, L \cdot S_W / 2) = 5.362\ m$

$I_H = 1.895 \cdot 10^5\ m^4$

$I_L = 1.409 \cdot 10^5\ m^4$

$A_W = 3775\ m^2$

However, $\frac{V_D - V}{A_W \cdot (D-d)} = 1.1697 > 1$

And $\Delta GM = 1.2919$

Whereas the ratio is $\Delta GM / GM = 1.7411$

For the alternative approach ΔGM is to be computed as one half the difference between the maximum and minimum GM value, considering the ship to be balance on ten different points along a wave with the above characteristics

$$\lambda = 181.2\ m \quad H = 0.0167 \cdot \lambda = 3.026\ m$$

Then ΔGM value is $\Delta GM = 0.772$

and the ratio $\Delta GM / GM = 1.0402$

The ratio $\Delta GM/GM$ has to be compared with the value of $R_{PR}$, since $C_M$=0.921

$$R_{PR} = 0.17 + 0.2125 \cdot \left( \frac{100 \cdot A_K}{L \cdot B} \right) \Rightarrow R_{PR} = 0.3670$$

However, with both options $\Delta GM/GM > R_{PR}$ and the loading condition is considered vulnerable to parametric roll. However, Level 2A check is required.

### *Level 2A Vulnerability Check*

Table 9.10 RoRo 180 Results for level 2A check for parametric roll for FLA

| Case No. | Weight Wi | Wave Length $\lambda_i$ [m] | Wave Height $H_i$ [m] | ΔGM/GM | $R_{PR}$ | $V_S$ (kn) | $V_{PR}$ (kn) | Ci |
|---|---|---|---|---|---|---|---|---|
| **1** | 0.000013 | 22.574 | 0.35 | 0.0325 | 0.367 | 21 | 7.6829 | 0 |
| **2** | 0.001654 | 37.316 | 0.495 | 0.0634 | 0.367 | 21 | 8.4771 | 0 |
| **3** | 0.020912 | 55.743 | 0.8575 | 0.2375 | 0.367 | 21 | 8.7958 | 0 |
| **4** | 0.092799 | 77.857 | 1.2945 | 0.4017 | 0.367 | 21 | 8.6902 | 1 |

| Case No. | Weight Wi | Wave Length $\lambda_i$ [m] | Wave Height $H_i$ [m] | ΔGM/GM | $R_{PR}$ | $V_S$ (kn) | $V_{PR}$ (kn) | Ci |
|---|---|---|---|---|---|---|---|---|
| **5** | 0.199218 | 103.655 | 1.732 | 0.7754 | 0.367 | 21 | 7.9027 | 1 |
| **6** | 0.248788 | 133.139 | 2.205 | 1.1247 | 0.367 | 21 | 6.8605 | 1 |
| **7** | 0.208699 | 166.309 | 2.6965 | 1.2038 | 0.367 | 21 | 5.0161 | 1 |
| **8** | 0.128984 | 203.164 | 3.1755 | 1.1647 | 0.367 | 21 | 2.4654 | 1 |
| **9** | 0.062446 | 243.705 | 3.625 | 1.076 | 0.367 | 21 | 0.6272 | 1 |
| **10** | 0.024790 | 287.931 | 4.04 | 0.9747 | 0.367 | 21 | 4.3362 | 1 |
| **11** | 0.008367 | 335.843 | 4.4205 | 0.8672 | 0.367 | 21 | 8.8019 | 1 |
| **12** | 0.002473 | 387.44 | 4.7695 | 0.762 | 0.367 | 21 | 14.0604 | 1 |
| **13** | 0.000658 | 442.723 | 5.097 | 0.6686 | 0.367 | 21 | 20.038 | 1 |
| **14** | 0.000158 | 501.691 | 5.3695 | 0.5763 | 0.367 | 21 | 26.9076 | 0 |
| **15** | 0.000034 | 564.345 | 5.621 | 0.5013 | 0.367 | 21 | 34.5282 | 0 |
| **16** | 0.000007 | 630.684 | 5.95 | 0.433 | 0.367 | 21 | 42.9334 | 0 |

The total $C_1$ index for level 2A in partial loading condition is

$$C_1 = \sum_{i=1}^{16} W_i \cdot C_i = 0.9772 > 0.06 = R_{PR0}$$

That means that loading condition is considered vulnerable to parametric roll at the speed of 21 kn, and level 2B check is required.

### *Level 2B Vulnerability Check*

For the examined loading condition the procedure of Appendix 2 (method for determining linear and cubic roll damping coefficients using the equivalent linear roll damping coefficients in Ikeda's simplified formula) at explanatory notes for parametric roll yields the following

Ikeda's dimensionless damping coefficients for roll angle of 1 and 20 degrees including bilge keel's and lift component for the speed of 21 kn are respectively

$$\hat{B}_{44,1} = 0.0041 \qquad \hat{B}_{44,20} = 0.0105$$

And by using Ikeda's normalizing

$$B_{44,1} = 4.6954 \cdot 10^7 \qquad B_{44,20} = 1.2022 \cdot 10^8$$

The procedure of deriving linear *(α)* and cubic *(γ)* roll damping coefficients yields:

$$a = \frac{B_{44,1}}{2 \cdot (I_{XX} + J_{XX})} \frac{\pi}{\omega_f} = 0.1128 \qquad a_e = \frac{B_{44,20}}{2 \cdot (I_{XX} + J_{XX})} \frac{\pi}{\omega_f} = 0.2889$$

Where $I_{XX}$ is the moment of inertia calculated as $I_{XX} = \rho \cdot V \cdot (0.4B)^2 = 1.8912 \cdot 10^9$ and $J_{XX}$ is the added mass in roll calculated as $J_{XX} = 0.25 \cdot I_{XX} = 0.4728 \cdot 10^9$ in the absence of specific data for the ship

$$c = \frac{a - a_e}{\varphi_m^2} = 0.9248 \quad \text{,where } \varphi_m = 25 \text{ deg} = 0.436 \text{ rad}$$

However, $\alpha = \frac{\omega_f}{\pi} \cdot a = 0.0099 \qquad \gamma = \frac{4c}{3\pi^2}\left(\frac{2\pi}{\omega_f}\right) = 2.8387$

The quantic fit of GZ curve in calm water from which 5th and 3rd order restoring coefficients are calculated is shown on figure ..

GZ curve in calm water is modelled as $GZ = 0.4536 \cdot \varphi + 0.6926 \cdot \varphi^3 - 1.1063 \cdot \varphi^5$, The restoring coefficients are

$$I_5 = \frac{-1.1063}{0.4536} = -2.4389 \qquad I_3 = \frac{0.6926}{0.4536} = 1.5268$$

On level 2B check wave frequency is fixed to a specific value due to the fact that only wave height is varied and not wave length. However, for the waterline length of 162 m the following result yields for wave frequency

$$\omega_0 = \sqrt{\frac{2 \cdot \pi \cdot g}{L}} \Rightarrow \omega_0 = 0.5836 \text{ rad/sec}$$

The calculation of parametric roll amplitude for seven different direction (0°,30°,60° for following seas, 120°,150°,180° for head seas and 0° for zero speed). The encounter frequencies for the design speed of 21 kn and for each wave direction are shown in table 9.11

Table 9.11 RoRo 180, encounter frequencies for 21 kn

| **Wave direction** | **Encounter frequency** |
|---|---|
| 0 | 0.2089 |
| 30 | 0.2591 |
| 60 | 0.3962 |
| 120 | 0.7709 |
| 150 | 0.9081 |
| 180 | 0.9583 |

The wave characteristics of level 2B check and the values of $GM_{mean}$, defined as $GM_{mean} = 0.5(GM_{MAX} + GM_{MIN})$ and $GM_{amp}$ defined as $GM_{amp} = 0.5(GM_{MAX} - GM_{MIN})$ are shown in table 9.12

Table 9.12 RoRo 180 wave characteristic for level 2B check for FLA

| **Case No.** | **Weight Wi** | **Wave Length $\lambda_i$ [m]** | **Wave Height $H_i$ [m]** | **Steepness $s_i=H_i/\lambda_i$** | **$GM_{mean}$** | **$GM_{amp}$** |
|---|---|---|---|---|---|---|
| **1** | 0.2296 | 181 | 1.81 | 0.01 | 0.595 | 0.545 |
| **2** | 0.1843 | 181 | 3.62 | 0.02 | 0.577 | 0.868 |
| **3** | 0.0868 | 181 | 5.43 | 0.03 | 0.565 | 1.086 |
| **4** | 0.0316 | 181 | 7.24 | 0.04 | 0.5755 | 1.2515 |
| **5** | 0.0093 | 181 | 9.05 | 0.05 | 0.6125 | 1.3995 |
| **6** | 0.0023 | 181 | 10.86 | 0.06 | 0.664 | 1.535 |
| **7** | 0.0005 | 181 | 12.67 | 0.07 | 0.7105 | 1.6515 |
| **8** | 0.0001 | 181 | 14.48 | 0.08 | 0.7185 | 1.7165 |
| **9** | 0 | 181 | 16.29 | 0.09 | 0.6255 | 1.6685 |
| **10** | 0 | 181 | 18.1 | 0.1 | 0.5795 | 1.6585 |

C2 index calculating with the two available options for calculation of parametric roll amplitude *(A)* is

$$C2=0.0471<0.15=R_{PR1}\text{: (A) calculated with averaging method}$$

$$C2=0.0468<0.15=R_{PR1}\text{: (A) calculated with time domain method}$$

However, in both methods vulnerability index is smaller than 0.15 and vulnerability is not detected.

Although vulnerability did not detected, significant steady parametric roll amplitudes occurs. Firstly, in head seas, at speeds smaller than design speed at wave heights above 5 m, at the design speed of 21 kn large parametric roll amplitudes occurs only at large wave heights above 11 m, while parametric roll resonance is not occur at the speed of 23 kn. On the other hand in following seas the situation is opposite, so as speed is increasing large parametric roll amplitudes occurs at higher than design speeds for waves heights around 7 m.

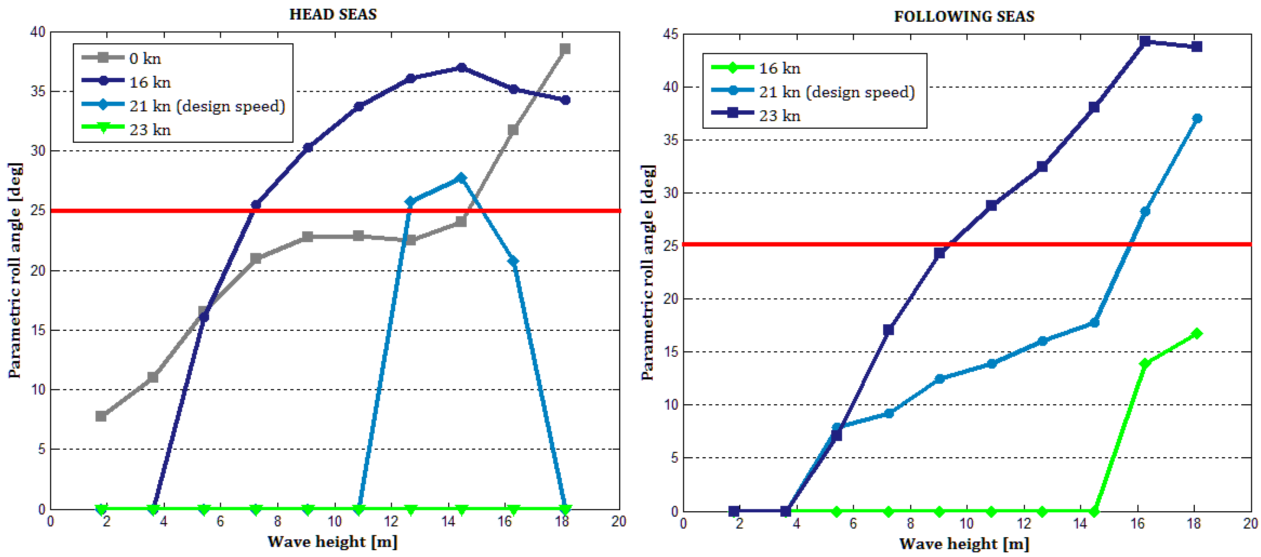



Figure 9.15 RoRo 180, Parametric roll angles obtained by TDM as a function of wave height for different speeds in pure head and following seas for loading condition FLA

### 9.6.2 Vessel: RoRo 130 / Loading Condition: Full Load Arrival (FLA)

#### Level 1 Vulnerability Check

For FLA condition we have :

$L = 134.9\ m$

$V = 11774\ m^3$

$d = 6.4\ m$

$d_{FULL} = 6.5\ m$

$V_D = 37936\ m^3$

$d_H = d + \min(D - d, L \cdot S_W / 2) = 7.5264\ m$

$d_L = d + \min(d - 0.25 \cdot d_{FULL}, L \cdot S_W / 2) = 5.2736\ m$

$I_H = 1.0341 \cdot 10^5\ m^4$

$I_L = 8.0961 \cdot 10^4\ m^4$

$A_W = 2536\ m^2$

However, $\frac{V_D - V}{A_W \cdot (D - d)} = 1.12 > 1$

And $\Delta GM = 0.9532$

Whereas the ratio is $\Delta GM / GM = 1.2477$

For the alternative approach ΔGM is to be computed as one half the difference between the maximum and minimum GM value, considering the ship to be balance on ten different points along a wave with the above characteristics

$$\lambda = 134.9\ m \quad H = 0.0167 \cdot \lambda = 2.253\ m$$

Then ΔGM value is $\Delta GM = 0.600$

and the ratio $\Delta GM / GM = 0.7853$

The ratio $\Delta GM/GM$ has to be compared with the value of $R_{PR}$, since $C_M$=0.920

$$R_{PR} = 0.17 + 0.2125 \cdot \left( \frac{100 \cdot A_K}{L \cdot B} \right) \Rightarrow R_{PR} = 0.3861$$

However, with both options $\Delta GM/GM > R_{PR}$ and the loading condition is considered vulnerable to parametric roll. However, Level 2A check is required.

### Level 2A Vulnerability Check

Table 9.14 RoRo 130 Results for level 2A check for parametric roll for FLA

| Case No. | Weight Wi | Wave Length $\lambda_t$ [m] | Wave Height $H_i$ [m] | ΔGM/GM | $R_{PR}$ | $V_S$ (kn) | $V_{PR}$ (kn) | Ci |
|---|---|---|---|---|---|---|---|---|
| **1** | 0.000013 | 22.574 | 0.35 | 0.0482 | 0.3861 | 19 | 7.4188 | 0 |
| **2** | 0.001654 | 37.316 | 0.495 | 0.1231 | 0.3861 | 19 | 8.0633 | 0 |
| **3** | 0.020912 | 55.743 | 0.8575 | 0.2702 | 0.3861 | 19 | 8.2116 | 0 |
| **4** | 0.092799 | 77.857 | 1.2945 | 0.5694 | 0.3861 | 19 | 7.71 | 1 |
| **5** | 0.199218 | 103.655 | 1.732 | 0.8352 | 0.3861 | 19 | 6.7618 | 1 |
| **6** | 0.248788 | 133.139 | 2.205 | 0.8829 | 0.3861 | 19 | 5.0302 | 1 |
| **7** | 0.208699 | 166.309 | 2.6965 | 0.8494 | 0.3861 | 19 | 2.591 | 1 |

| Case No. | Weight Wi | Wave Length $\lambda_i$ [m] | Wave Height $H_i$ [m] | ΔGM/GM | $R_{PR}$ | $V_S$ (kn) | $V_{PR}$ (kn) | Ci |
|---|---|---|---|---|---|---|---|---|
| **8** | 0.128984 | 203.164 | 3.1755 | 0.7752 | 0.3861 | 19 | 0.4871 | 1 |
| **9** | 0.062446 | 243.705 | 3.625 | 0.6972 | 0.3861 | 19 | 4.2291 | 1 |
| **10** | 0.024790 | 287.931 | 4.04 | 0.6124 | 0.3861 | 19 | 8.7556 | 1 |
| **11** | 0.008367 | 335.843 | 4.4205 | 0.5364 | 0.3861 | 19 | 14.0381 | 1 |
| **12** | 0.002473 | 387.44 | 4.7695 | 0.4634 | 0.3861 | 19 | 20.1229 | 0 |
| **13** | 0.000658 | 442.723 | 5.097 | 0.4043 | 0.3861 | 19 | 27.0103 | 0 |
| **14** | 0.000158 | 501.691 | 5.3695 | 0.3443 | 0.3861 | 19 | 34.7177 | 0 |
| **15** | 0.000034 | 564.345 | 5.621 | 0.2912 | 0.3861 | 19 | 43.2449 | 0 |
| **16** | 0.000007 | 630.684 | 5.95 | 0.249 | 0.3861 | 19 | 52.4367 | 0 |

The total $C_1$ index for level 2A in partial loading condition is

$$C_1 = \sum_{i=1}^{16} W_i \cdot C_i = 0.9741 > 0.06 = R_{PR0}$$

That means that loading condition is considered vulnerable to parametric roll at the speed of 19 kn, and level 2B check is required.

### *Level 2B Vulnerability Check*

For the examined loading condition the procedure of Appendix 2 (method for determining linear and cubic roll damping coefficients using the equivalent linear roll damping coefficients in Ikeda's simplified formula) at explanatory notes for parametric roll yields the following

Ikeda's dimensionless damping coefficients for roll angle of 1 and 20 degrees including bilge keel's and lift component for the speed of 19 kn are respectively

$$\hat{B}_{44,1} = 0.0041 \qquad \hat{B}_{44,20} = 0.0103$$

And by using Ikeda's normalizing

$$B_{44,1} = 2.4208 \cdot 10^7 \qquad B_{44,20} = 6.1792 \cdot 10^7$$

The procedure of deriving linear *(α)* and cubic *(γ)* roll damping coefficients yields:

$$a = \frac{B_{44,1}}{2 \cdot (I_{XX} + J_{XX})} \frac{\pi}{\omega_f} = 0.0996 \qquad a_e = \frac{B_{44,20}}{2 \cdot (I_{XX} + J_{XX})} \frac{\pi}{\omega_f} = 0.2543$$

Where $I_{XX}$ is the moment of inertia calculated as $I_{XX} = \rho \cdot V \cdot (0.4B)^2 = 1.03081 \cdot 10^9$ and $J_{XX}$ is the added mass in roll calculated as $J_{XX} = 0.25 \cdot I_{XX} = 0.2595 \cdot 10^9$ in the absence of specific data for the ship

$$c = \frac{a - ae}{\varphi_m^2} = 0.9248 \quad \text{,where } \varphi_m\text{=25 deg=0.436 rad}$$

However, $\alpha = \frac{\omega_f}{\pi} \cdot a = 0.0094 \qquad \gamma = \frac{4c}{3\pi^2}\left(\frac{2\pi}{\omega_f}\right) = 2.3281$

The quantic fit of GZ curve in calm water from which 5th and 3rd order restoring coefficients are calculated is shown on figure ..

GZ curve in calm water is modelled as $GZ = 0.5145 \cdot \varphi + 0.7725 \cdot \varphi^3 - 0.9495 \cdot \varphi^5$, The restoring coefficients are

$$I_5 = \frac{-0.9495}{0.5145} = -1.8455 \qquad I_3 = \frac{0.7725}{0.5145} = 1.5015$$

On level 2B check wave frequency is fixed to a specific value due to the fact that only wave height is varied and not wave length. However, for the waterline length of 134.9 m the following result yields for wave frequency

$$\omega_0 = \sqrt{\frac{2 \cdot \pi \cdot g}{L}} \Rightarrow \omega_0 = 0.6760 \text{ rad/sec}$$

The calculation of parametric roll amplitude for seven different direction (0°,30°,60° for following seas, 120°,150°,180° for head seas and 0° for zero speed). The encounter frequencies for the design speed of 19 kn and for each wave direction are shown in table 9.15

Table 9.15 RoRo 130 encounter frequencies for 19 kn

| Wave direction | Encounter frequency |
|---|---|
| 0 | 0.2211 |
| 30 | 0.2820 |
| 60 | 0.4485 |
| 120 | 0.9034 |
| 150 | 1.0699 |
| 180 | 1.1308 |

The wave characteristics of level 2B check and the values of $GM_{mean}$, defined as $GM_{mean} = 0.5(GM_{MAX} + GM_{MIN})$ and $GM_{amp}$ defined as $GM_{amp} = 0.5(GM_{MAX} - GM_{MIN})$ are shown in table 9.16

Table 9.16 RoRo 130 wave characteristic for level 2B check for FLA

| Case No. | Weight Wi | Wave Length $\lambda_i$ [m] | Wave Height $H_i$ [m] | Steepness $s_i=H_i/\lambda_i$ | $GM_{mean}$ | $GM_{amp}$ |
|---|---|---|---|---|---|---|
| **1** | 0.1963 | 134.9 | 1.349 | 0.01 | 0.6525 | 0.4225 |
| **2** | 0.2288 | 134.9 | 2.698 | 0.02 | 0.638 | 0.676 |
| **3** | 0.1593 | 134.9 | 4.047 | 0.03 | 0.6445 | 0.8745 |
| **4** | 0.0884 | 134.9 | 5.396 | 0.04 | 0.647 | 1.013 |
| **5** | 0.0426 | 134.9 | 6.745 | 0.05 | 0.6605 | 1.1315 |
| **6** | 0.0183 | 134.9 | 8.094 | 0.06 | 0.689 | 1.242 |
| **7** | 0.0067 | 134.9 | 9.443 | 0.07 | 0.7325 | 1.3535 |
| **8** | 0.0024 | 134.9 | 10.792 | 0.08 | 0.778 | 1.458 |
| **9** | 0.0008 | 134.9 | 12.141 | 0.09 | 0.813 | 1.545 |
| **10** | 0.0002 | 134.9 | 13.49 | 0.1 | 0.827 | 1.604 |

C2 index calculating with the two available options for calculation of parametric roll amplitude *(A)* is

$C2=0.0268<0.15=R_{PR1}$: *(A)* calculated with averaging method

$C2=0.0496<0.15=R_{PR1}$: *(A)* calculated with time domain method

However, in both methods vulnerability index is smaller than 0.15 and vulnerability is not detected. For the case of standard wave frequency of level 2B, significant parametric roll amplitudes does not occur even in head or following seas. The critical situation is the case of zero speed where large roll angles occur from a wave height near to 7 m. In addition at a slow steaming operational speed near to 15 kn parametric roll resonance occurs for waves higher than 10 m in head seas.

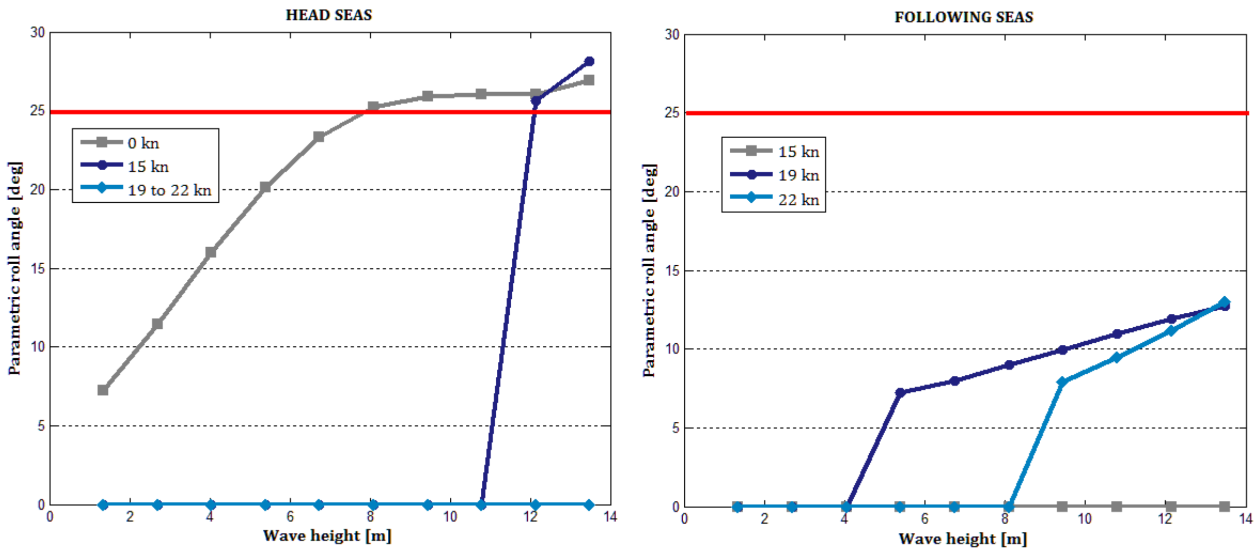



Figure 7.16 RoRo 130, Parametric roll angle obtained by TDM as a function of wave height for different speeds in pure head and following seas for loading condition FLA

## 9.7 PARAMETRIC ROLL CRITERIA EVALUATION

### 9.7.1 Relationship between the two available methods for the calculation of parametric roll amplitude *A* on Level 2B

The calculations showed that for all vessels and loading conditions the two available options (algebraic-eq.9.9 and time-domain simulation eq.9.11) for the calculation of parametric roll amplitude satisfactorily agree, and detect large parametric roll amplitudes for exactly the same wave cases, when the relationship of eq 9.10 is satisfied. On the other hand, there are some inconsistencies that should be mentioned. When the algebraic method is applied without the satisfaction of eq 9.10, large parametric roll amplitudes are detected by it for some wave cases, which are definitely not consistent with the result of time domain approach. In this case the total *C2* vulnerability index that is emerged from algebraic method is by far larger than the time domain's one. In addition with the application of eq.9.10 was observed that the algebraic method was not able to detect large amplitudes in the case of following seas, that were detected from time domain method only. Another critical issue is the fact that the two methods are consistent on the basis that most times detect amplitudes for the same waves cases. However, the amplitudes that are obtained by the algebraic equation are smaller than amplitudes obtained by the time domain method. Amplitude could be smaller than 25 deg with algebraic method while at the same wave case could be larger than 25 deg with time domain, so the total *C2* index that are obtained by the two methods could have a very different value, for some loadcases. Nevertheless it seems that the status is not affected due to the fact that the difference is not large. In general time-domain simulation is more stable and more accurate than algebraic method, something that also have recognized by the most delegations.

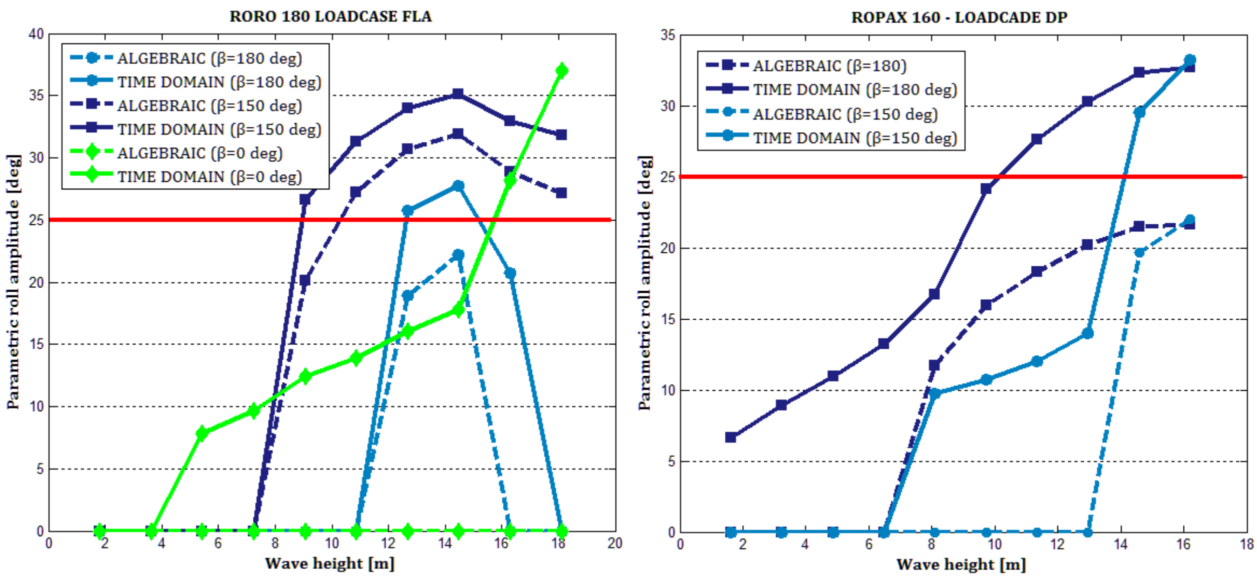



Figure 9.17 Relationship between the two available methods for the calculation of parametric roll amplitude ($A$) on Level 2B

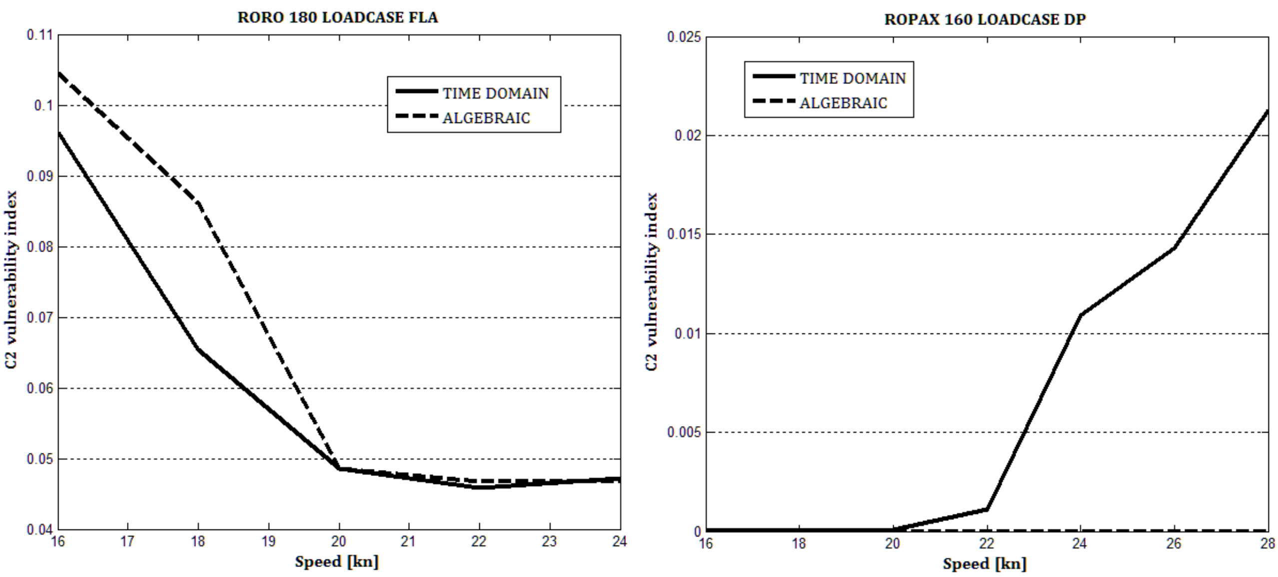



Figure 9.18 C2 index that arise from the different calculation methods as a function of speed

### 9.7.2 Effect of the vessel's length using on level 2B check

According to draft regulation the calculations on level 2B is going to carry out by using the waterline length of the examined loading condition. For the most ships the waterline length is approximately equal to $L_{BP}$. However, on some ships like fast RoPax vessels, where a goose neck bulb and a ducktail at stern are commonly adjusted, the difference between $L_{WL}$ and $L_{BP}$ may be close to 10%. If we take into account the fact that the using length is connected with the wave length and as a result with wave frequency, the results for parametric roll amplitudes may be different.

Systematic calculations for all sample ships show that *C2* index is not change significantly when $L_{BP}$ instead of $L_{WL}$ is used. However, for the RoPax 110 when $L_{BP}$ was used, both with the time domain and algebraic methods very large parametric roll amplitudes corresponding to capsize, are detected at DP condition in head seas, while on the same time when $L_{WL}$ is used parametric roll amplitudes are not detected and *C2* index is equal to zero.

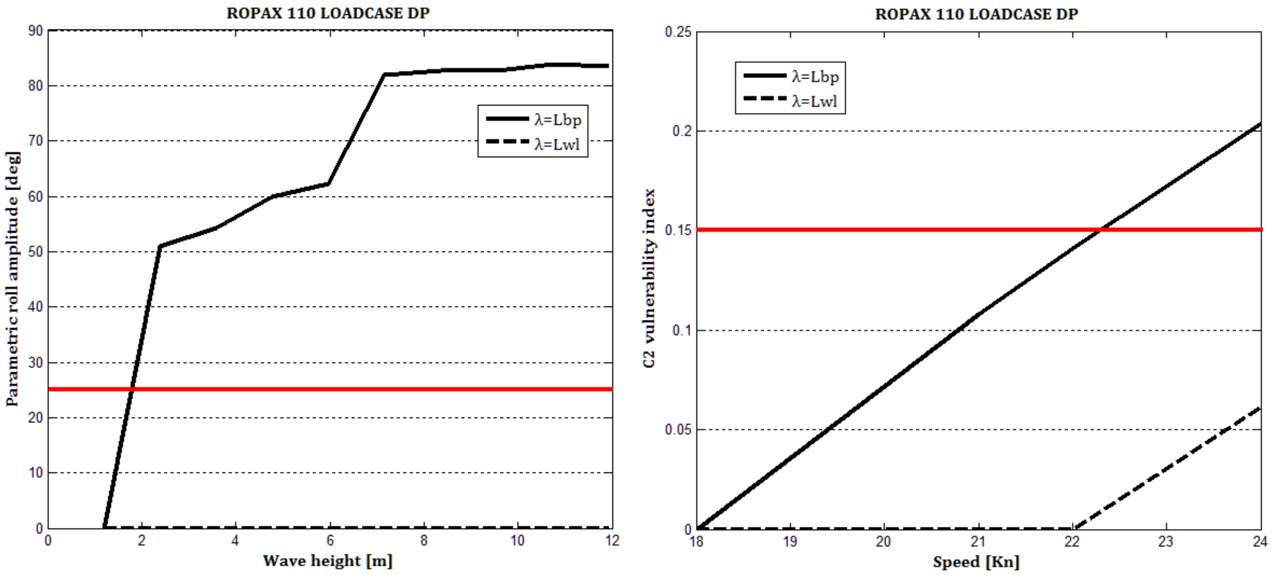



Figure 9.19 RoPax 110 Parametric roll amplitudes and sensitivity of *C2* vulnerability index on different ship length

### 9.7.3 Effect of roll period on level 2B vulnerability check

The effect of the value of roll natural period is investigated. The calculation of roll period is given by equation 9.12, where $r_g$ is the roll radius and *C* is coefficient that expresses $r_g$ as a percentage of ship's breadth.

$$T_R = \frac{2\pi \cdot r_g}{\sqrt{g \cdot GM}} = \frac{2\pi \cdot C \cdot B}{\sqrt{g \cdot GM}} \cong \frac{2 \cdot C \cdot B}{\sqrt{GM}} \qquad (9.12)$$

For the calculation of *C* coefficient the well-known IMO formula can be used. In addition *C* can be derived from the Kato formula. In general for the most ships C derived from the formula of IMO is around 0.37 - 0.40. On the other hand calculations for the ships of this thesis, showed that Kato formula gives *C* values in the space of 0.58 to 0.65 for modern RoRo ships, something that cannot be considered acceptable. According to Papanikolaou [39] the value of *C* coefficient for modern RoPax ships is preferably to be considered as 0.45 B as is referred on the conclusion of a relevant study. On second generation intact stability criteria's calculations there is the proposal that the calculation of the natural roll period should be carried out with Kato formula. On the following figures the effect of the value of *C* coefficient on parametric roll amplitudes and on C2 vulnerability index is presented. When roll period is calculated with Kato formula C2 index is by far smaller and large parametric roll amplitudes are not detected for the RoPax 160 and RoRo 180.

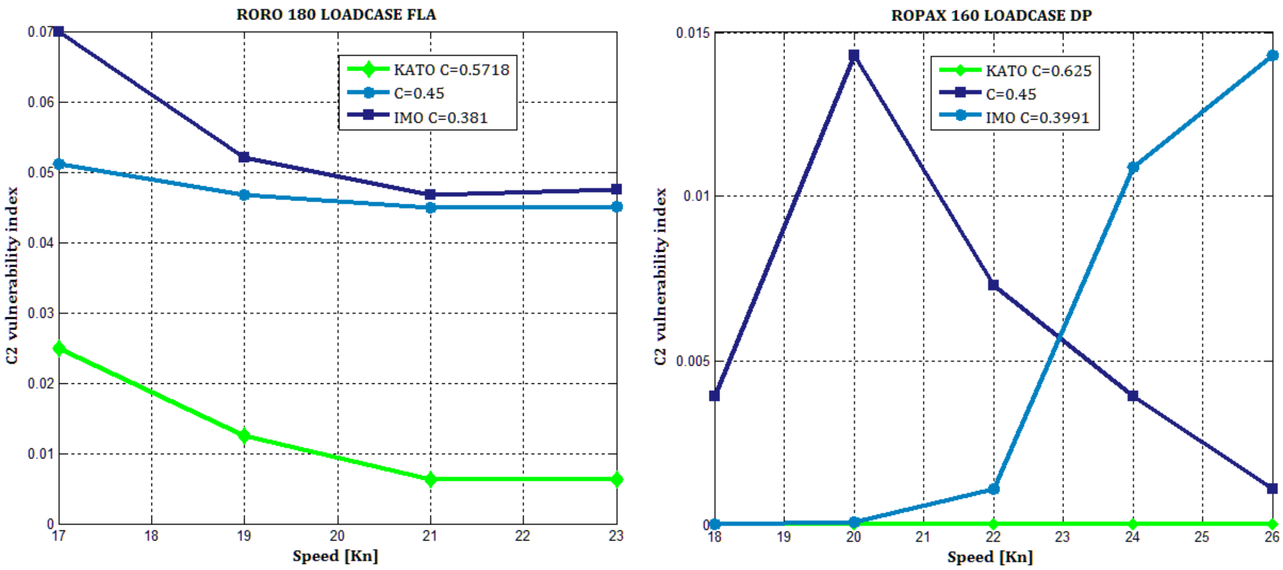



Figure 9.20 Effect of various method for calculating roll radius of gyration on C2 index

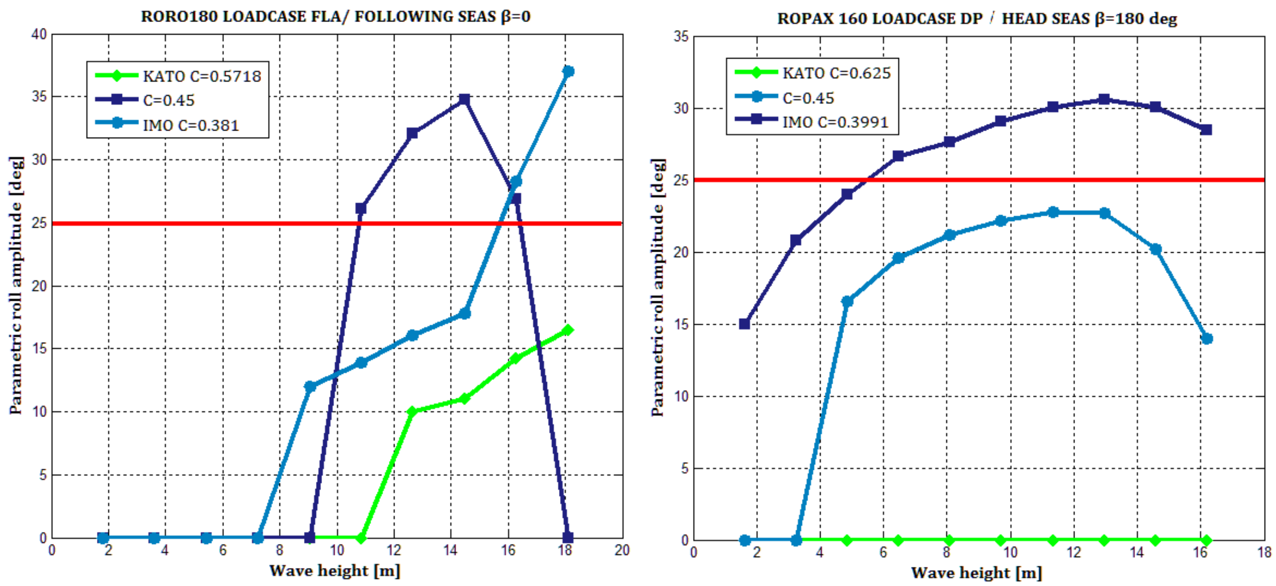



Figure 9.21 Effect of various method for calculating roll radius of gyration on calculated parametric roll amplitude

Based on the above calculations, we can observe that small differences on the value of the roll period have a strong influence on C2 vulnerability index and on the calculated parametric roll amplitude. If we replace the *C* value that is derived from IMO's formula with the value 0.45, the parametric roll problem that is detected for DP condition in head seas for the RoPax 160 is eliminated, while for the RoRo 180 a more serious condition is observe in the case of following seas, However, the calculation of roll period seems to be a very significant parameter in the detection and the evaluation of parametric roll seriousness

Last but not least it seems that Kato formula is very problematic due to the fact that lead to unrealistic $r_g$ values for RoPax ships and it should not be adopted on the final regulations.

### 9.7.4 Effect of investigated waves to level 2B index

On level 2B vulnerability check parametric roll amplitude *(A)* is calculated for 10 waves where the length is fixed at λ=L and the height is varying. However, by limiting wave length only one wave period is taken into account and as a result encounter frequency $\omega_e$ depends solely on ship's speed and wave direction, so only one value of $\alpha = 4 \cdot \omega_f^2 / \omega_e^2$ is investigated. In this way more critical condition for other wave lengths where $\omega_e/\omega_f$ could have a value in the vicinity of 1 (fundamental resonance $\omega_e=\omega_f$) or 2 (principal resonance $\omega_e=2\omega_f$) are neglected. For the above reason level 2B check was carried out and *C2* index was calculated for all the examined ships (RoPax ships at DP/RoRo ships at FLA) using the steepness and probability of 10 completely different wave cases derived from the table 6-A-1 (option A for pure loss of stability level 2 check) this waves have double steepness from the waves based on which level 2A parametric roll check is carried out and seem more appropriate. From the 16 waves of the table only the last 10 were selected in order to achieve ratios λ/Lbp from around 0.7 to 2.5 and investigate the influence of smaller or larger than the ship waves to the appearance of parametric roll resonance from the point of $\alpha = 4 \cdot \omega_f^2 / \omega_e^2$ ratio as well as GZ variations in waves. The selected wave cases are summarized on table 9.17

Table 9.17 Alternative wave cases for level 2B check

| Case No. | Weight Wi | Wave Length $\lambda_i$ [m] | Wave frequency $\omega_0$[rad/s] | Wave Height $H_i$ [m] | Steepness $s_i=H_i/\lambda_i$ |
|---|---|---|---|---|---|
| **1** | 0.0928 | 77.857 | 0.8898 | 2.589 | 0.0332 |
| **2** | 0.1992 | 103.655 | 0.7711 | 3.464 | 0.0334 |
| **3** | 0.2488 | 133.139 | 0.6804 | 4.41 | 0.0331 |
| **4** | 0.2087 | 166.309 | 0.6088 | 5.393 | 0.0324 |
| **5** | 0.129 | 203.164 | 0.5508 | 6.351 | 0.0312 |
| **6** | 0.0624 | 243.705 | 0.5029 | 7.25 | 0.0297 |
| **7** | 0.0248 | 287.931 | 0.4627 | 8.08 | 0.0281 |
| **8** | 0.0084 | 335.843 | 0.4284 | 8.841 | 0.0263 |
| **9** | 0.0025 | 387.44 | 0.3989 | 9.539 | 0.0246 |
| **10** | 0.0007 | 442.723 | 0.3731 | 10.194 | 0.0230 |

As one can observe on the following figures that refer to the case of following or head seas there are waves that can trigger parametric roll and cannot be taken into account from level 2B check with its current form. In addition C2 index is greater for all vessels something leading to a more accurate vulnerability assessment. C2 index calculating with the above wave cases as a function of speed is shown on figure 9.26 for all examined ships

Table 9.18 RoRo 180 introduction of alternative wave cases for level 2B check

| Case No. | $\lambda_t$ /Lbp | $GM_{amp}$/ $GM_{mean}$ | $\omega_e$/ $\omega_f$ Head (21 kn) | $4(\omega_e^2/\omega_f^2)$ Head (21 kn) | $\omega_e$/$\omega_f$ Follow (21 kn) | $4(\omega_e^2/\omega_f^2)$ Follow (21 kn) |
|---|---|---|---|---|---|---|
| 1 | 0.433986 | 0.7538 | 6.368 | 0.0986 | 0.0676 | 877.16 |
| 2 | 0.577787 | 1.4766 | 5.1549 | 0.1505 | 0.4225 | 22.403 |
| 3 | 0.742135 | 1.9612 | 4.3029 | 0.2160 | 0.6185 | 10.457 |
| 4 | 0.927029 | 2.0231 | 3.6764 | 0.2959 | 0.7269 | 7.5710 |
| 5 | 1.132464 | 1.885 | 3.1992 | 0.3908 | 0.7845 | 6.4958 |
| 6 | 1.358445 | 1.736 | 2.8252 | 0.5012 | 0.8123 | 6.0617 |
| 7 | 1.604967 | 1.5655 | 2.5251 | 0.6274 | 0.8214 | 5.9284 |
| 8 | 1.872035 | 1.4189 | 2.2796 | 0.7679 | 0.819 | 5.9635 |
| 9 | 2.159643 | 1.2722 | 2.0755 | 0.9286 | 0.8094 | 6.1056 |
| 10 | 2.467798 | 1.1356 | 1.9034 | 1.1041 | 0.7954 | 6.3226 |

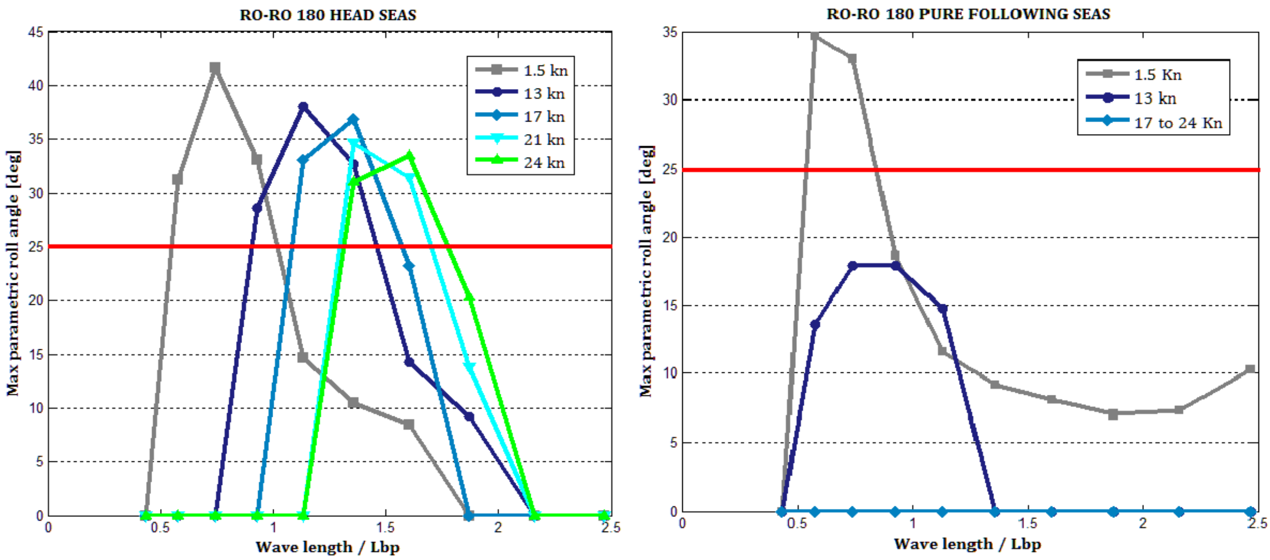



Figure 9.22 RoRo 180, Parametric roll amplitudes for wave cases of table 9.17 at various speeds on pure head and following seas for FLA

Table 9.19 RoRo 130, introduction of alternative wave cases for level 2B check for FLA

| Case No. | $\lambda_t$ /Lbp | $GM_{amp}$/ $GM_{mean}$ | $\omega_e$/ $\omega_f$ Head (19 kn) | $4(\omega_e^2/\omega_f^2)$ Head (19 kn) | $\omega_e$/$\omega_f$ Follow (19 kn) | $4(\omega_e^2/\omega_f^2)$ Follow (19 kn) |
|---|---|---|---|---|---|---|
| 1 | 0.587157 | 1.0587 | 5.6644 | 0.1247 | 0.3431 | 33.978 |
| 2 | 0.781712 | 1.4279 | 4.6017 | 0.1889 | 0.6048 | 10.934 |
| 3 | 1.004065 | 1.4338 | 3.8529 | 0.2695 | 0.7411 | 7.2828 |
| 4 | 1.254216 | 1.3445 | 3.3008 | 0.3671 | 0.8096 | 6.1021 |
| 5 | 1.532157 | 1.2287 | 2.8791 | 0.4826 | 0.8399 | 5.6709 |
| 6 | 1.837896 | 1.1103 | 2.5478 | 0.6162 | 0.8478 | 5.5654 |
| 7 | 2.171425 | 0.9939 | 2.2814 | 0.7685 | 0.8425 | 5.6351 |
| 8 | 2.532753 | 0.8814 | 2.0631 | 0.9398 | 0.8295 | 5.8140 |
| 9 | 2.92187 | 0.7803 | 1.8812 | 1.1303 | 0.8119 | 6.0688 |
| 10 | 3.338786 | 0.6931 | 1.7276 | 1.3403 | 0.7917 | 6.3810 |

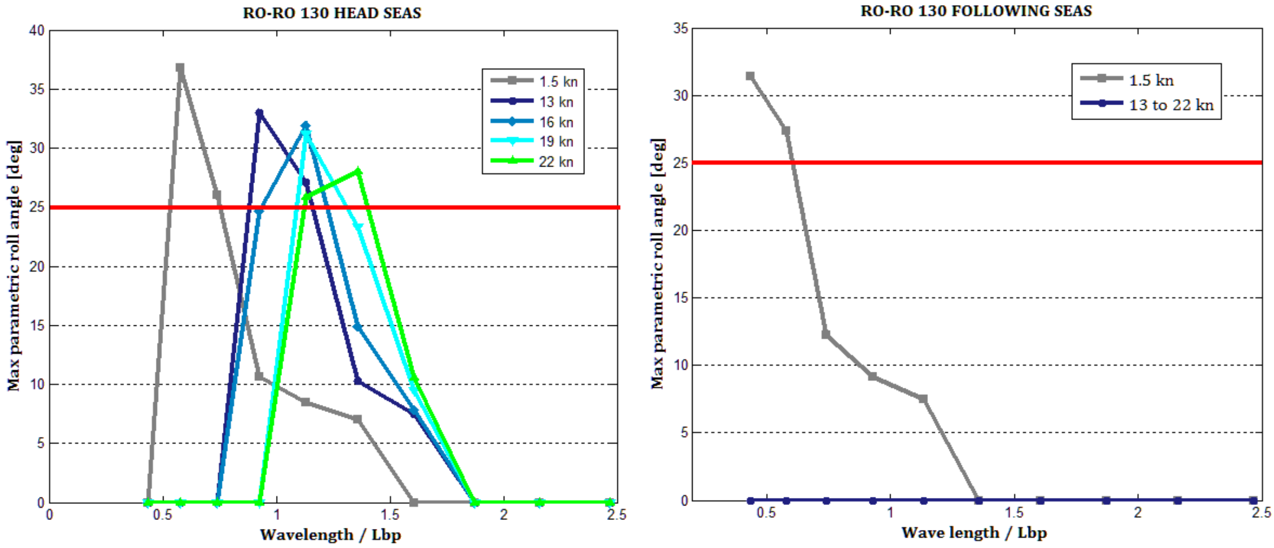



Figure 9.23 RoRo 130, Parametric roll amplitudes for wave cases of table 9.17 at various speeds in pure head and following seas for FLA

Table 9.20 RoPax 160, introduction of alternative wave cases for level 2B check for FLA

| Case No. | $\lambda_t$ /Lbp | $GM_{amp}/GM_{mean}$ | $\omega_e/\omega_f$ Head (21 kn) | $4(\omega_e^2/\omega_f^2)$ Head (21 kn) | $\omega_e/\omega_f$ Follow (21 kn) | $4(\omega_e^2/\omega_f^2)$ Follow (21 kn) |
|---|---|---|---|---|---|---|
| **1** | 0.494016 | 0.3830 | 4.4374 | 0.2 | 0.0471 | 1806 |
| **2** | 0.657709 | 0.8557 | 3.5921 | 0.3 | 0.2944 | 46.1 |
| **3** | 0.844791 | 0.8998 | 2.9983 | 0.4 | 0.431 | 21.5 |
| **4** | 1.05526 | 0.8573 | 2.5618 | 0.6 | 0.5065 | 15.6 |
| **5** | 1.289112 | 0.8032 | 2.2293 | 0.8 | 0.5468 | 13.4 |
| **6** | 1.546352 | 0.7470 | 1.9686 | 1.0 | 0.566 | 12.5 |
| **7** | 1.826973 | 0.6867 | 1.7595 | 1.3 | 0.5724 | 12.2 |
| **8** | 2.130984 | 0.6272 | 1.5885 | 1.6 | 0.5707 | 12.3 |
| **9** | 2.458376 | 0.5748 | 1.4463 | 1.9 | 0.564 | 12.6 |
| **10** | 2.809156 | 0.5243 | 1.3263 | 2.3 | 0.5542 | 13.0 |

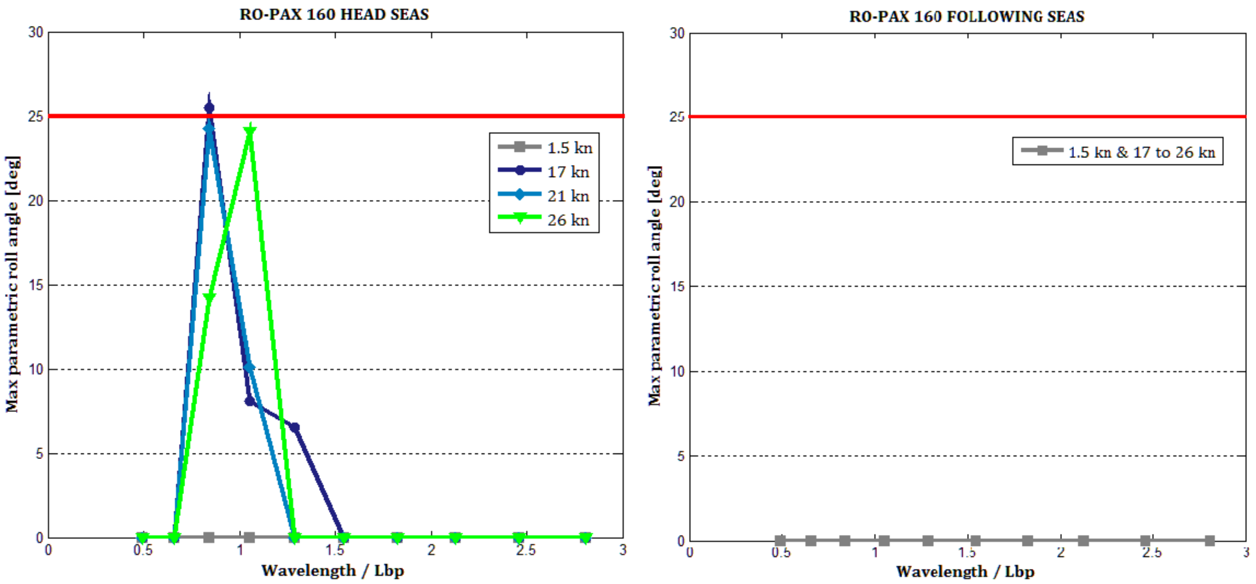
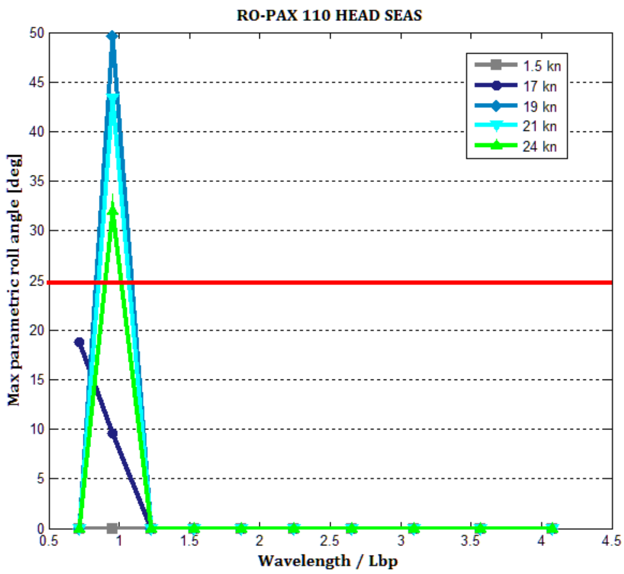



Figure 9.24 RoPax 160, Parametric roll amplitudes for wave cases of table 9.17 at various speeds in pure head and following seas for DP

Table 9.21 RoPax 110, introduction of alternative wave cases for level 2B check for FLA

| Case No. | $\lambda_t$ /Lbp | $GM_{amp}$/ $GM_{mean}$ | $\omega_e$/ $\omega_f$ Head (21 kn) | $4(\omega_e^2/\omega_f^2)$ Head (21 kn) | $\omega_e$/$\omega_f$ Follow (21 kn) | $4(\omega_e^2/\omega_f^2)$ Follow (21 kn) |
|---|---|---|---|---|---|---|
| 1 | 0.716915 | 0.7628 | 3.1225 | 0.4 | 0.0331 | 3648 |
| 2 | 0.954466 | 0.8117 | 2.5277 | 0.6 | 0.2071 | 93.2 |
| 3 | 1.225958 | 0.7618 | 2.1099 | 0.9 | 0.3033 | 43.5 |
| 4 | 1.53139 | 0.7028 | 1.8027 | 1.2 | 0.3564 | 31.5 |
| 5 | 1.870755 | 0.6456 | 1.5687 | 1.6 | 0.3848 | 27.0 |
| 6 | 2.244061 | 0.5776 | 1.3853 | 2.1 | 0.3983 | 25.2 |
| 7 | 2.651298 | 0.5209 | 1.2381 | 2.6 | 0.4028 | 24.7 |
| 8 | 3.092477 | 0.4594 | 1.1178 | 3.2 | 0.4016 | 24.8 |
| 9 | 3.567587 | 0.4188 | 1.0177 | 3.9 | 0.3969 | 25.4 |
| 10 | 4.076639 | 0.3755 | 0.9333 | 4.6 | 0.39 | 26.3 |



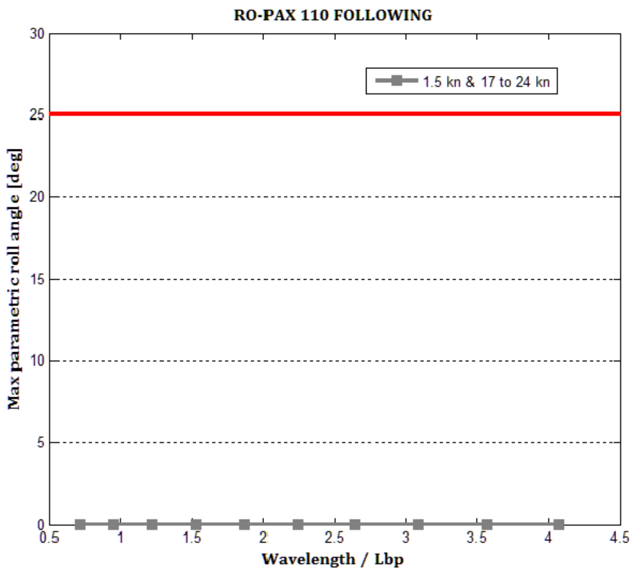




Figure 9.25 RoPax 110, Parametric roll amplitudes for wave cases of table 9.17 at various speeds in pure head and following seas for DP

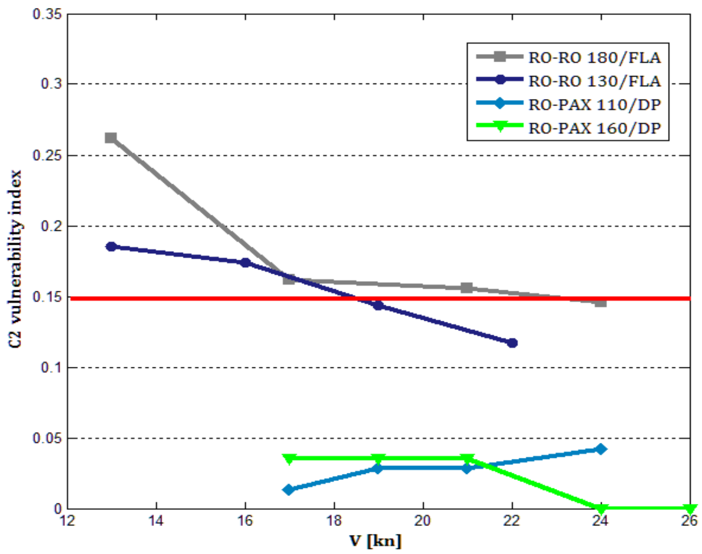



Figure 9.26 C2 index calculating with the alternative wave cases of table 7.17 as a function of operational speed

## 9.8 CONCLUSION AND POSSIBILITIES FOR IMPROVEMENTS ON PARAMETRIC ROLL CRITERIA

Some important issues concerning parametric roll criteria should be mentioned as a conclusion. As far as level 1 and level 2A checks are concerned, it seems that both of them fulfil their purpose adequately. However, there are some discrepancies that are focused on the fact that a ship, which under specific condition can be vulnerable to parametric roll to a large extent, may pass level 1 and level 2A checks very easy. This was observed on the partial condition of RoPax 110.

On the other hand level 2B seems to be quite problematic, and many important issues require further processing. First of all, the fact that only one wave length is examined is questionable, because by no doubt there are a lot of wave cases with $\lambda$ slightly smaller or larger than vessel's length connected to the occurrence of very large parametric roll amplitudes. Furthermore the fact that only the design speed is taken into account is also questionable. The calculations on sample ships showed that sailing speed plays a very important role. As an example on RoPax 160 larger parametric roll amplitudes was detected on the design speed of 26 Kn than on the slow-steaming operational speed of 21 Kn. In addition on RoRo 180 parametric roll problem in both head and following seas is more intense at a slow steaming speed close to 16 Kn than on design speed of 21 Kn. Today the majority of RoPax ships rarely operate at the design speed especially the fast ones

Another very important aspect that seems to create trouble and affects the credibility of level 2B check is the fact that the regulation with its current form requires the calculation of parametric roll amplitude, not only in head and following seas, but also in the heading angles of 30,60,120 and 150. However the 1 degree of freedom parametric roll differential equation that is used is capable to simulate only head and following seas, since wave excitation is not included. In case of heading angles of 60 or 150 degrees transverse Froude-Krylov forces are created due to the fact that the integration of pressure around the wetted surface are not parallel to the roll axis of the vessel. In addition the values of $GM_{mean}$ and $GM_{amp}$ as the wave passes the ship are calculated for the head or following seas cases, at an approximately beam seas case where the heading angle of 60 and 150 degrees correspond, the values of $GM_{mean}$ and $GM_{amp}$ is by no doubt very different. If one also take into account the fact that those *GM* values model the restoring variations in waves and play a very important role on parametric roll resonance, can obviously come to the conclusion that the results for possible detected parametric roll angles at those heading angles are not reliable, even though the frequency criterion is fulfilled.

The *C2* vulnerability index of level 2B is a weighted average of 7 different wave heading angles. However, by considering also the heading angles 60 and 150 degrees the *C2* value reduces as is divided with 7. In addition based on the sample calculations it is believed that the value 0.15 that corresponds to vulnerability limit is very high, leading to less conservative criterion for no apparent reason. Furthermore the analysis for the GM limit curves of level 2B which is presented in chapter 9 shows that the GM values that is required from draft regulation are totally unacceptable and questionable

As a conclusion it should be mentioned that level 2B requires further development and probably changes to its structure. The effect of different operational speeds should be included. Also the check should be done for different wave lengths for instance on a 3 wave length smaller equal and larger than ship's length. Moreover the check on heading angles of 60 and 150 degrees should be eliminated, and the check on 30 and 60 degrees should be reconsidered.

Finally the value 0.15 for the vulnerability limit should be reconsidered too. Last but not least, It should be underlined, that the adoption of 25 deg as a limit value for parametric roll amplitude is in the right direction because of the fact that lashing materials on RoRo ships have a yield limit close to 25 to 30 deg.

# Chapter 10 – Excessive Accelerations

## 10.1 PHYSICAL BACKGROUND

Extreme lateral accelerations can be developed on the highest accommodation decks of passenger ships or containerships under severe rolling motion. This accelerations may cause accidents such as the accident of the containership 'Chicago Express' that led to the fatal injury of 1 crew member. In addition may cause cargo shifting affecting dramatically the safety of the vessel.

According to [38] when the ship is under the effect of harmonic rolling with steady amplitude $\varphi\alpha$. The response is also harmonic and is expressed as follows

$$\varphi = \varphi_{\alpha} \cdot \sin\left(\omega_0 t\right) \tag{10.1}$$

Where $\omega$ is the natural roll frequency

In order to calculate roll amplitude the roll equation can be used

$$I_{XX} \cdot \ddot{\varphi} + B \cdot \dot{\varphi} + mg \cdot GM \cdot \varphi = M \sin\left(\omega_e t\right) \tag{10.2}$$

Where $\omega_e$ is the encounter frequency, while $M$ is the amplitude of wave excitation.

By neglecting diffraction forces $M$ is obtained as follows

$$M = k \cdot a_w \cdot m \cdot g \cdot GM \cdot \sin\mu \tag{10.3}$$

Where $k$ is the coefficient of wave excitation reduction due to finite wave length, $a_w$ is the effective wave slope and $\mu$ is the direction of waves.

Assuming $\omega_e$=$\omega$=wave frequency and by substituting eq. 8.3 and setting $I_{XX} = m \cdot k_{\varphi}^2$ where $k_{\varphi}$ is the radius of gyration and $\delta = \pi \cdot B / \left(\omega_0 \cdot I_{XX}\right)$ eq. 8.2 becomes

$$k_{\varphi}^2 \cdot \ddot{\varphi} + \left(\delta / \pi\right) \cdot \omega_0 \cdot k_{\varphi}^2 \cdot \dot{\varphi} + g \cdot GM \cdot \varphi = k \cdot a_w \cdot m \cdot g \cdot GM \cdot \sin\mu \sin\left(\omega\, t\right) \tag{10.4}$$

The solution of eq.. is a harmonic roll motion with amplitude $\varphi\alpha$

$$\frac{\varphi_{\alpha}}{\zeta_{\alpha}} = \frac{k \cdot \omega^2 \cdot \omega_0^2 \cdot \sin\mu}{g \cdot \left[\left(\omega_0^2 - \omega^2\right)^2 + \omega^2 \cdot \omega_0^2 \cdot \left(\delta / \pi\right)^2\right]^{1/2}} \tag{10.5}$$

Where $\zeta_{\alpha} = a_w \cdot \lambda_w / 2\pi$ is the wave amplitude, while $\lambda_w$ is the wave length

By neglecting lateral acceleration due to yaw and assuming $\sin\varphi_{\alpha}=\varphi_{\alpha}$ the lateral acceleration at a height $h$ above the roll axis can be expressed as follows

$$a_y = \varphi_\alpha \cdot \left( g + h \cdot \omega^2 \right) \tag{10.6}$$

However, via eq.. an expression for the lateral acceleration αy that occurs under the effect of harmonic wave of height $\zeta_\alpha$ and length $\lambda_w$. Nevertheless, it is wiser to use the variance of roll amplitude $\sigma_\varphi^2$ for a sea state with spectrum $S(\omega)$ instead of $\varphi_\alpha$

The variance of roll amplitude can be calculated as follows:

$$\sigma_\varphi^2 = \int_0^\infty \int_0^{2\pi} \left( \frac{\varphi_\alpha}{\zeta_\alpha} \right)^2 D\left(\mu - \mu_0\right) S\left(\omega\right) d\omega d\mu \tag{10.7}$$

Where $D$ is spectrum's spreading function

## 10.2 LEVEL 1 VULNERABILITY CRITERION FOR EXCESSIVE ACCELERATIONS

Level 1 vulnerability check is to be applied on the highest location along the length of the vessel, where passengers or crew may be present. A loading condition is considered vulnerable to excessive lateral accelerations if the following equation is satisfied

$$\phi k_L (g + 4\pi^2 h / T_r^2) < R_{EAI} \tag{10.8}$$

Where $\varphi$(rad) is the characteristic roll amplitude, $k_L$ is a non-dimensional factor taking into account vertical accelerations and yaw motion, g = 9.81 m/s$^2$ is the gravity acceleration, $h$(m) is the height of the bridge deck above the roll axis, $T_r$(s) is the natural roll period , $k_L$ is a factor taking into account simultaneous action of roll, yaw and pitch motions, and $R_{EAI}$(m/s$^2$) is the standard for lateral acceleration, that have not yet defined (5.3), (8.9), (8.69 or above)

## 10.3 LEVEL 2 VULNERABILITY CRITERION FOR EXCESSIVE ACCELERATIONS

Level 2 vulnerability check is based on the calculation The standard deviation of the lateral acceleration at zero speed and in a beam seaway, $\sigma_{LAi}$, is determined using the spectrum of roll motions due to the action of waves. The square of this standard deviation is calculated according to the following formula [9]

$$\sigma_{LAi}^2 = \frac{3}{4} \sum_{j=1}^{N} \left( a_y\left(\omega_j\right) \right)^2 S_{ZZ}\left(\omega_j\right) \Delta\omega \quad or \quad \sigma_{LAi}^2 = \frac{3}{4} \int_{\omega 1}^{\omega 2} \left( a_y\left(\omega_j\right) \right)^2 S_{ZZ}\left(\omega_j\right) d\omega \tag{10.9}$$

The short-term excessive acceleration condition stability failure index, $C_i$, for the loading condition and location under consideration and for the short-term environmental condition under consideration is a measure of the probability that the ship will exceed a specified lateral acceleration at least once in the exposure time considered, calculated according to the following formula [9]

$$C_i = \exp\left[ -R_2^2 / \left( 2 \cdot \sigma_{LAi}^2 \right) \right] \tag{10.10}$$

Where, $R_2$ = [9.81] m/s$^2$

The value for C is calculated as a weighted average from a set of wave conditions specified as

$$C = \sum_{i=1}^{N} W_i C_i \qquad (10.11)$$

Vulnerability is not detected when $C<R_{EA2}$=(0.001) or (0.0281) or (0.043 or above)

## 10.4 APPLICATION OF EXCESSIVE ACCELERATION CRITERIA ON RO-RO PASSENGER SHIPS

According to level 1 draft regulation for excessive acceleration, the criterion should be applied on the highest location along the length of the ship where passengers or crew may be present. On passenger ships designed with extensive superstructures bridge and upper bridge decks may extend from bow to stern and passengers or crew could be present on the whole length. The largest values of accelerations are present on the fore and aft part of the ship and the smallest values near amidships

### 10.4.1 Vessel: RoPax 160

Level 1 check is firstly applied on ship's bridge, located at 144 m forward of A.P and 28.6 m above B.L. and secondly on the whole length of bridge and upper bridge deck. Level 1 check is applicable only if the two following conditions is simultaneously satisfied.

$$H > 0.7B \text{ and } GM > 0.08B$$

Where ($H$) is the vertical distance from the waterline of the examined loading condition to the examined position. For the RoPax 160, the applicability of level 1 in the three examined loading condition is summarized on table 10.1

Table 10.1 Applicability of level 1 check for excessive acceleration for the RoPax 160

| Load case | | Bridge deck | | Upper Bridge deck | |
|---|---|---|---|---|---|
| DS | Deepest | H=22.6>17.64=0.7B<br>GM=2.077>2.016=0.08B | applicable | H=25.6>17.64=0.7B<br>GM=2.077>2.016=0.08B | applicable |
| DP | Partial | H=23.05>17.64=0.7B<br>GM=1.624<2.016=0.08B | not applicable | H=26.05>17.64=0.7B<br>GM=1.624<2.016=0.08B | not applicable |
| DL | Lightest | H=23.8>17.64=0.7B<br>GM=2.804>2.016=0.08B | applicable | H=26.8>17.64=0.7B<br>GM=2.804>2.016=0.08B | applicable |

**Loading Condition: Lightest Draft (DL)**

***Level 1 Vulnerability Check***

For vessel's bridge the following results are yielded.

Factor $k_L$ is related to the longitudinal position of the examined location along the ship, from after perpendicular, therefore

$$x = 144 \Rightarrow x > 0.65L = 102.4 \text{ m}$$

$$K_L = 0.527 + 0.727 \cdot x / L \Rightarrow K_L = 0.527 + 0.727 \cdot 144 / 152.7 \Rightarrow K_L = 1.1913$$

Natural roll period ($T_R$)

$$C = 0.373 + 0.023(B/T) - 0.043(L_{WL}/100) = 0.3996$$

$$T_r = \frac{2C \cdot B}{GM^{0.5}} = 12.03 \ s$$

Effective wave slope coefficient ($r$)

$$\tilde{B} = 2\pi^2 B / (gT_r^2) = 0.3502$$

$$\tilde{T} = 4\pi^2 C_B T / (gT_r^2) = 0.0868$$

$$\beta = \sin(\tilde{B}) / (\tilde{B}) = 0.979$$

$$\tau = \exp(-\tilde{T}) / \tilde{T} = 10.566$$

$$K_1 = g\beta T_r^2 (\tau + \tau \tilde{T} - 1/\tilde{T}) / (4\pi^2) = -1.4435$$

$$K_2 = g\tau T_r^2 (\beta - \cos \tilde{B}) / (4\pi^2) = 15.353$$

$$F = \beta(\tau - 1/\tilde{T}) = -0.9384$$

$$\mathrm{OG} = \mathrm{KG} - \mathrm{T} = 5.373$$

$$r = \frac{K_1 + K_2 + OG \cdot F}{\frac{B^2}{12C_B T} - \frac{C_B T}{2} - OG} = 0.8852$$

Wave steepness s according to the steepness table for roll period $T_r = 12.03$ s

$$s = 0.0648$$

Logarithmic decrement of roll decay $\delta_\varphi$ :

$$A_K = 37.15 \text{ m}^2$$

$$100 \cdot A_K / L \cdot B = 0.9 < 4$$

$$C_m < 0.94$$

$$\delta_\varphi = 4/15 + 1/3 \cdot (100 A_{BK} / (L \cdot B)) = 0.5785$$

Roll amplitude φ : $\phi = 4.43 rs / \delta^{0.5} = 0.3343$ rad = 19.15 deg

Lateral acceleration:

$h = 20.363$ m (roll axis assumed to be located at the midpoint between the examined d and KG)

$$\phi k_L (g + 4\pi^2 h / T_r^2) = 6.118 \ \text{m/s}^2$$

$$6.118 \ > R_1 = 5.3 \ \text{m/s}^2$$

Thus, Condition is vulnerable to excessive lateral accelerations. Accelerations arise from the application of level 1 for the whole length of bridge and upper bridge decks are shown on figure 10.1

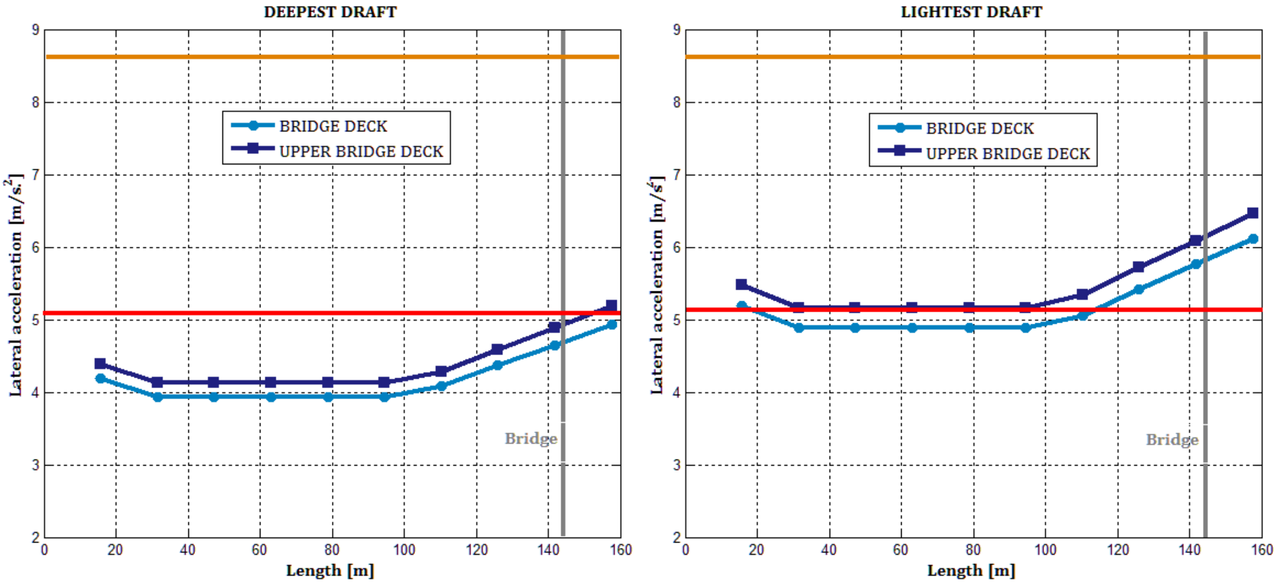



Figure 10.1 RoPax 160 level 1 acceleration on bridge and upper bridge deck for DS and DL

### *Level 2 Vulnerability Check*

For each short-term environmental condition the square of standard deviation of lateral acceleration at zero speed in a beam seaway is calculated as

$$\sigma_{LAi}{}^2 = \frac{3}{4} \int_{\omega 1}^{\omega 2} \left( ay(\omega) \right)^2 \cdot Szz(\omega) d\omega$$

According to draft regulation effective wave slope coefficient for each wave frequency should be derived from the standard methodology using on level 2 dead ship stability calculation.

However in this thesis the calculations were also carried out using the constant effective wave slope that is derived from the formula of level 1 check for excessive accelerations

Table 10.2 RoPax 160 level 2 excessive accelerations for DS

| **Deepest Draft** | | | |
|---|---|---|---|
| **X** | **[C] Index E.W.S.F Standard** | **Status if $R_{DS}$=0.001** | **Status if $R_{DS}$=0.043** |
| **Bridge Deck** (29.1 m ab. B.L) | | | |
| **0.1 L** | 0.0019 | **Fail** | Pass |
| **0.3 L** | 0.0015 | **Fail** | Pass |
| **0.5 L** | 0.000005 | Pass | Pass |
| **0.7 L** | 0.000006 | Pass | Pass |
| **0.9 L** | 0.0000129 | Pass | Pass |
| **1.0 L** | 0.000018 | Pass | Pass |
| **Upper Bridge Deck** (32.1 m ab. B.L) | | | |
| **0.1 L** | 1.18E-05 | Pass | Pass |
| **0.3 L** | 8.39E-06 | Pass | Pass |
| **0.5 L** | 8.33E-06 | Pass | Pass |
| **0.7 L** | 1.22E-06 | Pass | Pass |
| **0.9 L** | 2.13E-06 | Pass | Pass |
| **1.0 L** | 2.92E-06 | Pass | Pass |

Table 10.3 RoPax 160 level 2 excessive accelerations for DL

| **Lightest Draft** | | | | | | |
|---|---|---|---|---|---|---|
| **X** | **[C] Index E.W.S.F Standard** | **Status if $R_{DS}$=0.001** | **Status if $R_{DS}$=0.043** | **[C] Index E.W.S.F Constant** | **Status if $R_{DS}$=0.001** | **Status if $R_{DS}$=0.043** |
| **Bridge Deck** (29.1 m ab. B.L) | | | | | | |
| **0.1 L** | 6.77E-05 | Pass | Pass | 0.0013 | **Fail** | Pass |
| **0.3 L** | 5.00E-05 | Pass | Pass | 0.001 | Pass | Pass |
| **0.5 L** | 5.00E-05 | Pass | Pass | 0.001 | Pass | Pass |
| **0.7 L** | 6.00E-05 | Pass | Pass | 0.0012 | **Fail** | Pass |
| **0.9 L** | 1.12E-04 | Pass | Pass | 0.0018 | **Fail** | Pass |
| **1.0 L** | 1.45E-04 | Pass | Pass | 0.0022 | **Fail** | Pass |
| **Upper Bridge Deck** (32.1 m ab. B.L) | | | | | | |
| **0.1 L** | 1.12E-04 | Pass | Pass | 0.0018 | **Fail** | Pass |
| **0.3 L** | 8.44E-05 | Pass | Pass | 0.0015 | **Fail** | Pass |
| **0.5 L** | 8.44E-05 | Pass | Pass | 0.0015 | **Fail** | Pass |
| **0.7 L** | 9.90E-05 | Pass | Pass | 0.0017 | **Fail** | Pass |
| **0.9 L** | 1.81E-04 | Pass | Pass | 0.0026 | **Fail** | Pass |
| **1.0 L** | 2.33E-04 | Pass | Pass | 0.0031 | **Fail** | Pass |

### 10.4.2 Vessel: RoPax 110

Table 10.4 Applicability of level 1 check for excessive acceleration for the RoPax 110

| **Load case** | | **Bridge deck** | | **Upper Bridge deck** | |
|---|---|---|---|---|---|
| DS | Deepest | H=13.9>12.88=0.7B<br>GM=1.904>1.472=0.08B | applicable | H=16.7>12.88=0.7B<br>GM=1.904>1.472=0.08B | applicable |
| DP | Partial | H=14.13>12.88=0.7B<br>GM=1.834>1.472=0.08B | applicable | H=16.93>12.88=0.7B<br>GM=1.834>1.472=0.08B | applicable |
| DL | Lightest | H=14.47>12.88=0.7B<br>GM=2.304>1.472=0.08B | applicable | H=17.27>12.88=0.7B<br>GM=2.304>1.472=0.08B | applicable |

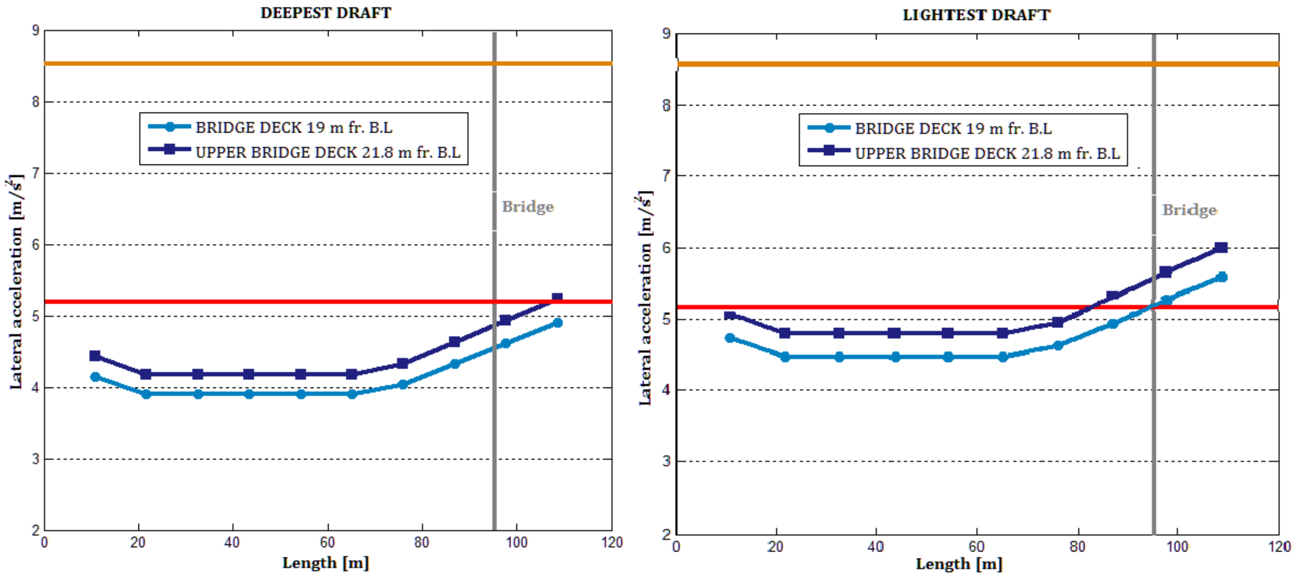



Figure 10.2 RoPax 110 level 1 acceleration on bridge and upper bridge deck for DS and DL

## *Level 2 Vulnerability Check*

Table 10.5 RoPax 110 level 2 excessive accelerations for DS

| Deepest Draft | | | | | | |
|---|---|---|---|---|---|---|
| **X** | **[C] Index E.W.S.F Standard** | **Status if $R_{DS}$=0.001** | **Status if $R_{DS}$=0.043** | **[C] Index E.W.S.F Constant** | **Status if $R_{DS}$=0.001** | **Status if $R_{DS}$=0.043** |
| **Bridge Deck** (19 m ab. B.L) | | | | | | |
| **0.1 L** | 0.0891 | **Fail** | **Fail** | 0.1536 | **Fail** | **Fail** |
| **0.3 L** | 0.0809 | **Fail** | **Fail** | 0.1431 | **Fail** | **Fail** |
| **0.5 L** | 0.0809 | **Fail** | **Fail** | 0.1431 | **Fail** | **Fail** |
| **0.7 L** | 0.0857 | **Fail** | **Fail** | 0.1491 | **Fail** | **Fail** |
| **0.9 L** | 0.092 | **Fail** | **Fail** | 0.1731 | **Fail** | **Fail** |
| **1.0 L** | 0.102 | **Fail** | **Fail** | 0.1846 | **Fail** | **Fail** |
| **Upper Bridge Deck** (21.8 m ab. B.L) | | | | | | |
| **0.1 L** | 0.0962 | **Fail** | **Fail** | 0.1795 | **Fail** | **Fail** |
| **0.3 L** | 0.0926 | **Fail** | **Fail** | 0.1681 | **Fail** | **Fail** |
| **0.5 L** | 0.0926 | **Fail** | **Fail** | 0.1681 | **Fail** | **Fail** |
| **0.7 L** | 0.0925 | **Fail** | **Fail** | 0.1748 | **Fail** | **Fail** |
| **0.9 L** | 0.1143 | **Fail** | **Fail** | 0.2003 | **Fail** | **Fail** |
| **1.0 L** | 0.1161 | **Fail** | **Fail** | 0.2127 | **Fail** | **Fail** |

Table 10.6 RoPax 110 level 2 excessive accelerations for DL

| Lightest Draft | | | | | | |
|---|---|---|---|---|---|---|
| **X** | **[C] Index E.W.S.F Standard** | **Status if $R_{DS}$=0.001** | **Status if $R_{DS}$=0.043** | **[C] Index E.W.S.F Constant** | **Status if $R_{DS}$=0.001** | **Status if $R_{DS}$=0.043** |
| **Bridge Deck** (29.1 m ab. B.L) | | | | | | |
| **0.1 L** | 0.0017 | **Fail** | Pass | 0.0055 | **Fail** | Pass |
| **0.3 L** | 0.0014 | **Fail** | Pass | 0.0047 | **Fail** | Pass |
| **0.5 L** | 0.0014 | **Fail** | Pass | 0.0047 | **Fail** | Pass |
| **0.7 L** | 0.0016 | **Fail** | Pass | 0.0052 | **Fail** | Pass |
| **0.9 L** | 0.0024 | **Fail** | Pass | 0.0073 | **Fail** | Pass |
| **1.0 L** | 0.0029 | **Fail** | Pass | 0.0085 | **Fail** | Pass |
| **Upper Bridge Deck** (32.1 m ab. B.L) | | | | | | |
| **0.1 L** | 0.0027 | **Fail** | Pass | 0.0079 | **Fail** | Pass |
| **0.3 L** | 0.0022 | **Fail** | Pass | 0.0067 | **Fail** | Pass |
| **0.5 L** | 0.0022 | **Fail** | Pass | 0.0067 | **Fail** | Pass |
| **0.7 L** | 0.0025 | **Fail** | Pass | 0.0074 | **Fail** | Pass |
| **0.9 L** | 0.0036 | **Fail** | Pass | 0.0102 | **Fail** | Pass |
| **1.0 L** | 0.0043 | **Fail** | Pass | 0.0118 | **Fail** | Pass |

### 10.4.3 Vessel: RoPax 75

Table 10.7 Applicability of level 1 check for excessive acceleration for the RoPax 75

| **Load case** | | **Bridge deck** | | **Upper Bridge deck** | |
|---|---|---|---|---|---|
| DS | Deepest | H=9.55<10.08=0.7B<br>GM=1.57>1.152=0.08B | Not applicable | H=12.05>10.08=0.7B<br>GM=1.57>1.152=0.08B | applicable |

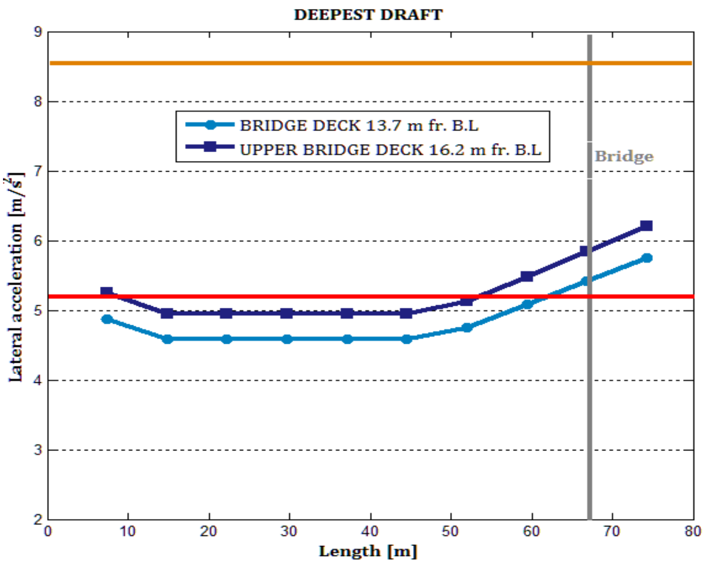



Figure 10.3 RoPax 75 level 1 acceleration on bridge and upper bridge deck for DS

As one can observe on figures 10.1, 10.2, 10.3 on RoPax ships for all loading conditions vulnerability on level 1 is not detected for all positions along the bridge and upper bridge deck. If $R_{EAI}$=8.69 m/s²

### *Level 2 Vulnerability Check*

Table 10.8 RoPax 75 level 2 excessive accelerations for DS

| Deepest Draft | | | |
|---|---|---|---|
| **X** | **[C] Index E.W.S.F Standard** | **Status if $R_{DS}$=0.001** | **Status if $R_{DS}$=0.043** |
| **Bridge Deck** (13.6 m ab. B.L) | | | |
| **0.1 L** | 0.0018 | **Fail** | Pass |
| **0.3 L** | 0.0015 | **Fail** | Pass |
| **0.5 L** | 0.0015 | **Fail** | Pass |
| **0.7 L** | 0.0017 | **Fail** | Pass |
| **0.9 L** | 0.0026 | **Fail** | Pass |
| **1.0 L** | 0.0031 | **Fail** | Pass |
| **Upper Bridge Deck** (16.2 m ab. B.L) | | | |
| **0.1 L** | 0.0029 | **Fail** | Pass |
| **0.3 L** | 0.0025 | **Fail** | Pass |
| **0.5 L** | 0.0025 | **Fail** | Pass |
| **0.7 L** | 0.0028 | **Fail** | Pass |
| **0.9 L** | 0.0041 | **Fail** | Pass |
| **1.0 L** | 0.0048 | **Fail** | Pass |

## 10.5 APPLICATION OF EXCESSIVE ACCELERATION CRITERIA ON RO-RO CARGO SHIPS

On RoRo Cargo ships bridge deck have a small length. The superstructure for crew accommodation could be located even on bow or stern-amidships. However the higher location where crew may be present is restricted to a small percentage of vessel's length. Loading condition with low GM values are not vulnerable to excessive accelerations and level 1 criterion is not applied. On the other hand loading condition with light displacements and high GM values such as ballast conditions is connected with large accelerations. For the two examined RoRo cargo ships level 1 check is applied on ballast departure condition

### *Level 1 Vulnerability Check*

Table 10.9 Applicability of level 1 check for excessive acceleration for the RoRo 180

| | **Load case** | **Bridge deck** | | **Upper Bridge deck** | |
|---|---|---|---|---|---|
| BD | Ballast Departure | H=27>17.92=0.7B<br>GM=3.93>2.048=0.08B | applicable | H=30>17.92=0.7B<br>GM=3.93>2.048=0.08B | applicable |

Table 10.10 Applicability of level 1 check for excessive acceleration for the RoRo 130

| **Load case** | | **Bridge deck** | | **Upper Bridge deck** | |
|---|---|---|---|---|---|
| BD | Ballast Departure | H=24.13>16.24=0.7B<br>GM=3.76>1.856=0.08B | applicable | H=27.13>16.24=0.7B<br>GM=3.76>1.856=0.08B | applicable |

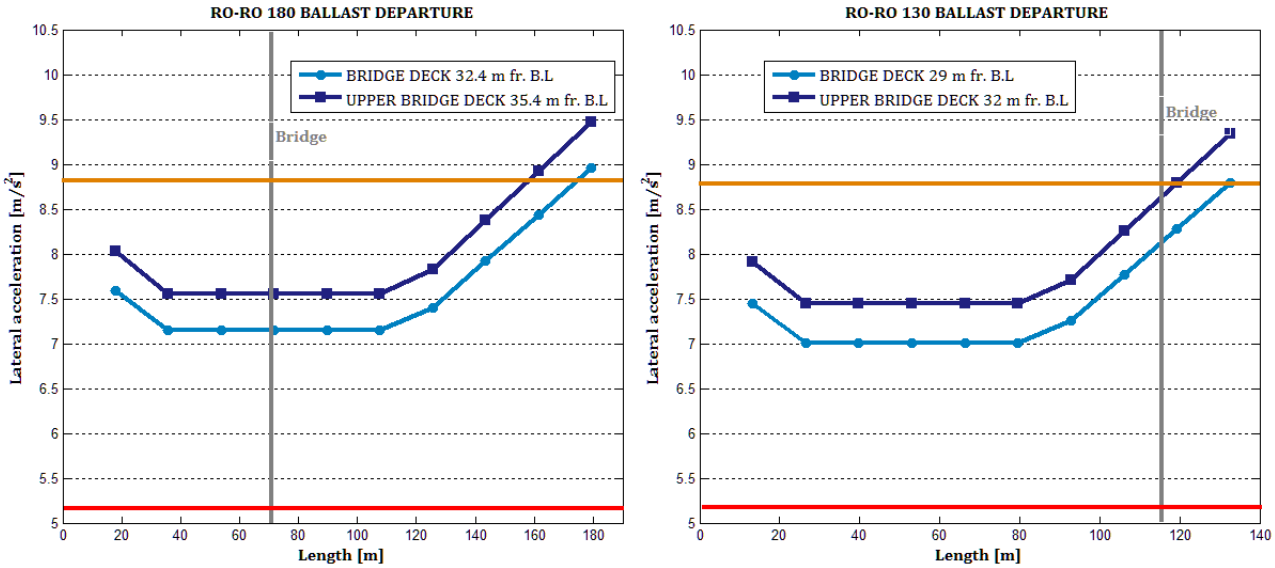



Figure 10.4 RoRo 180 &130 level 1 acceleration on bridge and upper bridge deck for BA

However, for both vessels vulnerability is not detected for the bridge, but vulnerability is detected on the upper bridge deck when the accommodation-superstructure is located on the fore position if $R_{EAI}$=8.69 m/s². On the other hand vulnerability is detected if $R_{EAI}$=5.3 m/s²

### *Level 2 Vulnerability Check*

Table 10.11 RoRo 180 level 2 excessive accelerations for BD

| **Ballast Departure** | | | | | | |
|---|---|---|---|---|---|---|
| **X** | **[C] Index E.W.S.F Standard** | **Status if $R_{DS}$=0.001** | **Status if $R_{DS}$=0.043** | **[C] Index E.W.S.F Constant** | **Status if $R_{DS}$=0.001** | **Status if $R_{DS}$=0.043** |
| **Bridge Deck** (32.1 m ab. B.L) | | | | | | |
| **0.1 L** | 0.0228 | Fail | Pass | 0.061 | Fail | Fail |
| **0.3 L** | 0.0201 | Fail | Pass | 0.0551 | Fail | Fail |
| **0.5 L** | 0.0201 | Fail | Pass | 0.0551 | Fail | Fail |
| **0.7 L** | 0.0223 | Fail | Pass | 0.0598 | Fail | Fail |
| **0.9 L** | 0.0292 | Fail | Pass | 0.0738 | Fail | Fail |
| **1.0 L** | 0.0327 | Fail | Pass | 0.0809 | Fail | Fail |
| **X** | **[C] Index E.W.S.F Standard** | **Status if $R_{DS}$=0.001** | **Status if $R_{DS}$=0.043** | **[C] Index E.W.S.F Constant** | **Status if $R_{DS}$=0.001** | **Status if $R_{DS}$=0.043** |
| **Upper Bridge Deck** (35.4 m ab. B.L) | | | | | | |
| **0.1 L** | 0.0284 | Fail | Pass | 0.0722 | Fail | Fail |
| **0.3 L** | 0.0252 | Fail | Pass | 0.0659 | Fail | Fail |
| **0.5 L** | 0.0258 | Fail | Pass | 0.0659 | Fail | Fail |
| **0.7 L** | 0.0278 | Fail | Pass | 0.0711 | Fail | Fail |
| **0.9 L** | 0.0359 | Fail | Pass | 0.0868 | Fail | Fail |
| **1.0 L** | 0.0399 | Fail | Pass | 0.0947 | Fail | Fail |

Table 10.12 RoRo 130 level 2 excessive accelerations for BD

| Ballast Departure | | | | | | |
|---|---|---|---|---|---|---|
| **X** | **[C] Index E.W.S.F Standard** | **Status if $R_{DS}$=0.001** | **Status if $R_{DS}$=0.043** | **[C] Index E.W.S.F Constant** | **Status if $R_{DS}$=0.001** | **Status if $R_{DS}$=0.043** |
| **Bridge Deck** (29 m ab. B.L) | | | | | | |
| **0.1 L** | 0.006 | **Fail** | Pass | 0.0186 | **Fail** | Pass |
| **0.3 L** | 0.0051 | **Fail** | Pass | 0.0163 | **Fail** | Pass |
| **0.5 L** | 0.0051 | **Fail** | Pass | 0.0163 | **Fail** | Pass |
| **0.7 L** | 0.0056 | **Fail** | Pass | 0.0176 | **Fail** | Pass |
| **0.9 L** | 0.008 | **Fail** | Pass | 0.0233 | **Fail** | Pass |
| **1.0 L** | 0.0093 | **Fail** | Pass | 0.0263 | **Fail** | Pass |
| **Upper Bridge Deck** (32 m ab. B.L) | | | | | | |
| **0.1 L** | 0.0082 | **Fail** | Pass | 0.0238 | **Fail** | Pass |
| **0.3 L** | 0.0069 | **Fail** | Pass | 0.021 | **Fail** | Pass |
| **0.5 L** | 0.0069 | **Fail** | Pass | 0.021 | **Fail** | Pass |
| **0.7 L** | 0.0076 | **Fail** | Pass | 0.0226 | **Fail** | Pass |
| **0.9 L** | 0.0106 | **Fail** | Pass | 0.0295 | **Fail** | Pass |
| **1.0 L** | 0.0112 | **Fail** | Pass | 0.0331 | **Fail** | Pass |

## 10.6 EXCESSIVE ACCELERATION CRITERIA EVALUATION

Some important issues related to the current form of vulnerability criteria for excessive accelerations should be underlined. First of all, taking into consideration that level 1 vulnerability assessment have to be applied on the highest location along the length of ship where passengers or crew may be present, it should be mentioned that on the majority of RoRo and containerships the above location is the bridge deck, on the other hand for large cruise ships the highest location where passengers may be present is much higher than the bridge deck. Although the criterion seems to be related with people on board, actually is not, because of the fact that the acceleration value under which the majority of passengers could perform seasickness or the crew could be affected is around 0.2g, namely 1.962 $m/s^2$ by far smaller than 5.3 or 8.69 $m/s^2$ namely 0.54g and 0.88g respectively, values that are connected with the detection of vulnerability on level 1 criterion. However is clearly shown that the approach of checking vulnerability at locations where passengers and crew are present and at the same time vulnerability indicator to be close to gravitational acceleration is inconsistent. On the other hand if vulnerability index sets to 0.2g for location such as passenger or crew spaces, all ships will automatically fail on level 1 in all loading condition even if GM is very low (below 1 m) if level 1 check will carry out with the current draft regulation. Based on the above is obvious that the value 5.3 or 8.69 $m/s^2$ is not related with passengers or crew but with vessels safety, more specifically with lashing equipment. This seems to be in the correct direction because the safety of containerships and RoRo ships in case of large transverse accelerations is connected with cargo security devices and the probability of material failure on lashings due to the appearance of forces which exceed the design load, so a cargo shifting is very possible to take place and stability will be dramatically affected. In the current draft regulation is nothing directly mentioned about the connection of lashing failure and occurrence of excessive transverse accelerations but is obvious that is indicated indirectly. Nevertheless there are some critical issues that should be mentioned. First of all, on containerships the highest location where containers is loaded is slightly below bridge deck so the application of level 1 on bridge may be connected with lashing. However, the fact that the largest values of accelerations are occurred on vessel's bow and not near amidships where bridge is located on large containerships is very crucial. According to calculations on the two examined RoRo vessels the acceleration that yields from level 1 procedure for the bow may be even 1.5 times higher than amidships so the acceleration for containers at bow may be close to 12 m/s$^2$ if the acceleration at bridge is close to 8 m/s$^2$ . The value 12 m/s$^2$ is very high and may be higher than fixed acceleration based on which lashing equipment is designed. The above observations concern RoRo ships too, where accelerations for lashing design are equal to those used on containerships with the difference that a position where a trailer may be loaded is by far lower. Based on the above level 1 check should not confined on bridge but it should applied on the whole length of the ship

### 10.6.1 Consistency between Level 1 and 2

Based on the calculations on the sample ships of this thesis we can observe that the value of long term probability index C should be 0.043 for consistency between level 1 and level 2 if $R_{EAI}$ remains 5.3 m/s$^2$. However the form of the function *C=f(GM)* show a problematic form similar to those of level 2 dead ship stability. This problem is focusing on the fact that the function is very sensitive in GM alternations. So vulnerability can be detected on a loading condition with a certain GM value while vulnerability is not detected if the GM is slightly smaller or larger than the designed one. For the above reason BD condition of the RoRo 180 and DS condition of the RoPax 110 found vulnerable at level 2

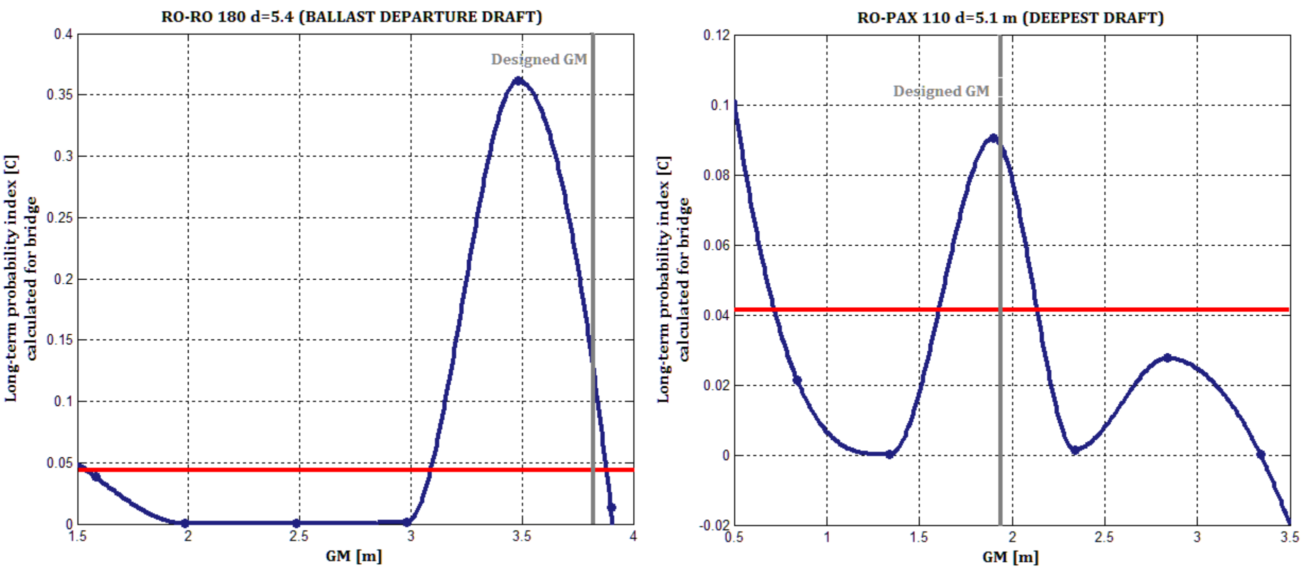



Figure 10.5 : Long-term index *C* versus *GM*

### 10.6.2 Connection of level 1 check with the cargo security manual

On a cargo security manual booklet of a RoRo or container vessel the strength limit of lashing equipment are calculated based on some reference accelerations transverse, vertical and longitudinal related to transverse, vertical and longitudinal equilibrium of a trailer accommodated on a vehicle deck. Therefore reference accelerations are a function of the location in which a trailer is placed along the depth and length of the vessel. The reference acceleration that are summarized on table 10.13 are corrected based on the specific characteristics of the examined vessel according to table 10.14

Table 10.13 Basic accelerations for lashing calculations

| **Transverse acceleration $a_y$ in $m/s^2$** | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **on deck, high** | 7.1 | 6.9 | 6.8 | 6.7 | 6.7 | 6.8 | 6.9 | 7.1 | 7.4 |
| **on deck, low** | 6.5 | 6.3 | 6.1 | 6.1 | 6.1 | 6.1 | 6.3 | 6.5 | 6.7 |
| **tween deck** | 5.9 | 5.6 | 5.5 | 5.4 | 5.4 | 5.5 | 5.6 | 5.9 | 6.2 |
| **lower hold** | 5.5 | 5.3 | 5.1 | 5.0 | 5.0 | 5.1 | 5.3 | 5.5 | 5.9 |

The above basic acceleration data are to be considered as valid under the following operational conditions

1. Operation in unrestricted area
2. Operation during the whole year
3. Duration of voyage is 25 days
4. Length of the ship is 100 m
5. Service speed is 15 knots
6. B/GM>=13

For ships of a length other than 100 m and a service speed other than 15 knots basic accelerations should be corrected by the following correction factor for ship lengths between 50 and 300 m

$$\text{correction factor} = (0.345 \cdot V/\sqrt{L}) + (58.62 \cdot L - 1034.5)/L^2$$

In addition for ships with B/GM less than 13, the transverse acceleration figures should be corrected by a factor given in table 10.14

Table 10.14 Correction factors for B/GM <13

| **B/GM** | **7** | **8** | **9** | **10** | **11** | **12** | **13 or above** |
|---|---|---|---|---|---|---|---|
| **on deck, high** | 1.56 | 1.40 | 1.27 | 1.19 | 1.11 | 1.05 | 1.00 |
| **on deck, low** | 1.42 | 1.30 | 1.21 | 1.14 | 1.09 | 1.04 | 1.00 |
| **tween deck** | 1.26 | 1.19 | 1.14 | 1.09 | 1.06 | 1.03 | 1.00 |
| **lower hold** | 1.15 | 1.12 | 1.09 | 1.06 | 1.04 | 1.02 | 1.00 |

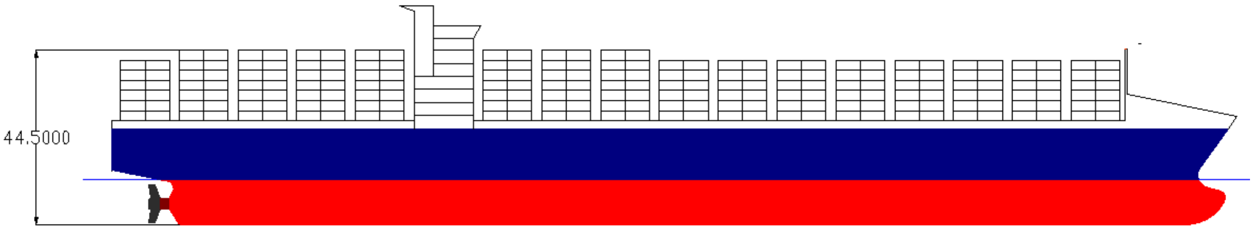
The following cautions should be observed:

In the case of marked roll resonance with amplitudes above ±30°, the given figures of transverse acceleration may be exceeded. Effective measures should be taken to avoid this condition. In the case of heading into the seas at high speed with marked slamming shocks, the given figures of longitudinal and vertical acceleration may be exceeded. An appropriate reduction of speed should be considered.

In the current thesis became an effort to correlate acceleration that are arose by the application of level 1 criterion on the highest point where lashing equipment are present, with the those arise by the procedure given on Annex 13 of IMO CSS regulation. In order to investigate if accelerations on based on level 1 check are higher than accelerations of Annex 13 based on which lashing strength is calculated. For this purpose a post-panamax containership of the following characteristics is introduced

Table 10.15 Characteristics of post-panamax containership

| | | | | | |
|---|---|---|---|---|---|
| Particulars | $L_{BP}$ | 264.4 m | loadcase | d | 13.5 m |
| | B | 40 m | | KG (FSM) | 16.20 m |
| | D | 24.5 m | | GM | 3.851 m |
| | $C_B$ | 0.599 | | Max height for container storage fr. B.L | 44.5 m |
| | $C_M$ | 0.98 | | | |
| | $V_S$ (as design speed) | 16 kn | | | |
| | Ak | 52.9 m$^2$ | | | |



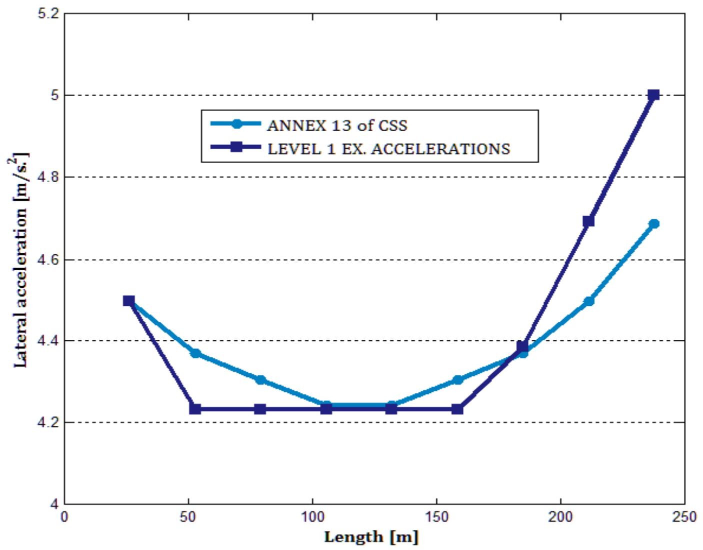




Figure 10.6 accelerations of level 1 and Annex 13 as a function of vessel's length for a post-panamax containership

However, in the case of post-panamax containership designed for a low speed of around 16 kn at a loading condition with high GM value, when level 1 is applied on the whole length of the ship accelerations larger than accelerations based on which lashing is calculated according to IMO CSS, are emerged. It is obvious that the value 8.69 m/s$^2$ above which vulnerability is detected is very high, If the acceleration on bridge is close to 8 m/s$^2$ then the acceleration on fore tiers of containers could be close to 11.2 m/s$^2$ according to simplified calculations

## 10.7 CONCLUSION

Another crucial issue that should be mentioned is the fact that the current draft regulation for excessive accelerations is based on the linear model of roll equation under Froude-Krylov wave excitation, on a beam sea scenario. However, large accelerations may occur too during parametric rolling of large amplitude. In order to detect vulnerability for excessive lateral accelerations during parametric roll another model should be introduced embracing parametric roll excitation in the right part of roll equation. Last but not least it should be mentioned that material failure at lashing equipment is possible in case of roll amplitudes larger than +-30 degrees, emerge either from beam sea case or parametric rolling. IMO propose on CSS Code that effective measures should be taken to avoid the above conditions. Based on all the above, the connection of excessive acceleration criteria with lashing seems to be essential.

# Chapter 11 – Possible Impact on Design and Operation

## 11.1 POSSIBILITIES OF IMPACTS ON RO-RO SHIP DESIGN

### 11.1.1 RoRo Passenger Ships

The compliance of a vessel with stability regulations in any operational draft is ensured with the well-known GM-required curves which is an inextricable part of a stability booklet. However, the compliance with the second generation intact stability criteria have to be ensured with the same matter. The GM-required curves of the current intact stability regulations 2008 I.S Code as long as the curves of second generation intact stability criteria are shown in figure 9.1 for RoPax 160 and RoPax 110. As one can observe weather criterion is prevailing on light drafts and damage stability on deeper drafts. Dead ship stability level 2 and parametric roll level 2B require extremely low stability as it has already been mentioned, less than those required by of I.S Code 2008

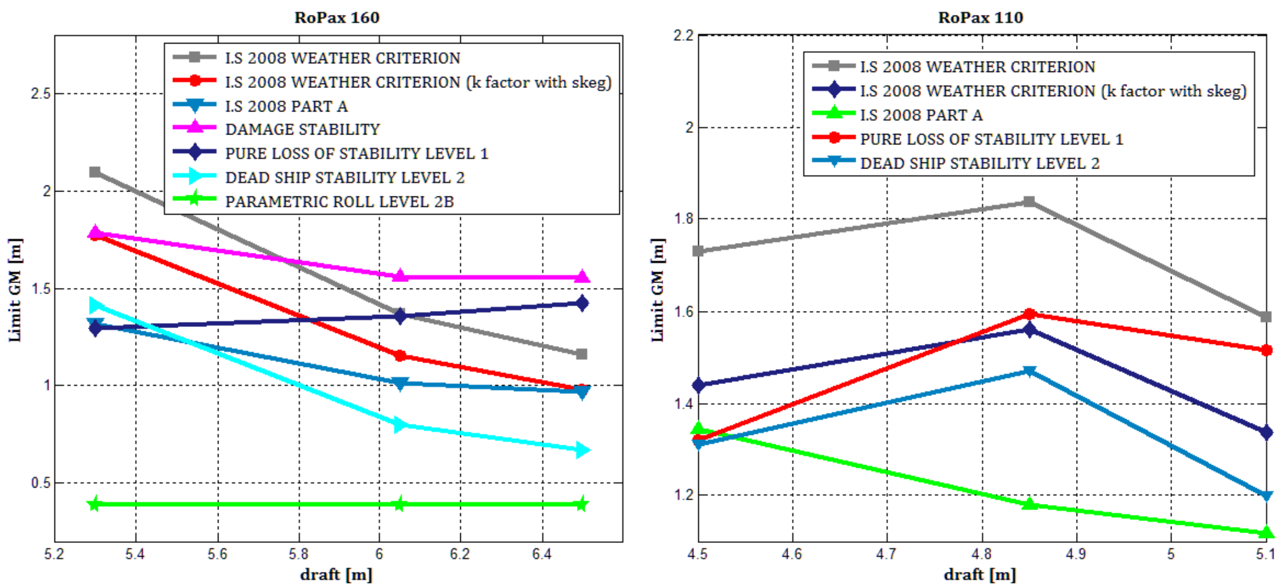



Figure 11.1 GM limit curves including 2nd generation intact stability for RoPax 160 and RoPax110

#### *Dead Ship Stability*

The current level 2 draft regulation of dead ship stability failure mode seems to be more favorable for large ships, like large cruise ships, medium and large RoPax, in comparison with the weather criterion which is quite strict for them, and is the strictest regulation especially on light drafts. For the medium size RoPax 160, the required GM curve of dead ship level 2 is considerably lower than the curve of weather criterion. However, as long as the majority of vessels will have characteristics outside the limits of the weather criterion a level 2 analysis will be required. The strictest regulation will be damage stability for all drafts, and ships with more expanded superstructures and smaller GM values could be designed, because *C* index is remaining small even in case of large windage areas assuming that stability characteristics and draft remain constant as one can observe in figure 11.2 On the other hand the small-sized RoPax vessels like small and handysize ones, will probably confront difficulties in compliance with level 2 regulation for unrestricted operation, especially if $R_{DS}$ index is 0.04 and flooding angle is relatively small. Those vessels will be probably designed in higher or smaller GM values in order to comply with the regulation, or lateral projected areas will be decreased, and unprotected opening will be located higher for increasing of flooding angle.

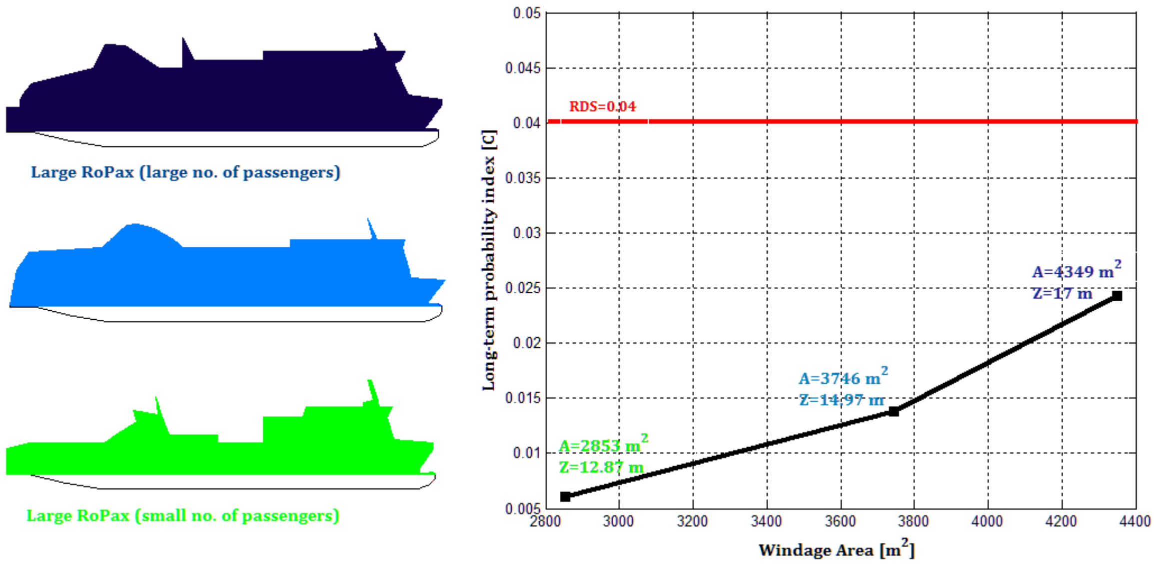



Figure 11.2: RoPax 160, Effect of windage area on level 2 dead ship stability index *C*

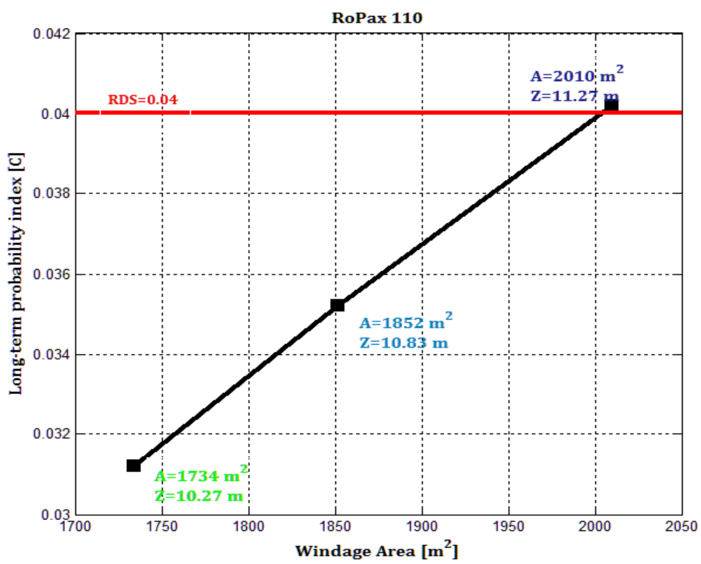



Figure 11.3 RoPax 110, Effect of windage area on level 2 dead ship stability index *C*

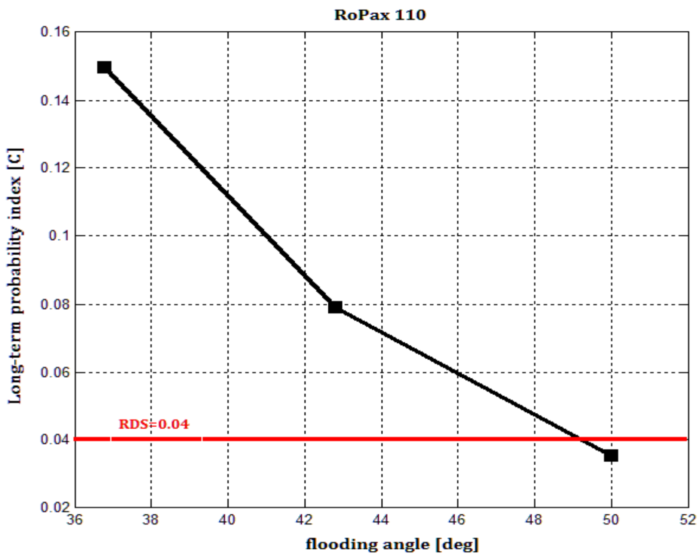



Figure 11.4 : RoPax 110, Effect of progressive flooding angle on level 2 dead ship stability index

Bilge keels of increased breadth are also considered possible to be introduced on small vessels, due to the fact that dead ship vulnerability index is very sensitive in damping. However as long as bilge keel's component is the predominant one *C* index can be reduced with increased bilge keel's breadth.

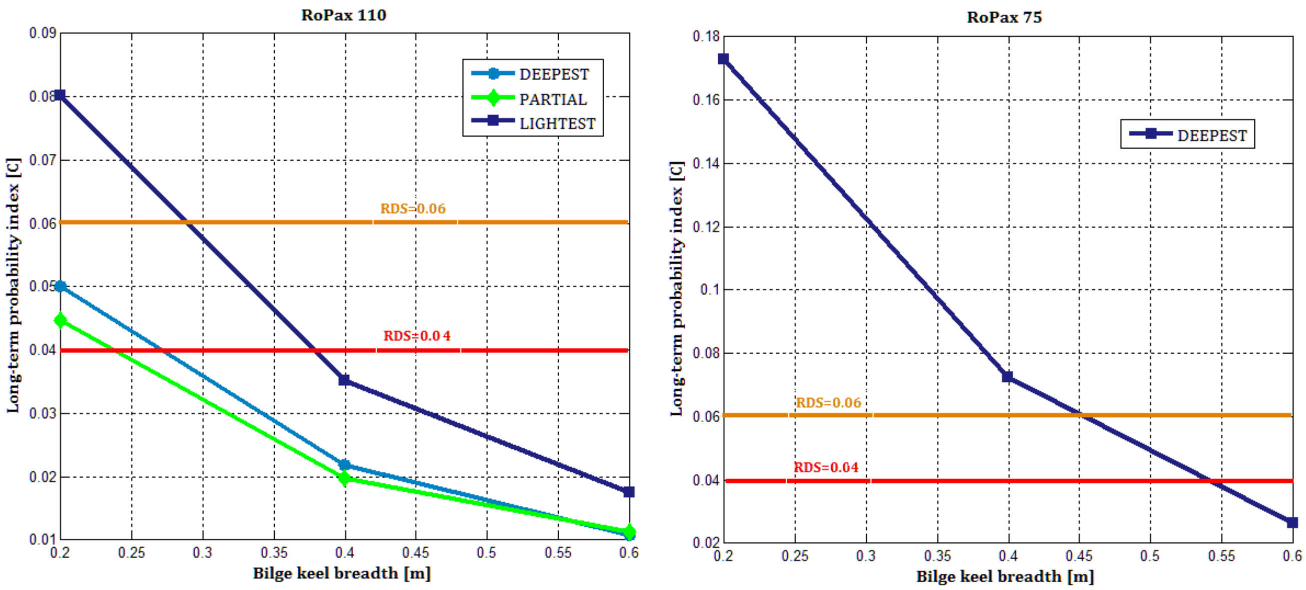



Figure 11.5 : Effect of progressive flooding angle on level 2 dead ship stability index

It is important to be mentioned that on some loading conditions intact and damage stability may come to contrast based on the observation that *C=f(GM)* function has a standard form as analyzed previously, so damage stability regulations could require high GM values in which level 2 regulation will give a *C* index higher than vulnerability limit.

### *Pure Loss of Stability*

Level 1 pure loss of stability criterion was applied on three RoRo Passenger ships with modern hull form. It seems that this stability failure is very difficult to occur on a RoPax ship even at partial draft loading conditions that perform the lowest initial GM values. On figure .. the wave height on which pure loss of stability is detected, for a wave length equal to $L_{BP.}$ Negative GM can occur only partial and deepest loading conditions for RoPax 160 and RoPax 110, but on a wave height by far higher than the wave height used on level 1. Even the small ships may not be affected from high waves. However, there is a margin in order to increase the wave height based on which level 1 check is carried out in order to ensure the safety of a passenger ship as mentioned before

In general it is well-known that the design of passenger ship is governed by damage stability regulations, and sometimes by the weather criterion. As one can observe in figure 9.1 GM required curve for damage stability is higher than pure loss of stability level 1 for all operational drafts of RoPax 160, while weather criterion's curve is higher at light drafts, that means that damage stability regulations as well as weather criterion require higher initial GM values and as a result the vessel is less susceptible to stability failures in waves such as pure loss of stability. Nevertheless it should be mentioned that if dead ship stability level 2 is adopted, the weather criterion barrier will not exist, so supposing that SOLAS 2009 damage stability regulations have the same safety level as SOLAS 90 & Stockholm agreement regulation, then only damage stability safety barrier remains.

Finally it should be mentioned that even in case of failing at level 1, a RoPax ship is very easy to pass level 2 especially with the option B, and with the current form of regulation impact on design on RoPax ships from pure loss of stability criteria is not expected.

### *Parametric Roll*

RoPax ships is expected to pass easily, parametric roll checks, with the current draft regulation. In figure 9.1 is shown the GM-required curve for Level 2B for RoPax 160. This curve is extremely low and indicates the problematic form of regulation that have already mentioned. The regulation will definitely not contribute in the improvement of safety of RoPax ships. Similar to pure loss of stability, damage stability regulations that require high initial GM seem to provide protection against parametric resonance. Nevertheless, the probability of parametric roll occurrence on RoPax ships is not zero, on loading conditions with initial GM smaller than 2.0 m. Vessel's speed plays also an important role. In addition some vessels may confront problems when sailing at a very low speed for instance during a port approaching.

### *Excessive Accelerations*

The examined RoPax ships passed easily level 1 check for excessive accelerations at all examined loading conditions. However, the criterion does not concern RoRo ships in general, even at lightest loading conditions that perform the highest GM values. In the following table 9.1 are shown the GM values on which level 1 criterion detects vulnerability at the bridge deck, for each loading condition.

Table 11.1 GM values on which vulnerability is detected at level 1

| Vessel | Loading condition | GM | GM for vulnerability at level 1 | Margin % |
|---|---|---|---|---|
| RoPax 160 | Deepest | 2.077 | 4.20 | 50.50 |
| | Partial | 1.624 | 4.13 | 60.68 |
| | Lightest | 2.802 | 4.00 | 29.95 |
| RoPax 110 | Deepest | 1.904 | 5.15 | 63.03 |
| | Partial | 1.834 | 5.02 | 63.45 |
| | Lightest | 2.304 | 4.80 | 52.00 |
| RoPax 75 | Deepest | 1.577 | 3.60 | 56.19 |

It should be mentioned that only lightest draft loading condition can perform those high GM values

### 11.1.2 RoRo Cargo Ships

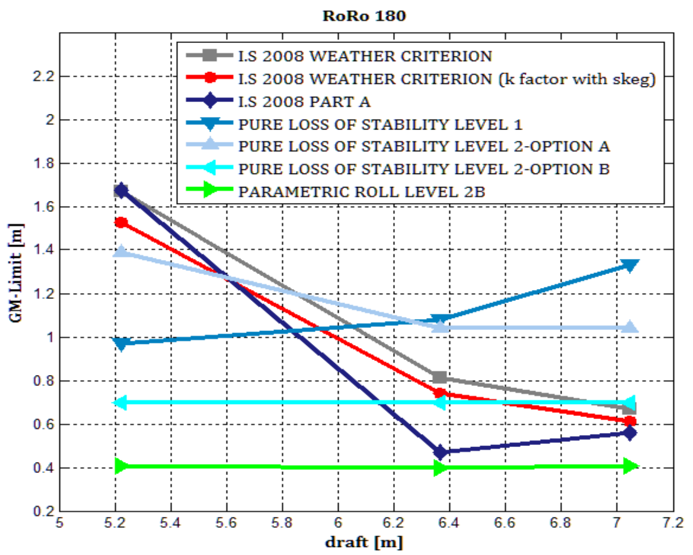



Figure 11.6 GM limit curves including 2nd generation intact stability for RoRo 180

#### *Dead Ship Stability*

RoRo cargo ships that are equipped with limited superstructures in contrast with RoPax ships, while are designed on higher displacements will easily pass level 2 check for dead ship stability, if the current form of regulation remain. Usually those ships performs low GM values on full load condition around 0.7 to 0.8 m, and the weather criterion governs the design. As long as the weather criterion will be replaced by level 2 dead ship stability, more flexibility is provided to the designer of a RoRo cargo vessel with the current form of draft regulation.

***Pure Loss of Stability***

Both RoRo 180 and RoRo 130 failed to pass level 1 check for pure loss of stability. In general RoRo cargo ships are by far more vulnerable to pure loss of stability than passenger ships, due the fact that, the strictest regulation is the weather criterion and not the damage stability. The limit GM for the weather criterion can be reduced when the skeg area is including on damping factor. However, a safety margin against pure loss of stability seems to not be provided by the weather criterion especially at deep drafts, so level 2 check will be probably required in the majority of the loading conditions of a vessel of such a type. The current form of regulation is not expected to lead to significant impact on the design due to the fact that the two available options of level 2 offer flexibility, especially option B

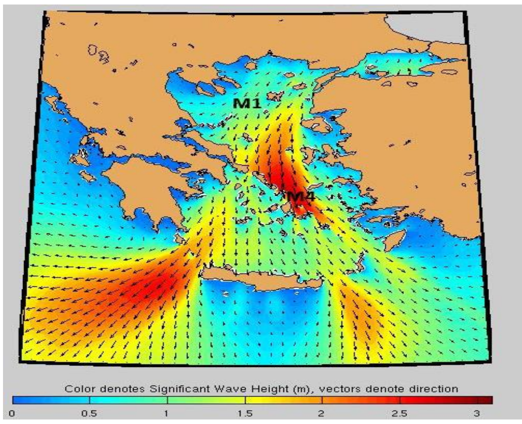
***Parametric Roll***

Similar to pure loss of stability RoRo cargo ships is more susceptible to parametric roll due to the low initial GM especially on deep loading conditions. As one can observe in figure 9.6 the GM-limit curve for parametric roll level 2B is very low. The calculations showed that parametric roll may occur on many different sea state conditions for full load arrival at various speeds also, while the problem is more significant in head seas. However, with the current form of regulation the problem is detected but undoubtedly is not be solved. Based on the above it is obvious that an impact on design of RoRo cargo ships from parametric roll regulation is not expected.

## 11.2 POSSIBILITIES FOR OPERATIONAL LIMITATIONS

Level 2 vulnerability index $C$ is calculated based on winter wave scatter diagram of North Atlantic, However IMO will probably accept alternative environmental conditions than North Atlantic statistics on second generation intact stability criteria calculations. This guideline may be used for ships operated only in restricted areas. In general RoPax ships operate on North Atlantic only for specific routes such as the crossings from Iceland to Faroe islands. The most ships are operating on specific areas such as Baltic sea, North sea, West Mediterranean sea, Aegean sea or specific areas of Pacific ocean such as Japanese sea. However, some areas for instance North sea may have similar with North Atlantic wave statistics.

Based on the calculations on the sample ships of this thesis we can conclude that operational limitations is not probable to be implemented on the major population of RoPax and RoRo Cargo ships because the most ships can easily pass level 2 check for parametric roll, pure loss of stability and dead ship stability failure modes with the North Atlantic wave scatter diagram. On the other hand there are specific cases where operational limitations are probable to be considered. For instance in [6] is presented there is the case of a medium sized fast displacement RoPax ship that fails on level 2 check for broaching-to on the design speed of 27 Kn. In addition on this thesis RoPax 75 that is a small RoPax ship failed on level 2 check for dead ship stability. On such a ship that does not operate in the Atlantic sea but in restricted areas such as Aegean sea, is reasonable to consider operational limitations in lieu of design changes.




### 11.2.1 Wave statistics for the Aegean sea at winter

In the following table 9.2 are presented wave data from measures in north Aegean at location M1 (Figure 9.7 ) at winter, derived from the wave-atlas of Hellenic Marine Research Institute [48]. Locations M1 of north Aegean and M4 of the Ikarian Sea demonstrate along with Karpathian Sea the most severe weather conditions in Aegean Sea, affecting many ferry routes. In general Aegean sea is an area calmer than the worldwide average

Figure 11.7 Sea state on the Aegean sea during a specific day at winter (Taken from [56])

Table 11.2 Short-Term waves condition occurrences for the region M1 at North Aegean

| NUMBER OF OCCURENCES 990 | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ***Tz*** / ***Hs*** | **1.9** | **2.6** | **3.1** | **3.8** | **4.6** | **5** | **5.5** | **6.1** | **6.7** | **7.4** | **8** | **8.9** | **9.8** | **10.8** | **11.9** | **13** |
| **0.25** | 0 | 19 | 16 | 29 | 19 | 0 | 1 | 1 | 0 | 1 | 2 | 0 | 0 | 0 | 0 | 0 |
| **0.5** | 0 | 17 | 13 | 41 | 59 | 9 | 1 | 3 | 4 | 1 | 0 | 0 | 0 | 0 | 0 | 0 |
| **0.75** | 0 | 1 | 5 | 21 | 58 | 32 | 11 | 5 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **1.00** | 0 | 0 | 0 | 7 | 21 | 31 | 27 | 16 | 4 | 1 | 0 | 0 | 0 | 0 | 0 | 0 |
| **1.25** | 0 | 0 | 0 | 0 | 6 | 14 | 17 | 29 | 5 | 2 | 0 | 0 | 0 | 0 | 0 | 0 |
| **1.50** | 0 | 0 | 0 | 0 | 2 | 9 | 30 | 37 | 14 | 6 | 0 | 0 | 0 | 0 | 0 | 0 |
| **1.75** | 0 | 0 | 0 | 0 | 0 | 1 | 8 | 27 | 25 | 6 | 3 | 0 | 0 | 0 | 0 | 0 |
| **2.00** | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 24 | 20 | 15 | 1 | 0 | 1 | 0 | 0 | 0 |
| **2.50** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 6 | 23 | 33 | 5 | 2 | 1 | 0 | 0 | 0 |
| **3.00** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 4 | 24 | 17 | 3 | 1 | 0 | 0 | 0 |
| **3.50** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 4 | 19 | 10 | 1 | 0 | 0 | 0 |
| **4.00** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 10 | 10 | 2 | 0 | 0 | 0 |
| **5.00** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 2 | 17 | 9 | 1 | 0 | 0 |
| **6.00** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 4 | 1 | 0 | 0 |
| **7.00** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **8.00** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **9.00** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

The Index C for dead ship stability was recalculated for RoPax 75 using wave statistics for the North Aegean sea, that correspond to operational limitations, However, a different wave spectrum is essential to be considered for this calculation. The Pierson-Moskowitz is appropriate for the Atlantic ocean but not for a semi-enclosed area such as Aegean sea, so the Jonswap spectrum given by equation 9.1 seems to be more appropriate

$$S(\omega)=a_w \cdot g \cdot \omega^{-5} \cdot \exp\left(-\frac{5}{4}\cdot\left(\frac{\omega}{\omega_p}\right)^{-4}\right)\cdot \gamma^{\exp\left(-0.5\cdot\left(\frac{\omega-\omega_p}{\sigma\omega_p}\right)^2\right)} \tag{11.1}$$

Where

$$a_w=\frac{5}{16}\cdot\left(\frac{Hs^2\cdot\omega_p^{2}}{g^2}\right)A_\gamma \qquad A_\gamma=1-0.287\cdot\ln(\gamma)$$

$\sigma=0.08$

$\gamma=5$

Table 11.3 RoPax 75 level 2 check for dead ship stability with operational limitations

| Vessel | Loading Condition | [C] Index E.W.S.F Standard | Status if $R_{DS}$=0.04 | Status if $R_{DS}$=0.06 | | [C] Index E.W.S.F Constant | Status if $R_{DS}$=0.04 | Status if $R_{DS}$=0.06 |
|---|---|---|---|---|---|---|---|---|
| RoPax 75 | Deepest | 0.0125 | Pass | Pass | | 0.0155 | Pass | Pass |

However, a large difference is observed on C index in case of a ship with operational limitations. It is reminded that C index for the FLD condition of RoPax 75 was 0.0732 when is calculated with North Atlantic's wave scatter diagram. In addition it worth to be mentioned that the spectrum's shape plays a very important role, when the above calculations is carried out with Pierson- Moskowitz spectrum, the derived C index is 0.000154 and very large difference is observed

## 11.3 POSSIBILITIES FOR IMPROVEMENTS ON RO-RO SHIP DESIGN

Undoubtedly, the second generation intact stability does not seem to bring any significant effects on RoRo ship design, especially, as far as concern parametric roll and pure loss of stability failure modes, in case IMO adopts the criteria as in their current form. However, the criteria may help the designer to detect dangerous conditions and improve the design willingly. In the following paragraphs some calculations are presented as an investigation about the possibilities of improving a design, when obvious vulnerabilities are being detected on a loading condition.

### 11.3.1 Effect of Bow Flare on Parametric Roll Amplitude

The effect of bow flare angle on parametric roll amplitude is investigated with a modification on the bow part of RoPax 160, the flare angle on fore perpendicular is reduced from 44 to 32 deg, and the parametric roll amplitudes for level 2B wave cases are being recalculated. The results are shown on figure 11.8 and reveal that a reduced flare angle fails to decrease parametric roll amplitude.

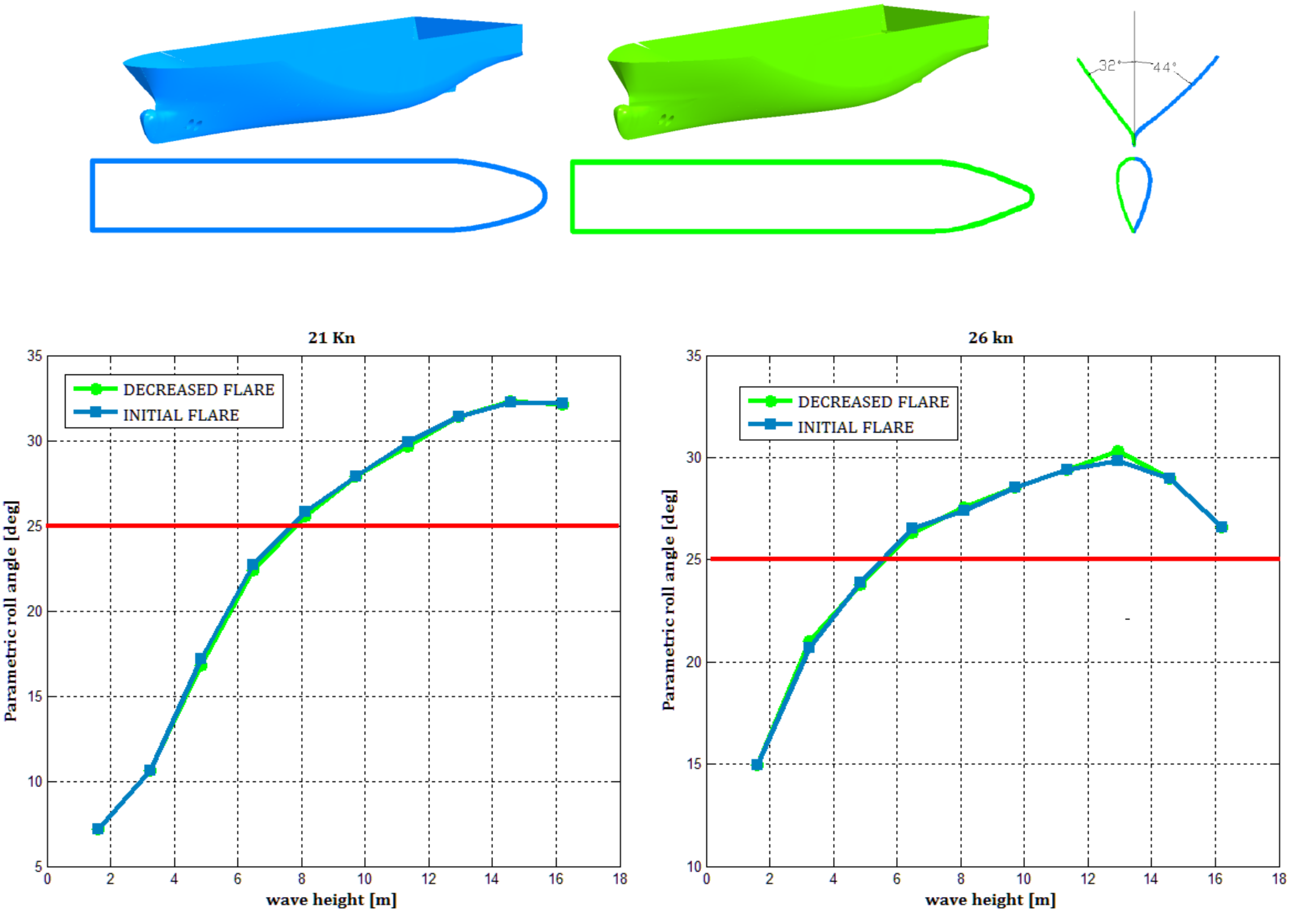



Figure 11.8 Effect of bow flare angle on parametric roll amplitude for RoPax 160

### 11.3.2 Effect of Initial GM on Parametric Roll Amplitude

The calculation for parametric roll level 2B on RoPax ships revealed the fact that parametric roll resonance is strongly connected with the initial GM of the vessel. Loading conditions with high GM values such as deepest and lightest ones, had a zero vulnerability index on Level 2B, while significant parametric roll amplitudes were not detected. On the other hand on partial draft loading conditions of RoPax 160 and RoPax 110 that perform the lower GM values, significant parametric roll amplitudes were detected at both 21 and 26 Kn for RoPax 160 and at 21 Kn for RoPax 110. The calculations were repeated at loading condition with the same draft but higher GM values, and significant decrease on amplitudes was observed.

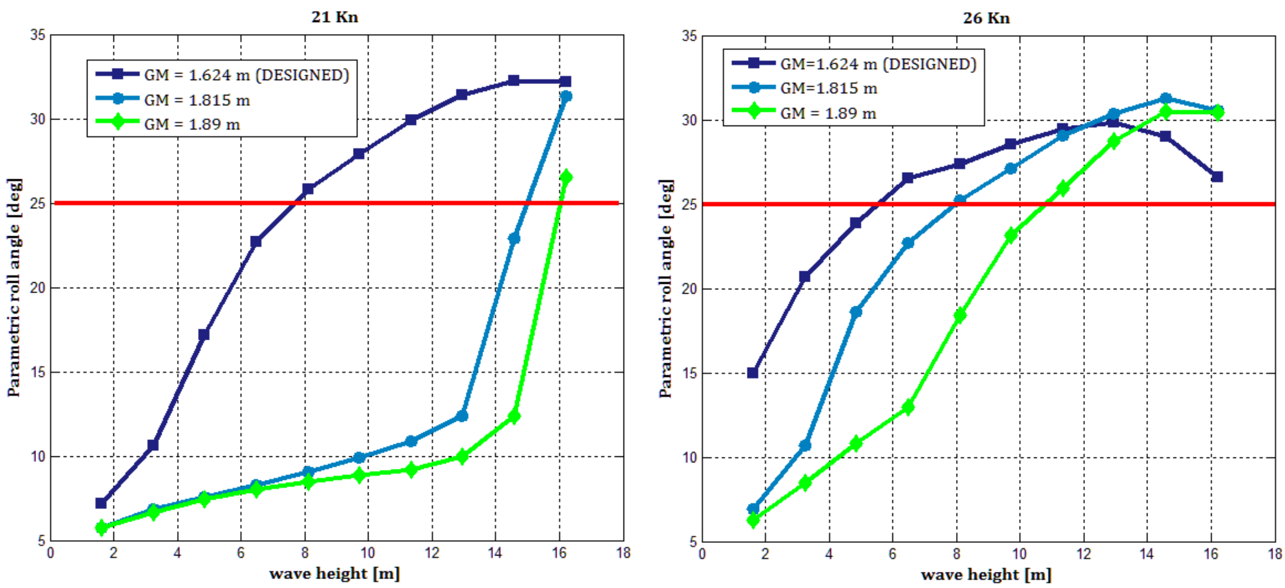



Figure 11.9 RoPax 160 Effect of initial GM on parametric roll amplitude at d=6.05 m for $\lambda=L_{WL}$ in head seas

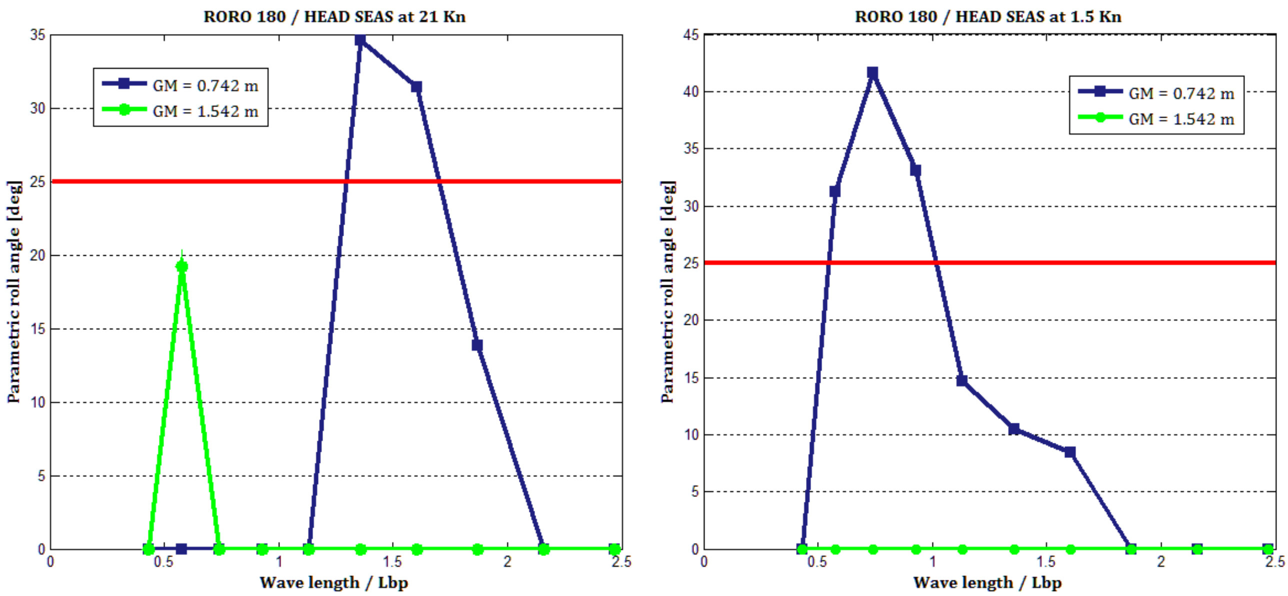



Figure 11.10 RoRo 180 Effect of initial GM on parametric roll amplitude at d=6.85 m for various waves

However, It seems that the first step for a designer in order to reduce vulnerability on parametric roll is increase of GM, even a slight increase seems to achieve a strong influence on amplitude reducing. The GM increasing should be carried out with a KG-modification, if possible, and not with hull modifications that may have a strong impact on vessel's efficiency. Otherwise a small increasing on breadth may be advantageous.

### 11.3.3 Effect of damping on Parametric Roll Amplitude

In most cases RoPax ships are using the fin stabilizers in rough weather in order to reduce the possible passenger discomfort. However, the 'extra' damping that is produced by stabilizers may have an effect on reduction of the possible parametric roll amplitudes. A method able to predict this kind of damping component is not available. Ikeda simplified method can predict the bilge keel's component only, while the ratios $b_{BK}/B$ and $l_{BK}/L_{BP}$ must be under specific limits. A usual fin stabilizer on a RoPax ships has a breadth of approximately 2.5 m and a length of approximately 1.5 m values that correspond to b/B and $l/L_{BP}$ ratios outside Ikeda's method limits. For the investigation of the effect of fin stabilizers on parametric roll a stabilizer that corresponds to the limits of Ikeda method was assumed so the $b_{BK}/B$ is equal to 0.06 and $l_{BK}/L_{BP}$ is equal to 0.05, For RoPax 160 the above values that lead to a stabilizer with length equal to 7.88 m and breadth equal to 1.50 m by far different compared to those with which the ship is equipped. Nevertheless an extra bilge keel damping component can be calculated which can be added on the component of bilge keels, the behavior of the vessel with the stabilizers can be simulated to some extent.

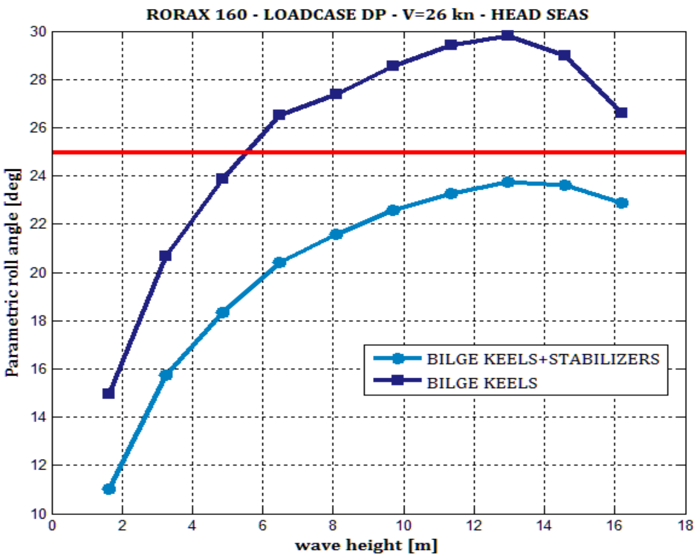



Figure 11.11 Effect of fin stabilizers on parametric roll amplitude

However it seems that when damping increased damping due to larger bilge keels or stabilizers can reduce parametric roll amplitudes

### 11.3.4 Effect of LCB Position on Parametric Roll and Pure Loss of Stability

The position of LCB plays an important role on RoRo ship design, and the ratio $LCB/L_{BP}$ is arisen by a compromise between the conflict requirements of optimum resistance and good seakeeping characteristics. In the majority of modern RoRo vessels, the LCB is located slightly aft amidships at around (0.46 – 0.48)$L_{BP}$ from aft perpendicular, where the large values correspond to RoPax ships, where better seakeeping is required. Calculations with the examined RoRo ships revealed that when LCB is being moved forward, (inside the above space) the initial stability (GM) is being increased but the area under GZ curve is decreasing for the same KG. On the other hand when LCB is moving aft even at 0.44 $L_{BP}$ the initial GM is decreasing while the area under GZ curve remains at acceptable values, for large angle stability requirements. In order for an investigation of the effect of LCB position on parametric roll amplitude to be performed, RoRo 180 was used and the LCB fixed on three different positions, while the KG of the loading condition remained constant. The results are presented on figures 11,12 The position of LCB has a strong influence especially on head seas parametric rolling. When LCB moves forward parametric roll amplitudes become larger even at small wave heights, even though the initial GM that also has a strong influence is higher.

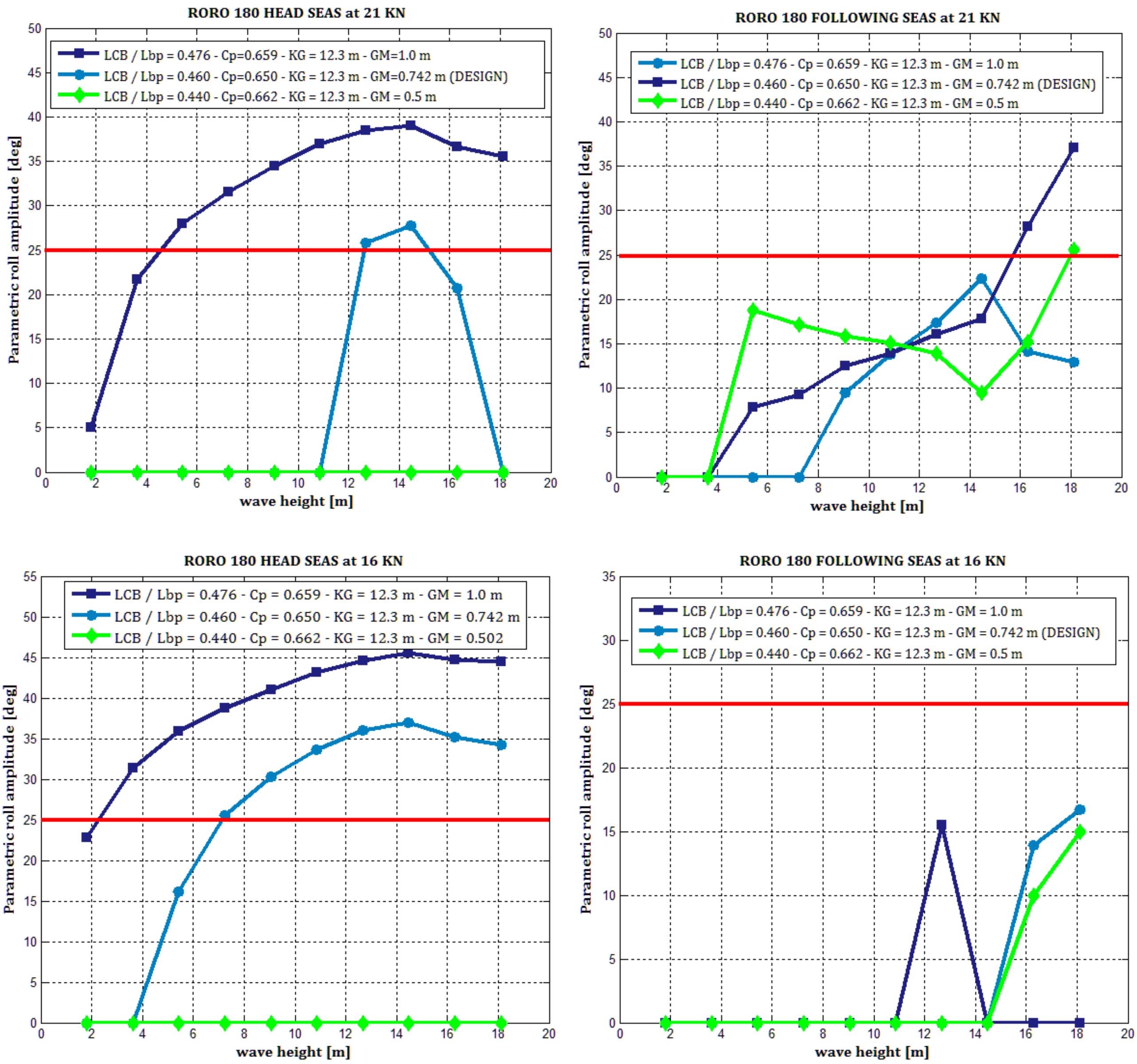



Figure 11.12 The effect of LCB position on parametric roll amplitude

# Chapter 12 – Discussion and Conclusions

In this thesis, an evaluation about the second generation intact stability criteria was made, based on the application of each criterion at the basic loading conditions of 3 RoPax and 2 RoRo Cargo vessels. The basic conclusions of the thesis are summarized as follow.

Level 2 criterion for dead ship stability that will probably replace the weather criterion needs further processing because of the fact that many problematic aspects are emerged. The major one is the proposed calculation method for the effective wave slope function that affects the vulnerability index to a large extent and leading to a liberal regulation, especially for RoRo ships in which the weather criterion have a strong effect on the design. Moreover the draft regulation with its current form is stricter for small ships and more liberal for large ones in comparison with the weather criterion. It is probable that in small RoPax ships operating in sea regions close or similar to North Atlantic design and operational impacts are expected either with the current form of effective wave slope function or not

Level 2B parametric roll criterion is also problematic to a large extent. The most critical aspect has to do the high value of vulnerability index that leads to a liberal regulation due to the fact that although parametric roll is detected in the most wave cases the small probability of occurrence of the wave case leads to a very small vulnerability index. Moreover there are a lot of wave cases with length close to ship length that can lead to parametric roll. This cases is not taken into account as the examined wave length is equal to ship's length. Last but not least there are still present some inconsistencies between the proposed calculation methods for the parametric roll amplitude. However, this inconsistencies will probably overcome soon because the last proposals for the application of algebraic method have provided more consistency with the analytical numerical solution of parametric roll differential equation.

Inconsistencies between the two available options for level 2 pure loss of stability criterion are also present with the option B to be problematic because it cannot provide the same safety level with option A.

A very critical aspect for the further development of the criteria is how the minimum requirements will be set. The required GM values for the passing of the criteria are presented to be extremely low, in some cases require less stability than the criteria of Part A of the current 2008 intact stability code. However, this low initial GM values are definitely connected with instabilities in waves.

Generally, the calculations of this thesis confirmed the fact that ships operating with large initial GM values is by far less vulnerable to stability failures in waves such as pure loss of stability and parametric roll. This observation is also verified by the occurred accidents, where RoPax that are affected by strict damage stability criteria are rarely involved with accidents relative to instabilities in waves, in comparison with RoRo Cargo ships, while both types have similar hull forms.

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# Appendix – Draft Regulations

## 2.13 ASSESSMENT OF SHIP VULNERABILITY TO THE DEAD SHIP CONDITION FAILURE MODE[1]

### 2.13.1 Application

2.13.1.1 For each condition of loading, a ship that:

.1 meets the standard contained in the criteria contained in 2.13.2 is considered not to be vulnerable to the dead ship condition failure mode;

.2 does not meet the standard contained in the criteria contained in 2.13.2 should be subject to more detailed assessment of vulnerability to the failure mode by applying the criteria contained in 2.13.3.

2.13.1.2 For each condition of loading, a ship that neither meets the criteria contained in 2.13.2 nor meets the criteria contained in 2.13.3 should be subject to a direct stability assessment for the dead ship condition failure mode that is performed according to recommended specifications developed by the Organization[2].

2.13.1.3 A detailed assessment of vulnerability according to the criteria contained in 2.13.3 or a direct stability assessment as provided in 2.13.1.2 may be performed without the requirement to perform a more simplified assessment in 2.13.2 or 2.13.3, respectively.

### 2.13.2 Level 1 Vulnerability Criteria for Dead ship condition

2.13.2.1 A ship in the specified loading condition is considered not to be vulnerable in dead ship condition when fulfilling the requirements of the severe wind and rolling criterion (weather criterion) in Section 2.3 of Part A, but using the value of wave steepness factor, *s*, from Table 2.13.2.1 in lieu of that obtained from Table 2.3.4-4 in Section 2.3 of Part A.[3]

Table 2.13.2.1 – Values of wave steepness factor, *s*

| Rolling period, *T* (s) | Wave steepness factor, *s* |
|---|---|
| ≤ 6 | 0.100 |
| 7 | 0.098 |
| 8 | 0.093 |
| 12 | 0.065 |
| 14 | 0.053 |
| 16 | 0.044 |
| 18 | 0.038 |
| 20 | 0.032 |
| 22 | 0.028 |

1 Application details are reported in the Explanatory Notes
2 To be developed.
3 The definition of $A_K$ in 2.13.2.1 is that in Section 2.3 of Part A.

| | |
|---|---|
| 24 | 0.025 |
| 26 | 0.023 |
| 28 | 0.021 |
| ≥ 30 | 0.020 |

Where,

$T$ = rolling period as determined in 2.3.4 of Section 2.3 of Part A (s);
$s$ = wave steepness $= H / \lambda$;
$H$ = wave height (m); and
$\lambda$ = wave length (m).

**2.13.3 Level 2 Vulnerability Criteria for Dead ship condition**

2.13.3.1 A ship is considered not to be vulnerable to the dead ship condition failure mode if:

$$C \le R_{DS0}$$

Where, $R_{DS0}$ = [0.06] [0.04]
$C$ = a long-term probability index that measures the vulnerability of the ship to a stability failure in the dead ship condition based on the probability of occurrence of short-term environmental conditions as specified according to 2.13.3.2.

2.13.3.2 The value for $C$ is calculated as a weighted average from a set of short-term environmental conditions specified in 2.13.3.3.

$$C = \sum_{i=1}^{N} W_i C_{S,i}$$

Where,

$W_i$ = the weighting factor for the short-term environmental condition specified in 2.13.3.3;

$C_{S,i}$ = the short-term dead ship stability failure index for the short-term environmental condition under consideration calculated as specified in 2.13.3.2.1;

$N$ = the number of considered short-term environmental conditions according to 2.13.3.3.

2.13.3.2.1 The short-term dead ship stability failure index, $C_{S,i}$, for the short-term environmental condition under consideration is a measure of the probability that the ship will exceed specified heel angles at least once in the exposure time considered, taking into account an effective relative angle between the vessel and the waves. Each index $C_{S,i}$ is calculated according to the following formula:

$C_{S,i}$ = 1, if either:

.1 the mean wind heeling lever $\bar{l}_{wind,tot}$ (according to 2.13.2.2) exceeds the righting lever (*GZ*) at each angle of heel to leeward, or

2. the stable heel angle under the action of steady wind, $\phi_S$, is greater than the angle of capsize to leeward, $\phi_{cap,+}$;

= $1-\exp\left(-\lambda_{EA}\cdot T_{\exp}\right)$, otherwise;

Where,

The GZ curve, as well as all relevant derived quantities, are to be calculated with free surface correction taken into account[4];

Heel angles are to be taken as positive to leeward and negative to windward;

$T_{exp}$ = exposure time, to be taken as equal to *3600 s*;

$\lambda_{EA}$ = $\frac{1}{T_{z,C_S}}\cdot\left[\exp\left(-\frac{1}{2\cdot RI_{EA+}^2}\right)+\exp\left(-\frac{1}{2\cdot RI_{EA-}^2}\right)\right]$ (1/s);

$RI_{EA+}$ = $\frac{\sigma_{C_S}}{\Delta\phi_{res,EA+}}$;

$RI_{EA-}$ = $\frac{\sigma_{C_S}}{\Delta\phi_{res,EA-}}$;

$T_{z,C_S}$ = reference average zero up-crossing period of the effective relative roll motion under the action of wind and waves determined according to 2.13.3.2.3 (s);

$\sigma_{C_S}$ = standard deviation of the effective relative roll motion under the action of wind and waves determined according to 2.13.3.2.3 (rad);

$\Delta\phi_{res,EA+}$ = range of residual stability to the leeward equivalent area limit angle, to be calculated aS

$\phi_{EA+}-\phi_S$, (rad);

$\Delta\phi_{res,EA-}$ = range of residual stability to the windward equivalent area limit angle, to be calculated as

$\phi_S-\phi_{EA-}$ (rad)

$\phi_{EA-}$ = equivalent area virtual limit angle to leeward, to be calculated as

[4] In accordance with Part B, 3.1

$$\phi_{EA+} = \phi_S + \left( \frac{2 \cdot A_{res,+}}{GM_{res}} \right)^{1/2} \text{ (rad);}$$

$\phi_{EA+}$ = equivalent area virtual limit angle to windward, to be calculated as

$$\phi_{EA-} = \phi_S - \left( \frac{2 \cdot A_{res,-}}{GM_{res}} \right)^{1/2} \text{ (rad);}$$

$\phi_S$ = stable heel angle under the action of steady wind calculated as the first intersection between the righting lever curve ($GZ$ curve) and the mean wind heeling lever, $\bar{l}_{wind,tot}$, determined according to 2.13.3.2.2 (rad);

$A_{res+}$ = area under the residual righting lever curve (i.e., $GZ - \bar{l}_{wind,tot}$) from $\phi_S$ to $\phi_{cap,+}$ ($\text{m} \cdot \text{rad}$);

$A_{res-}$ = area under the residual righting lever curve (i.e., $GZ - \bar{l}_{wind,tot}$) from $\phi_{cap,-}$ to $\phi_S$ ($\text{m} \cdot \text{rad}$);

$GM_{res}$ = residual metacentric height, to be taken as the slope of the residual righting lever curve (i.e., $GZ - \bar{l}_{wind,tot}$) at $\phi_S$ (m);

$\phi_{cap,+}$ = angle of capsize to leeward, to be taken as $\min\{\phi_{VW,+}, \phi_{crit,+}\}$ (rad);

$\phi_{cap,-}$ = angle of capsize to windward, to be taken as $\max\{\phi_{VW,-}, \phi_{crit,-}\}$ (rad);

$\phi_{VW,+}$ = angle of second intercept to leeward between the mean wind heeling lever $\bar{l}_{wind,tot}$ and $GZ$ curve;

$\phi_{VW,-}$ = angle of second intercept to windward between the mean wind heeling lever $\bar{l}_{wind,tot}$ and $GZ$ curve;

$\phi_{crit,+}$ = critical angle to leeward, to be taken as $\min\{\phi_{f,+}, 50\deg\}$ (rad);

$\phi_{crit,-}$ = critical angle to windward, to be taken as $\max\{\phi_{f,-}, -50\deg\}$ (rad);

$\phi_{f,+}, \phi_{f,-}$ = angles of downflooding to leeward and windward, respectively, in accordance with the definition in Part A, 2.3.1.4 (rad);

2.13.3.2.2 The mean wind heeling lever $\bar{l}_{wind,tot}$ is a constant value at all angles of heel and is calculated according to the following formula:

$$\bar{l}_{wind,tot} = \frac{\overline{M}_{wind,tot}}{\Delta} \quad \text{(m)}$$

Where,

$\overline{M}_{wind,tot}$ = mean wind heeling moment, to be calculated as

$$\frac{1}{2}\rho_{air} \cdot U_w^2 \cdot C_m \cdot A_L \cdot Z \qquad (\mathrm{N \cdot m});$$

$\Delta$ = ship displacement force (N)

$\rho_{air}$ = air density to be taken as equal to 1.222 kg/m$^3$;

$U_w$ = mean wind speed, to be calculated as

$$\left(\frac{H_S}{0.06717}\right)^{2/3} \quad (\mathrm{m/s})$$

Different expressions can be used when considering alternative environmental conditions, to the satisfaction of the Administration, in accordance with 2.13.3.3.3;

$C_m$ = wind heeling moment coefficient, to be taken as equal to 1.22 or as determined by other methods, to the satisfaction of the Administration;

$A_L$ = projected lateral area of the portion of the ship and deck cargo above the waterline (m$^2$);

$Z$ = vertical distance from the centre of $A_L$ to the centre of the underwater lateral area or approximately to a point at one-half the mean draft, $d$ (m); and

$H_s$ = significant wave height for the short-term environmental condition under consideration, according to 2.13.3.3 (m).

2.13.3.2.3 For the short-term environmental condition under consideration, the reference average zero up-crossing period of the effective relative roll motion, $T_{z,C_S}$, and the corresponding standard deviation, $\sigma_{C_S}$, to be used in the calculation of the short-term dead ship stability failure index, $C_{S,i}$, are determined using the spectrum of the effective relative roll motion under to the action of wind and waves, in accordance with the following formulae:

$$\sigma_{C_S} = (m_0)^{1/2}$$

$$T_{z,C_S} = 2\pi \cdot (m_0 / m_2)^{1/2}$$

Where,

$m_o$ = area under the spectrum $S(\omega)$ (rad$^2$);

$m_2$ = area under the function of $\omega^2 \cdot S(\omega)$ (rad⁴/s²);

$\omega$ = generic circular frequency (rad/s);

$S(\omega)$ = spectrum of the effective relative roll angle, to be calculated as follows:

$$H_{rel}^2(\omega) \cdot S_{\alpha\alpha,c}(\omega) + H^2(\omega) \cdot \frac{S_{\delta M_{wind,tot}}(\omega)}{(\Delta \cdot GM)^2} \quad \text{(rad}^2\text{/(rad/s))}$$

$$H_{rel}^2(\omega) = \frac{\omega^4 + (2 \cdot \mu_e \cdot \omega)^2}{\left(\omega_{0,e}^2(\phi_S) - \omega^2\right)^2 + (2 \cdot \mu_e \cdot \omega)^2}$$

$$H^2(\omega) = \frac{\omega_0^4}{\left(\omega_{0,e}^2(\phi_S) - \omega^2\right)^2 + (2 \cdot \mu_e \cdot \omega)^2}$$

$S_{\alpha\alpha,c}(\omega)$ = spectrum of the effective wave slope, to be calculated as

$$r^2(\omega) \cdot S_{\alpha\alpha}(\omega) \quad \text{(rad}^2\text{/(rad/s))}$$

$S_{\alpha\alpha}(\omega)$ = spectrum of the wave slope, to be calculated as

$$\frac{\omega^4}{g^2} \cdot S_{zz}(\omega) \quad \text{(rad}^2\text{/(rad/s))}$$

$g$ = gravitational acceleration of 9.81m/s²;

$S_{zz}(\omega)$ = sea elevation spectrum. The standard expression for $S_{zz}(\omega)$ is as follows

$$\frac{4 \cdot \pi^3 \cdot H_S^2}{T_Z^4} \cdot \omega^{-5} \cdot \exp\left(-\frac{16 \cdot \pi^3}{T_Z^4} \cdot \omega^{-4}\right) \quad \text{(m}^2\text{/(rad/s))}$$

Different expressions can be used when considering alternative environmental conditions, to the satisfaction of the Administration, in accordance with 2.13.3.3.3;

$S_{\delta M_{wind,tot}}(\omega)$ = spectrum of moment due to the action of the gust, to be calculated as

$$\left[\rho_{air} \cdot U_w \cdot C_m \cdot A_L \cdot Z\right]^2 \cdot \chi^2(\omega) \cdot S_v(\omega) \quad (\mathrm{N \cdot m^2/rad/s})$$

$\chi(\omega)$ = standard aerodynamic admittance function, to be taken as a constant equal to 1.0 . [Alternative formulations can be accepted to the satisfaction of the Administration.];

$S_v(\omega)$ = spectrum of the gust. The standard expression for $S_v(\omega)$ is as follows

$$4 \cdot K \cdot \frac{U_w^2}{\omega} \cdot \frac{X_D^2}{\left(1+X_D^2\right)^{\frac{4}{3}}} \qquad ((\text{m/s})^2/(\text{rad/s}))$$

with $K = 0.003$ and $X_D = 600 \cdot \omega / (\pi \cdot U_w)$. Different expressions can be used when considering alternative environmental conditions, to the satisfaction of the Administration, in accordance with 2.13.3.3.3;

$\Delta$ = ship displacement force (N);

$GM$ = metacentric height corrected for free surface effects[5] (m);

$\mu_e$ = equivalent linear roll damping coefficient calculated according to the stochastic linearization method. This coefficient depends on linear and nonlinear roll damping coefficients and on the specific roll velocity standard deviation in the considered short-term environmental conditions[6];

$\omega_{0,e}(\phi_S)$ = modified roll natural frequency close to the heel angle $\phi_S$, to be calculated as

$$\omega_0 \cdot \left(\frac{GM_{res}(\phi_S)}{GM}\right)^{1/2} \qquad (\text{rad/s})$$

$\omega_0$ = upright roll natural frequency (rad/s);

$r(\omega)$ = effective wave slope function determined according to 2.13.3.2.4

$H_s$ = significant wave height for the short-term environmental condition under consideration, according to 2.13.3.3 (m);

$T_Z$ = zero up-crossing wave period for the short-term environmental condition under consideration, according to 2.13.3.3 (s);

and other variables as defined in 2.13.3.2.1 and 2.13.3.2.2.

2.13.3.2.4 The effective wave slope function, $r(\omega)$, should be specified using a reliable method, based on computations or derived from experimental data, to the satisfaction of the Administration. In absence of sufficient information the standard methodology[7] for the estimation of the effective wave slope function should be used, which is based on the following assumptions and approximations:

[5] In accordance with Part B, 3.1

[6] The detailed calculation procedure is reported in the Explanatory Notes.

[7] The detailed calculation procedure is reported in the Explanatory Notes.

.1 The underwater part of each transversal section of the ship is substituted by an "equivalent underwater section" having, in general, the same breadth at waterline and the same underwater area of the original section. However:

.1 Sections having zero breadth at waterline, such as those in the region of the bulbous bow, are neglected;

.2 The draught of the "equivalent underwater section" is limited to the ship sectional draught;

.2 The effective wave slope coefficient for each wave frequency is determined by using the "equivalent underwater sections" considering only the undisturbed linear wave pressure;

.3 For each section, a formula is applied, which is exact for rectangles.

The standard methodology is applied [with the ship having zero trim and results are used also for trim different from zero] [considering the actual trim of the ship]. The standard methodology for the estimation of the effective wave slope is applicable only to standard monohull vessels. For a ship which, to the opinion of the Administration, does not fall in this category, alternative prediction methods should be applied.

2.13.2.5 The upright roll natural frequency should be estimated as follows:

$$\omega_0 = \frac{2\pi}{T_\varphi}$$

where $T_\varphi$ is the ship natural roll period defined in 2.11.3.2.2.

2.13.3.3 Short-term wave conditions, consisting of both a significant wave height, $H_s$, and an average zero up-crossing wave period, $T_z$, used for the assessment of the short-term dead ship stability failure index, $C_{S,i}$, are obtained from wave statistics that describe the probability of occurrence of a short-term condition ($H_s$, $T_z$) as the fraction of occurrences for a given total number of occurrences.

2.13.3.3.1 Each combination of $H_s$ and $T_z$ for which the number of occurrences is not zero provides the parameters of the wave spectrum, $S_{zz}(\omega)$, as defined in 2.13.3.2.3. The value of $H_s$ is also used to define the mean wind speed $U_w$ in 2.13.3.2.2.

2.13.3.3.2 The value of the weighting factor $W_i$ for the short-term wave condition ($H_s$, $T_z$) and corresponding $U_w$, to be used in the determination of the long-term probability index $C$ according to 2.13.3.2, is obtained as the number of occurrences of the condition ($H_s$, $T_z$) in Table 2.13.3.3.2 divided by the total number of reported occurrences.

**Table 2.13.3.3.2**

**Short-term waves condition occurrences**

| Number of occurrences: 100 000 / $T_z$ (s) = average zero up-crossing wave period / $H_s$ (m) = significant wave height | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **$T_z$ (s) ►**<br>**$H_s$ (m) ▼** | **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** | 1.3 | 133.7 | 865.6 | 1186.0 | 634.2 | 186.3 | 36.9 | 5.6 | 0.7 | 0.1 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| **1.5** | 0.0 | 29.3 | 986.0 | 4976.0 | 7738.0 | 5569.7 | 2375.7 | 703.5 | 160.7 | 30.5 | 5.1 | 0.8 | 0.1 | 0.0 | 0.0 | 0.0 |
| **2.5** | 0.0 | 2.2 | 197.5 | 2158.8 | 6230.0 | 7449.5 | 4860.4 | 2066.0 | 644.5 | 160.2 | 33.7 | 6.3 | 1.1 | 0.2 | 0.0 | 0.0 |
| **3.5** | 0.0 | 0.2 | 34.9 | 695.5 | 3226.5 | 5675.0 | 5099.1 | 2838.0 | 1114.1 | 337.7 | 84.3 | 18.2 | 3.5 | 0.6 | 0.1 | 0.0 |
| **4.5** | 0.0 | 0.0 | 6.0 | 196.1 | 1354.3 | 3288.5 | 3857.5 | 2685.5 | 1275.2 | 455.1 | 130.9 | 31.9 | 6.9 | 1.3 | 0.2 | 0.0 |
| **5.5** | 0.0 | 0.0 | 1.0 | 51.0 | 498.4 | 1602.9 | 2372.7 | 2008.3 | 1126.0 | 463.6 | 150.9 | 41.0 | 9.7 | 2.1 | 0.4 | 0.1 |
| **6.5** | 0.0 | 0.0 | 0.2 | 12.6 | 167.0 | 690.3 | 1257.9 | 1268.6 | 825.9 | 386.8 | 140.8 | 42.2 | 10.9 | 2.5 | 0.5 | 0.1 |
| **7.5** | 0.0 | 0.0 | 0.0 | 3.0 | 52.1 | 270.1 | 594.4 | 703.2 | 524.9 | 276.7 | 111.7 | 36.7 | 10.2 | 2.5 | 0.6 | 0.1 |
| **8.5** | 0.0 | 0.0 | 0.0 | 0.7 | 15.4 | 97.9 | 255.9 | 350.6 | 296.9 | 174.6 | 77.6 | 27.7 | 8.4 | 2.2 | 0.5 | 0.1 |
| **9.5** | 0.0 | 0.0 | 0.0 | 0.2 | 4.3 | 33.2 | 101.9 | 159.9 | 152.2 | 99.2 | 48.3 | 18.7 | 6.1 | 1.7 | 0.4 | 0.1 |
| **10.5** | 0.0 | 0.0 | 0.0 | 0.0 | 1.2 | 10.7 | 37.9 | 67.5 | 71.7 | 51.5 | 27.3 | 11.4 | 4.0 | 1.2 | 0.3 | 0.1 |
| **11.5** | 0.0 | 0.0 | 0.0 | 0.0 | 0.3 | 3.3 | 13.3 | 26.6 | 31.4 | 24.7 | 14.2 | 6.4 | 2.4 | 0.7 | 0.2 | 0.1 |
| **12.5** | 0.0 | 0.0 | 0.0 | 0.0 | 0.1 | 1.0 | 4.4 | 9.9 | 12.8 | 11.0 | 6.8 | 3.3 | 1.3 | 0.4 | 0.1 | 0.0 |
| **13.5** | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.3 | 1.4 | 3.5 | 5.0 | 4.6 | 3.1 | 1.6 | 0.7 | 0.2 | 0.1 | 0.0 |
| **14.5** | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.1 | 0.4 | 1.2 | 1.8 | 1.8 | 1.3 | 0.7 | 0.3 | 0.1 | 0.0 | 0.0 |
| **15.5** | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.1 | 0.4 | 0.6 | 0.7 | 0.5 | 0.3 | 0.1 | 0.1 | 0.0 | 0.0 |
| **16.5** | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.1 | 0.2 | 0.2 | 0.2 | 0.1 | 0.1 | 0.0 | 0.0 | 0.0 |

2.13.3.3.3 Alternative environmental conditions can be used, to the satisfaction of the Administration, for ships in restricted service or subject to operational limitations[8].

### 3.5 Estimation of roll damping

3.5.1 In order to perform a prediction of roll motion characteristics according to 3.4.1, roll damping coefficients are to be specified for the considered ship, in the considered loading condition.

3.5.2 In absence of sufficient information, the standard methodology reported in 3.5.3 should be used. The standard methodology specified by the Organization is based on the so-called "simplified Ikeda's method". However, methods which, to the satisfaction of the Administration, are deemed to be at least equivalently reliable can be used as well.

The roll damping coefficients can be estimated with scaled model tests using the following the procedures in MSC.1/Circ.1200 or alternative test procedures approved by the Administration. In the absence of roll decay model test data, the roll damping coefficients may be estimated using either a simplified Ikeda's method or type-specific empirical data (with bilge keels geometry effect included), if appropriate. The forward speed effect may be taken into account for the lift component using Ikeda's or an equivalent method. The simplified Ikeda's formula is given in Appendix 4 of the Chapter 3 of the explanatory notes. [Alternatively, numerical simulations can be used for the estimation of roll damping, based on the solution of viscous hydrodynamic equations. In this case, validation of simulations should be performed for selected loading conditions to the satisfaction of Administration. Validation should be performed in comparison with model tests performed according to the procedures in MSC.1/Circ.1200 or alternative test procedures approved by the Administration.

[8] In accordance with the guidelines developed by the Organization [to be developed].

### 3.5.3 Standard methodology for the estimation of roll damping

3.5.3.1 The standard methodology for the estimation of roll damping is based on two steps:

.1 At first, the equivalent linear roll damping coefficient is determined as a function of the roll amplitude, assuming the ship to roll with a sinusoidal motion at the roll natural frequency. See 3.5.3.2;

.2 As a second step, the roll damping coefficients to be used in 3.4.1 are determined from the previously calculated data. See 3.5.3.3.

3.5.3.2 The standard methodology for the calculation of roll damping as a function of the rolling amplitude under sinusoidal periodic motion is that specified in Appendix 4 of the "explanatory notes on the vulnerability of ships to the parametric roll stability failure mode" assuming that the ship is at zero speed. Such methodology allows determining the equivalent linear roll damping coefficient $B_{44}$ ( $N \cdot m/(rad/s)$) as a function of the rolling amplitude $\phi_a$, i.e. $B_{44}(\phi_a)$.

3.5.3.3 Given the equivalent linear roll damping coefficient, $B_{44}(\phi_a)$, calculated as in 3.5.3.2 as a function of the rolling amplitude $\phi_a$ (*rad*), the roll damping coefficients $\mu$ (*1/s*), $\beta$ (*1/rad*), $\delta$ (*s/rad*$^2$), as specified in 3.4.1.2, should be calculated, in general, by the following least square fitting:

$$\frac{B_{44}(\phi_a)\cdot\omega_0^2}{2\cdot\Delta\cdot\overline{GM}} \rightarrow \mu + \frac{4}{3\cdot\pi}\cdot\beta\cdot\omega_0\cdot\phi_a + \frac{3}{8}\cdot\delta\cdot\omega_0^2\cdot\phi_a^2$$

where

$\omega_0$ (*rad/s*) is the upright roll natural frequency, $\Delta$ (*N*) is the ship displacement force and $\overline{GM}$ (*m*) is the upright metacentric height. However, depending on the shape of $B_{44}(\phi_a)$, one or more roll damping coefficients can be set a-priori to zero, provided that the final fitting is sufficiently accurate, to the satisfaction of the Administration.

3.5.3.4 When determining the roll damping coefficients through the least square fitting procedure as specified in 3.5.3.3, care should be exercised in order to perform the fitting in a range of rolling amplitudes which is as large as possible, but without extending outside the limits of validity of the method used for the determination of $B_{44}(\phi_a)$. Moreover, attention should be paid to avoid, as much as possible, that the roll damping model is used outside the fitting range. In particular, extrapolations should be avoided when the fitting 3.5.3.3-1 is carried out without a-priori setting to zero the cubic damping coefficient $\delta$.

## 3.6 The standard methodology for the estimation of the effective wave slop function

3.6.3.3 For each longitudinal position $x$ along the vessel, the draught $T_{eq}(x)$ (m), the breadth $B_{eq}(x)$ (m) and the underwater sectional area $A_{eq}(x)$ (m$^2$) of the "equivalent vessel" are to be calculated as follows:

$$
\begin{cases}
\text{if } A(x)>0 \text{ and } B(x)>0: & \begin{cases}
\text{if } \dfrac{A(x)}{B(x)} \leq T(x) \text{ then } \begin{cases} A_{eq}(x)=A(x) \\ B_{eq}(x)=B(x) \\ T_{eq}(x)=\dfrac{A(x)}{B(x)} \end{cases} \\
\text{if } \dfrac{A(x)}{B(x)} > T(x) \text{ then } \begin{cases} T_{eq}(x)=T(x) \\ B_{eq}(x)=B(x) \\ A_{eq}(x)=B_{eq}(x)\cdot T_{eq}(x) \end{cases}
\end{cases} \\
\text{otherwise: } & \begin{cases} A_{eq}(x)=0 \\ B_{eq}(x)=0 \\ T_{eq}(x)=0 \end{cases}
\end{cases}
$$

where $A(x)$ (m$^2$), $B(x)$ (m) and $T(x)$ (m) are, respectively, the underwater sectional area, the sectional breadth at waterline and the sectional draught of the ship.

3.6.3.4 The underwater volume $\nabla_{eq}$ (m$^3$), the transversal metacentric radius $BM_{T,eq}$ (m), the vertical position of the centre of buoyancy $KB_{eq}$ (m) and the vertical position of centre of gravity $KG_{eq}$ (m) of the "equivalent vessel" are to be calculated as follows:

$$
\begin{cases}
\nabla_{eq} = \int_L A_{eq}(x)dx \\
BM_{T,eq} = \dfrac{1}{\nabla_{eq}} \cdot \int_L \dfrac{1}{12} \cdot B_{eq}^3(x)dx \\
KB_{eq} = T + \dfrac{1}{\nabla_{eq}} \cdot \int_L \dfrac{-T_{eq}(x)}{2} \cdot A_{eq}(x)dx \\
KG_{eq} = KB_{eq} + BM_{T,eq} - \overline{GM}
\end{cases}
$$

where

$\overline{GM}$ (m) is the upright metacentric height and $T$ (m) is the draught amidships (at the keel point). The vertical positions $KB_{eq}$ and $KG_{eq}$ are defined with respect to the keel line of the ship.

**Calculation of derivative of $\overline{GZ}$ at $\phi_S$ ("local metacentric height" $\overline{GM}_{res}$) and correction of the natural roll frequency**

The residual metacentric height $\overline{GM}_{res}$ ($m$) is the derivative of the residual righting lever curve at $\phi_S$ (see Figure 3.3). Since the heeling moment due to the steady wind is assumed to be constant, it follows that:

$$\overline{GM}_{res}(\phi_s) = \left.\frac{d\left(\overline{GZ} - \bar{l}_{wind,tot}\right)}{d\phi}\right|_{\phi=\phi_s} \overset{\bar{l}_{wind,tot}\text{ not depending on the heeling angle}}{=} \left.\frac{d\overline{GZ}}{d\phi}\right|_{\phi=\phi_s}$$

**Calculation of spectrum of total roll moment due to the action of waves and gustiness**

The spectrum $S_{\alpha\alpha}$ ($rad^2/(rad/s)$) of the wave slope is to be calculated as:

$$S_{\alpha\alpha}(\omega) = \frac{\omega^4}{g^2} \cdot S_{ZZ}(\omega)$$

where: $\omega$ ($rad/s$) is the circular wave frequency;

$g = 9.81\ m/s^2$ is the gravitational acceleration.

The spectrum $S_{\alpha\alpha,c}$ ($rad^2/(rad/s)$) of the effective wave slope is to be calculated as:

$$S_{\alpha\alpha,c}(\omega) = r^2(\omega) \cdot S_{\alpha\alpha}(\omega)$$

where

$r(\omega)$ (-) is the effective wave slope function as a function of the wave circular frequency (see Section 3.6).

The spectrum $S_{M_{waves}}$ ($(N \cdot m)^2 / (rad/s)$) of the moment due to the action of the waves, as a function of the wave circular frequency $\omega$ ($rad/s$), is to be calculated as:

$$S_{M_{waves}}(\omega) = \left(\Delta \cdot \overline{GM}_{res}(f_S)\right)^2 \cdot S_{\alpha\alpha,c}(\omega) = \left(r(\omega) \cdot \Delta \cdot \overline{GM}_{res}(f_S)\right)^2 \cdot S_{\alpha\alpha}(\omega)$$

The spectrum $S_{\delta M_{wind,tot}}(\omega)$ ($(N \cdot m)^2 / (rad/s)$) of the moment due to the action of the gust, as a function of the wave circular frequency $\omega$ ($rad/s$), is to be calculated as:

$$S_{\delta M_{wind,tot}}(\omega)=\left[\rho_{air}\cdot U_w\cdot C_m\cdot A_L\cdot Z\right]^2\cdot\chi^2(\omega)\cdot S_v(\omega)$$

where

the function $\chi(\omega)$ (-) is the aerodynamic admittance function to be calculated in accordance with 3.4.1.6.5.

The standard aerodynamic admittance function is to be calculated as: $\chi(\omega)=1$

[Alternative formulation can be accepted to the satisfaction of the Administration.]

The spectrum $S_M(\omega)$ ($(N\cdot m)^2/(rad/s)$) of the total moment due to the action of waves and gust, as a function of the wave circular frequency $\omega$ (*rad/s*), is to be calculated as:

$$S_M(\omega)=S_{M_{waves}}(\omega)+S_{\delta M_{wind,tot}}(\omega)$$

**Determination of the spectrum of the roll oscillation**

The standard deviation $\sigma_{\dot{x}}$ (*rad/s*) of the roll velocity is obtained by numerically solving the following equation with respect to the single unknown $\sigma_{\dot{x}}$:

$$\begin{cases} F(\sigma_{\dot{x}})=0 \\ \text{with} \\ F(\sigma_{\dot{x}})=\sigma_{\dot{x}}^2-\displaystyle\int_0^\infty \frac{\omega^2\cdot\omega_0^4}{\left(\omega_{0,e}^2(\phi_S)-\omega^2\right)^2+\left(2\cdot\mu_e(\sigma_{\dot{x}})\cdot\omega\right)^2}\cdot\frac{S_M(\omega)}{\left(\Delta\cdot\overline{GM}\right)^2}d\omega \\ \mu_e(\sigma_{\dot{x}})=\mu+\sqrt{\frac{2}{\pi}}\cdot\beta\cdot\sigma_{\dot{x}}+\frac{3}{2}\cdot\delta\cdot\sigma_{\dot{x}}^2 \end{cases}$$

## 2.14 ASSESSMENT OF SHIP VULNERABILITY TO THE EXCESSIVE ACCELERATION FAILURE MODE

### 2.14.1 Application

2.14.1.1 The provisions given hereunder apply to each ship in each condition of loading for which both:

.1 the distance from the waterline to the highest location along the length of the ship where passengers or crew may be present exceeds [70%] of the breadth of the ship; and

.2 the metacentric height exceeds [8%] of the breadth of the ship.

2.14.1.2 For each condition of loading, a ship that:

.1 meets the standard contained in the criteria contained in 2.14.2 is considered not to be vulnerable to the excessive acceleration failure mode;

.2 does not meet the standard contained in the criteria contained in 2.14.2 should be subject to more detailed assessment of vulnerability to the failure mode by applying the criteria contained in 2.14.3.

2.14.1.3 For each condition of loading, a ship that neither meets the criteria contained in 2.14.2 nor meets the criteria contained in 2.14.3 should be subject to either:

.1 a direct stability assessment for the excessive acceleration failure mode that is performed according to recommended specifications developed by the Organization[9] from which operational guidance procedures are developed to the satisfaction of the Administration; or

.2 operational limitations based on outcomes of the application of 2.14.3[1].

2.14.1.4 A detailed assessment of vulnerability according to the criteria contained in 2.14.3 or a direct stability assessment as provided in 2.14.1.3.1 may be performed without the requirement to perform a more simplified assessment in 2.14.2 or 2.14.3, respectively.

[9] To be developed.

### 2.14.2 Level 1 Vulnerability Criteria for Excessive acceleration

2.14.2.1 A ship is not considered to be vulnerable to the excessive acceleration stability failure mode for both the loading condition and location under consideration if

$$\varphi\, k_L\, (g + 4\, \pi^2\, h\, /\, T^2) < R_{EA1}$$

Where,

| | | |
|---|---|---|
| $R_{EA1}$ | = | [5.3] [8.9] [8.69 or below] m/s$^2$ |
| $\varphi$ | = | characteristic roll amplitude (rad) = $4.43\, r\, s\, /\, \delta_\varphi^{0.5}$; |
| $k_L$ | = | $1.125 - 0.625\, x\, /L$, if $x < 0.2\, L$, |
| | = | 1.0, if $0.2\, L < x < 0.65\, L$, |
| | = | $0.527 + 0.727\, x\, /L$, if $x > 0.65\, L$; |
| $x$ | = | longitudinal distance of the location where passengers or crew may be present from the aft end of $L$; |
| $g$ | = | gravitational acceleration of 9.81 m/s$^2$; |
| $h$ | = | height above the roll axis of the location where passengers or crew may be present (m); |
| $T$ | = | rolling period as determined in 2.14.2.2 (s); |
| $r$ | = | non-dimensional effective wave slope = $\dfrac{(K_1 + K_2 + (OG)(F))}{\left(\dfrac{B^2}{12 C_B d} - \dfrac{C_B d}{2} - OG\right)}$; |
| $K_1$ | = | $g\, \beta\, T^2\, (\tau + \tau\, \tilde{T} - 1\, /\tilde{T})\, /\, (4\, \pi^2)$; |
| $K_2$ | = | $g\, \tau\, T^2\, (\beta - \cos \tilde{B})\, /\, (4\, \pi^2)$; |
| $OG$ | = | $KG - d$; |
| $F$ | = | $\beta\, (\tau - 1\, /\, \tilde{T})$; |
| $\beta$ | = | $\sin(\tilde{B})\, /\, \tilde{B}$; |
| $\tau$ | = | $\exp(-\tilde{T})\, /\, \tilde{T}$; |
| $\tilde{B}$ | = | $2\, \pi^2\, B\, /\, (g\, T^2)$; |
| $\tilde{T}$ | = | $4\, \pi^2\, C_B\, d\, /\, (g\, T^2)$; |
| $s$ | = | non-dimensional wave steepness as obtained from Table 2.13.2.1; |
| $\delta_\varphi$ | = | non-dimensional logarithmic decrement of roll decay = |
| | = | 44/15, if the ship has a sharp bilge[10]; and, otherwise, |
| | = | $4/15 + 2/3\, (100\, A_k\, /\, (L\, B))$, if $C_m \geq 0.96$, |
| | = | $4/15 + 1/3\, (1 + 50\, (C_m - 0.94))\, (100\, A_k\, /\, (L\, B))$, if $0.94 < C_m < 0.96$, |
| | = | $4/15 + 1/3\, (100\, A_k\, /\, (L\, B))$, if $C_m \leq 0.94$, and $(100\, A_k\, /\, (L\, B))$ should not exceed 4; |
| $L$ | = | Length of the ship, m; |
| $B$ | = | moulded breadth of the ship (m); |
| $d$ | = | mean moulded draft of the ship (m); |
| $C_B$ | = | block coefficient; |
| $KG$ | = | vertical centre of gravity (m), uncorrected for free surface effect; and |
| $A_k$, $C_m$ | = | [bilge keel area (m$^2$) and midship section coefficient, taken as defined in 2.11.2.1.][ bilge keel and bar keel area (m$^2$) as defined in section 2.3 of Part A and midship section coefficient defined in 2.11.2.1.] |

For the purpose of determining $h$, the roll axis may be assumed to be located at the midpoint between the waterline and the vertical centre of gravity.

10 See the Explanatory Notes.

2.14.2.2 The rolling period, $T$, may be determined as provided in 2.3 of Part A or as determined using methods defined in 2.14.3, a direct stability assessment for the excessive acceleration failure mode, formulae or model tests performed according to procedures acceptable to the Administration. In any case in which metacentric height, $GM$, is included as a factor, the $GM$ should not be corrected for free surface effects.

### 2.14.3 Level 2 Vulnerability Criteria for Excessive acceleration

2.14.3.1 A ship is considered not to be vulnerable to the excessive acceleration failure mode for both the loading condition and location under consideration if $R_{EA2}$, is greater than $C$,

Where, $R_{EA2}$ = [0.001] [0.0281 or above] [0.043 or above];
$C$ = a long-term probability index that measures the vulnerability of the ship to a stability failure in the excessive acceleration mode for both the loading condition and location under consideration based on the probability of occurrence of short-term environmental conditions as calculated according to 2.14.3.2.

2.14.3.2 The value for $C$ is calculated as a weighted average from a set of wave conditions specified in 2.14.3.3.

$$C = \sum_{i=1}^{N} W_i C_i$$

Where,
$W_i$ = the weighting factor for the short-term environmental wave condition specified in 2.14.3.3;
$C_i$ = the short-term dead-ship condition stability failure index for the loading condition and location under consideration and for the short-term environmental condition under consideration calculated as specified in 2.14.3.2.1;
$N$ = the number of wave conditions evaluated of those specified in 2.14.3.3.

2.14.3.2.1 The short-term excessive acceleration condition stability failure index, $C_i$, for the loading condition and location under consideration and for the short-term environmental condition under consideration is a measure of the conditional probability that the ship will exceed a specified lateral acceleration when the ship meets a wave cycle and is calculated according to the following formula:

$$C_i = \exp[-R_2^2 / (2\,\sigma_{LAi}^2)];$$

Where,
$R_2$ = [9.81] m/s$^2$;
$\sigma_{LAi}$ = standard deviation of the lateral acceleration at zero speed and in a beam seaway determined according to 2.14.3.2.2 (m/s$^2$);

2.14.3.2.2 The standard deviation of the lateral acceleration at zero speed and in a beam seaway, $\sigma_{LAi}$, used in the calculation of the short-term excessive acceleration condition stability failure index, $C_i$, for the short-term environmental condition under consideration is determined using the spectrum of the total roll moment due to the action of waves. The square of this standard deviation is calculated according to the following formula[11]:

$$\sigma_{LAi}^{2} = \frac{3}{4}\sum_{j=1}^{N}\left(a_y(\omega_j)\right)^2 S_{ZZ}(\omega_j)\Delta\omega$$

Where,

| | | |
|---|---|---|
| $\Delta\omega$ | = | the interval of wave frequency (rad/s) = $(\omega_2 - \omega_1) / N$ (rad/s); |
| $\omega_2$ | = | the upper limit of the wave frequency spectrum in the evaluation range = min((25 / $T$),2.0) (rad/s); |
| $\omega_1$ | = | the lower limit of the wave frequency spectrum in the evaluation range = max((0.5 / $T$),0.2) (rad/s); |
| $N$ | = | the number of intervals of wave frequency in the frequency spectrum evaluation range, not to be taken less than [10] [100]; |
| $\omega_j$ | = | wave frequency at the mid-point of the frequency interval considered = $\omega_1 + ((2j - 1) / 2)\, \Delta\omega$ (rad/s); |
| $S_{ZZ}(\omega_j)$ | = | wave frequency spectrum = $124\, H_s^2\, T_Z^{-4}\, \omega_j^{-5} \exp(-495\, T_Z^{-4}\, \omega_j^{-4})$ (m²/(rad/s)); |
| $\varsigma_a$ | = | wave amplitude (m); |
| $a_y(\omega_j)$ | = | lateral acceleration = $k_L\, (g \sin(\varphi_a(\omega_j)) + h\, \omega_j^{\,2} \varphi_a(\omega_j))$ (m/s²); |
| $k_L$ | = | as defined in 2.14.2.1; |
| $g$ | = | gravitational acceleration of 9.81 m/s²; |
| $h$ | = | as defined in 2.14.2.1; |
| $\varphi_a(\omega)$ | = | roll amplitude in regular waves at zero speed and waves encountering the ship with frequency $\omega_j$ = $(\varphi_r(\omega_j)^2 + \varphi_i(\omega_j)^2)^{0.5}$ (rad); |
| $\varphi_r(\omega_j)$ | = | $\dfrac{a(\Delta GM - I_{xx}\omega_j^2) + b\mu_e\omega_j}{\left(\Delta GM - I_{xx}\omega_j^2\right)^2 + (\mu_e\omega_j)^2}$ (rad); |
| $\varphi_i(\omega_j, \beta')$ | = | $\dfrac{b(\Delta GM - I_{xx}\omega_j^2) + a\mu_e\omega_j}{\left(\Delta GM - I_{xx}\omega_j^2\right)^2 + (\mu_e\omega_j)^2}$ (rad); |
| $a$, $b$ | = | real and imaginary parts, respectively, of the exciting roll moment both using the Froude-Krylov assumption and neglecting the wave diffraction moment, and which may be calculated either using an appropriate estimation or directly; |
| $GM$ | = | metacentric height not corrected for free surface effect (m) |
| $\mu_e$ | = | equivalent linear roll damping coefficient (t m s) calculated according to the stochastic linearization method. This coefficient depends on linear and nonlinear roll damping coefficients and on the specific roll velocity standard deviation in the considered short-term environmental conditions[12] |
| $r(\omega)$ | = | the effective wave slope function determined according to 2.14.3.2.X |
| $\Delta$ | = | displacement (t) |
| $I_{xx}$ | = | roll moment of inertia = $\Delta\, GM\, T^2 / (4\pi^2)$ (t m s²) |
| $H_s$ | = | significant wave height for the environmental condition under consideration as obtained from Table 2.14.3.3 (m); |
| $T_Z$ | = | zero upcrossing period for the environmental condition under consideration as obtained from Table 2.14.3.3 (m); |

[11] Integration of an equivalent formulation over the range, $\omega_1$ to $\omega_2$, may be substituted.

[12] The detailed calculation procedure is described in the Explanatory Notes.

And other variables as defined in 2.14.2.1.

2.14.3.3 Wave conditions, consisting of both a significant wave height, $H_s$, and an average zero upcrossing wave period, $T_z$, used for the assessment of the short-term excessive acceleration condition stability failure index, $C_i$, are obtained from wave statistics that describe the probability of a wave condition ($H_s$, $T_z$) as the number of occurrences for a given total number of observations.

2.14.3.3.1 Each combination of $H_s$ and $T_z$ for which the number of occurrences is not zero provides the parameters of the wave spectrum, $S_{ZZ}(\omega)$, as defined in 2.14.3.2.3. 2.

2.12.3.3.2 The value of the weighting factor for the short-term environmental wave condition, $W_i$, to be used in the formula in 2.14.3.2 for a wave condition ($H_s$, $T_z$) is obtained as the value in the table of wave condition occurrences (Table 2.12.3.3) divided by the number of occurrences given in the table. Table 2.12.3.3.2 provides the data needed to define the wave conditions and determine $W_i$ except if the Administration directs the use of other wave statistics for restricted service or operational limitations[13].

**Short-term waves condition occurrences**

| Number of occurrences: 100 000 / $T_z$ (s) = average zero up-crossing wave period / $H_s$ (m) = significant wave height | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **$T_z$ (s) ► / $H_s$ (m) ▼** | **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** | 1.3 | 133.7 | 865.6 | 1186.0 | 634.2 | 186.3 | 36.9 | 5.6 | 0.7 | 0.1 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| **1.5** | 0.0 | 29.3 | 986.0 | 4976.0 | 7738.0 | 5569.7 | 2375.7 | 703.5 | 160.7 | 30.5 | 5.1 | 0.8 | 0.1 | 0.0 | 0.0 | 0.0 |
| **2.5** | 0.0 | 2.2 | 197.5 | 2158.8 | 6230.0 | 7449.5 | 4860.4 | 2066.0 | 644.5 | 160.2 | 33.7 | 6.3 | 1.1 | 0.2 | 0.0 | 0.0 |
| **3.5** | 0.0 | 0.2 | 34.9 | 695.5 | 3226.5 | 5675.0 | 5099.1 | 2838.0 | 1114.1 | 337.7 | 84.3 | 18.2 | 3.5 | 0.6 | 0.1 | 0.0 |
| **4.5** | 0.0 | 0.0 | 6.0 | 196.1 | 1354.3 | 3288.5 | 3857.5 | 2685.5 | 1275.2 | 455.1 | 130.9 | 31.9 | 6.9 | 1.3 | 0.2 | 0.0 |
| **5.5** | 0.0 | 0.0 | 1.0 | 51.0 | 498.4 | 1602.9 | 2372.7 | 2008.3 | 1126.0 | 463.6 | 150.9 | 41.0 | 9.7 | 2.1 | 0.4 | 0.1 |
| **6.5** | 0.0 | 0.0 | 0.2 | 12.6 | 167.0 | 690.3 | 1257.9 | 1268.6 | 825.9 | 386.8 | 140.8 | 42.2 | 10.9 | 2.5 | 0.5 | 0.1 |
| **7.5** | 0.0 | 0.0 | 0.0 | 3.0 | 52.1 | 270.1 | 594.4 | 703.2 | 524.9 | 276.7 | 111.7 | 36.7 | 10.2 | 2.5 | 0.6 | 0.1 |
| **8.5** | 0.0 | 0.0 | 0.0 | 0.7 | 15.4 | 97.9 | 255.9 | 350.6 | 296.9 | 174.6 | 77.6 | 27.7 | 8.4 | 2.2 | 0.5 | 0.1 |
| **9.5** | 0.0 | 0.0 | 0.0 | 0.2 | 4.3 | 33.2 | 101.9 | 159.9 | 152.2 | 99.2 | 48.3 | 18.7 | 6.1 | 1.7 | 0.4 | 0.1 |
| **10.5** | 0.0 | 0.0 | 0.0 | 0.0 | 1.2 | 10.7 | 37.9 | 67.5 | 71.7 | 51.5 | 27.3 | 11.4 | 4.0 | 1.2 | 0.3 | 0.1 |
| **11.5** | 0.0 | 0.0 | 0.0 | 0.0 | 0.3 | 3.3 | 13.3 | 26.6 | 31.4 | 24.7 | 14.2 | 6.4 | 2.4 | 0.7 | 0.2 | 0.1 |
| **12.5** | 0.0 | 0.0 | 0.0 | 0.0 | 0.1 | 1.0 | 4.4 | 9.9 | 12.8 | 11.0 | 6.8 | 3.3 | 1.3 | 0.4 | 0.1 | 0.0 |
| **13.5** | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.3 | 1.4 | 3.5 | 5.0 | 4.6 | 3.1 | 1.6 | 0.7 | 0.2 | 0.1 | 0.0 |
| **14.5** | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.1 | 0.4 | 1.2 | 1.8 | 1.8 | 1.3 | 0.7 | 0.3 | 0.1 | 0.0 | 0.0 |
| **15.5** | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.1 | 0.4 | 0.6 | 0.7 | 0.5 | 0.3 | 0.1 | 0.1 | 0.0 | 0.0 |
| **16.5** | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.1 | 0.2 | 0.2 | 0.2 | 0.1 | 0.1 | 0.0 | 0.0 | 0.0 |

[13] In accordance with the guidelines developed by the Organization [to be developed].