Exploration of the Probabilities of Extreme Roll of Naval Vessels

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ABSTRACT

Dynamic stability simulation tools developed by the Cooperative Research Navies have been used to investigate the relationship between a number of stability criteria and the probability of exceeding a critical roll angle. Multiple roll response time series for several ships in various seaway conditions are generated to provide the probabilities. This paper describes the investigation into the probability results themselves, as a precursor to regression against GZ curve parameters. Specifically, it examines the effects of modelling choices and of variation and range in the input control variables.

Keywords: *Dynamic Stability, Probability of Capsize, Simulation*

1. INTRODUCTION

Tools for assessing dynamic stability of intact ships have been developed within the Cooperative Research Navies (CRNav) Dynamic Stability Project. Under tasking from the Naval Stability Standards Working Group (NSSWG), the tools were employed to investigate the relationship between risk of capsize and various geometry and stability parameters. The risk of capsize is characterized by the probability of exceeding a critical roll angle (PECRA), and although in the present case it is related to capsize, the critical roll angle may also take on a number of other important connotations, such as machinery or weapon limits.

The probability of exceeding a critical roll angle (PECRA) is determined by running multiple, time-domain simulations of a ship in a specific loading condition at a mean speed and heading (the operating point of the vessel) in waves of a given significant height and modal period (the environmental condition). The time series of roll responses are used to determine the PECRA. The probability outcomes are later used as the regressands (response variables) in regression analysis investigating relationships with parameters associated with ship stability.

This paper records the study into how the PECRA vary with the input control variables of ship speed (V), ship heading relative to the wave system (β), significant wave height (H), and modal wave period (τ). It also looks into the differences between ships and between loading conditions. It further seeks to address the issue of the range and resolution of the sets of input control variables that will fully characterize the total probability of exceeding a critical roll angle (TPECRA) across all input variables for each load condition of each ship.

The next section will discuss the scope of work to date, looking at the similarities and differences between three phases of work, each with slightly different goals. Following that will be a look at the different geometries of the ships used in Phase 2. The next section will briefly examine the effects of load conditions, operating points, and environmental conditions. After that will be a study into the consequences of choices relating to range and resolution of the input control variables (V, β, H, τ). This will be followed by a discussion on the use of Operational Overlays. Finally conclusions will be presented.

2. SCOPE OF WORK – 3 PHASES

2.1 Determination of Probabilities

FREDYN is a non-linear, semi-empirical, time-domain software for simulating ship motions in environmental conditions from calm water to severe wind and waves. It allows for studies in stability, seakeeping and manoeuvring. FREDYN is appropriate for any type of a relatively slender mono-hull with a Froude number less than 0.5. Specific to the current study, FREDYN is capable of predicting a range of capsize modes in regular and irregular waves.

Since 1999, the objectives of the NSSWG have been pursued through three phases of study for intact ships. Phase 1 (FREDYN version 8.2) used a strip theory approach to look at relationships between the risk of capsize and various stability-related and ship-form parameters. Phase 2 (FREDYN version 9.9) used panel methods and the emphasis of the study shifted to looking for the level of safety inherent in the current naval stability standards. In addition to using a panel method for the Froude-Krylov forces, the Frank Close Fit Method was implemented to replace a conformal mapping method, the roll damping method was improved, and the ship motion algorithm was upgraded. Phase 3 (FREDYN version 10.2) was conducted after a complete rewrite of the software to modularize the code. The Phase 3 study still used panel methods, but included a more accurate modelling of the effects of deck-edge immersion, as well as an automatic determination of the retardation function time interval and time step. The focus in Phase 3 was narrowed to finding criteria that would be suitable for stability standards, in particular the Naval Ship Code (ANEP 77, 2012).

The set of ships investigated was largely the same for all three phases, and included slender hulls with twin propellers and one or two rudders. Several different load conditions are explored for each ship, with each load condition delineated by draft (T) and vertical position of the centre of gravity (KG). The radii of gyration were held constant for a given ship for all load conditions (TKG). Some of the load conditions were common in two or more phases, but most were not.

What is common to all three phases is the general approach to determining the probability of exceeding the critical roll angle (PECRA). Simulations were run for each ship in specific load conditions, at standard operating points and environmental conditions.

The standard operating points are three speeds chosen by the NSSWG as typical for frigates, and 7 headings covering 0° to 180°, following the standard assumption that the symmetry of the ship will make the results from 180° to 360° a mirror image of those from 0° to 180°. In fact the 0° and 180° headings were changed to 1° and 179° to mimic the asymmetry of real vessels. The standard environmental conditions were taken as those define by the Bales North Atlantic scattergram (see Bales, Lee, and Voelker, 1981) as modified by McTaggart and De Kat (2000).

The same set of operating points and environmental conditions was used in Phase 2 as in Phase 1, but in Phase 3 there were fewer wave heights and periods and only one ship speed.

To be conservative, a single sea direction was assumed and wave spreading was not used, so that all the energy associated with the sea spectrum would be concentrated in the unidirectional wave train. This is expected to result in a more pessimistic estimate of risk.

Wind was modelled as a function of wave height and was set to be collinear with the wave, again to be conservative. No currents were included in the simulations.

Each environmental condition was modelled as a Bretschneider spectrum defined by the significant wave height and modal wave period. The spectrum is built by summing regular waves of different amplitudes, wavelengths and phase angles, and there are an infinite number of ways to realize (achieve) the spectrum, with each realization accomplished by a different choice of the pseudo-random seed number used to generate the component wave phase angles. Each realization is capable of producing a unique time series of wave conditions, and thus ship responses. This is the key to generating probabilistic results: under the assumption that any one of the unique realizations is equally likely to occur, performing multiple simulation runs (where each run is a unique realization) generates a statistical sample leading to the probability of exceeding the critical roll angle (PECRA).

The same operating points and environmental conditions were used in all cases within a given phase, but the number of seaway realizations was not necessarily the same for each ship, or even for each load condition for the same ship. The number of realizations depended on the quality of the probability result; (small) batches of simulations were added when the uncertainty in the probability result was higher than acceptable.

2.2 Post-Analysis

For Phases 1 and 2 a block maxima method called PCAPSIZE (see McTaggart and De Kat, 2000) was used to determine the probability of exceeding the critical roll angle (which for Phases 1 and 2 was 90°) within one hour.

For Phase 3 an envelope-peaks-over-threshold (EPOT) method called LORELEI (see Ypma and Harmsen, 2012) was developed to obtain the probability of exceeding the critical roll angle (which for Phase 3 was 70°) within an hour. This method makes fuller use of the time-series data and thus theoretically provides a more accurate value.

2.3 Current Investigation

For each load condition, the simulation results can be stored as a 4-dimensional hyper-cube with each dimension representing a single input control variable. While this makes it easy to index into the data, as well as to partition the data along any subset of variable ranges, for visually examining the data, it is necessary to "flatten" the data into at most 2 dimensions. It is intuitive to group the speed and heading together, and the wave height and period together. For each ship loading condition there can be up to 148 speed-heading tables or plots and up to 21 height-period tables or plots. Each phase has at least 37 loading conditions to consider, and over all 3 phases there are a total of 152 distinct loading conditions (i.e., not including repeated loading conditions) over 14 ships. The number of tables and/or plots to examine is large, so generalizations will be made by looking at single speed-heading plots that represents a sum of PECRA over all wave heights and periods for a given ship loading condition, and single height-period plot that represents a sum of PECRA over all ship speeds and headings for a given ship loading condition. These summations are known as marginal sums and can be denoted as MPECRA-HT and MPECRA-VB respectively. Each of these marginal summations can be further summed to a common number representing the total probability of exceeding the critical roll angel (TPECRA) for the load condition.

The marginal sums and the total sum are only possible by applying suitable probability distributions for the wave conditions, and/or ship's speed and heading. The choice of probability distributions for the input control variables will be discussed more fully under Operator Overlays. For this paper, uniform distributions were used to make it easy to investigate the relationships without any weighting issues.

The probability results vary across several orders of magnitude. It is arguably more intuitive to talk about these probabilities in terms of their order of magnitude than about the values themselves. Therefore the remainder of this paper concerns itself with the data in terms of the base-10 logarithm of the probabilities; i.e., O(PECRA), O(MPECRA-HT), O(MPECRA-VB), O(TPECRA).

2.4 Data Presentation

Typically, the data with respect to the operating point (ship speed and heading) would be plotted on a polar plot, or a half-polar plot given an assumption of symmetry of the ship leading to similar results for relative headings from 180° to 360° as for 0° to 180°. In this paper, a contour plot of the order of magnitude of TPECRA with respect to speed and heading will be given in the form of a rectangular contour plot.

Figure 1 shows the more complicated contour plot in terms of environmental conditions (wave height and period), in this case for the order of magnitude of the probability of observing the wave height-period combination according to Bales as modified by McTaggart and De Kat (2000). The plot is more complicated because of several features. Wave steepness (significant wave height divided by wavelength) is taken into account so that waves that are too steep to exist are not included. This results in the lower left corner being empty; other empty areas are the result of not having data for the height-period combination. Overlaid on the plot are wave steepness contours (lines sweeping down from the top left corner). Stokes wave theory predicts a limit of steepness of 1/7, while Buckley (see McTaggart and De Kat, 2000) gives an observed limit of about 0.049, based on significant wave height and peak wave period. Note that the Bales data only has valid elements below both limits (i.e. above those contours in the figure). The lines crossing the steepness contours are contours of constant (normalized) energy due to the incident wave.

The average energy per unit meter along the wave[1] (perpendicular to the direction of wave travel) is given by:

$$E = (1/16\pi)\rho g^2 H^2 \tau^2 \tag{1}$$

This is clearly a function of the wave height and period only (for a given density of water). The energy is normalized by the highest value, which would be at the largest values of height and period; hence the contours show an increase towards the lower right corner.

The dashed boxes added to this particular figure indicate the NATO STANAG 4194 (1994) Sea State definitions for reference (see also Bales, Lee, and Voelker, 1981).

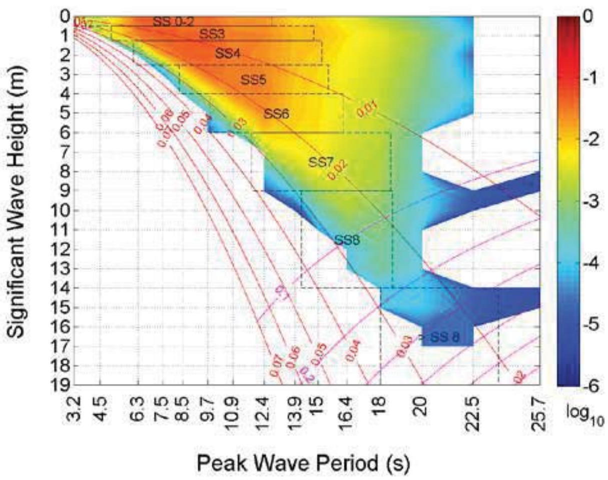

Figure 1. Order of Magnitude of Probabilities of Occurrence in Bales (modified) North Atlantic Wave Table.

[1] An estimate of the total energy imparted to the ship by the incident wave can be calculated by multiplying E by the waterline length of the ship times the sin of the relative heading to the wave. This estimate does not take into account radiation, diffraction, or other physical phenomena – only the energy in the incident wave.

2.5 Effects of Modelling and Analysis Choices

An attempt was made to track the changes between the phases of the intact stability study, in order to establish the effects of specific modelling choices, like the difference between strip theory and panel methods.

Across the set of ships and loading conditions in the three phases, there were 9 common loading conditions, representing 5 different ships. Some ships have one common condition and others have more. The loading conditions are numbered from 1 to 9 without regard to which ship they are associated with. Figures 2 through 4 show an example of the same loading condition in each phase. They show the maximum order of magnitude of PECRA over all speeds and headings, and do not, therefore, represent any particular operating point, nor are they marginal sums.

Because the ranges of wave heights and periods in phase 3 were reduced, Figures 2 and 3 have been cropped to show the Phase 3 Equivalent (P3E) ranges.

It is clear that each phase shows different orders of magnitude of the probabilities for the same conditions. Unfortunately, there were too many changes to the software in between phases to definitively assign changes in the probability results to specific modelling choices. Phase 2 data was chosen for this analysis because, as will be seen later, the ranges of input control variables provide for a more accurate characterization of the TPECRA.

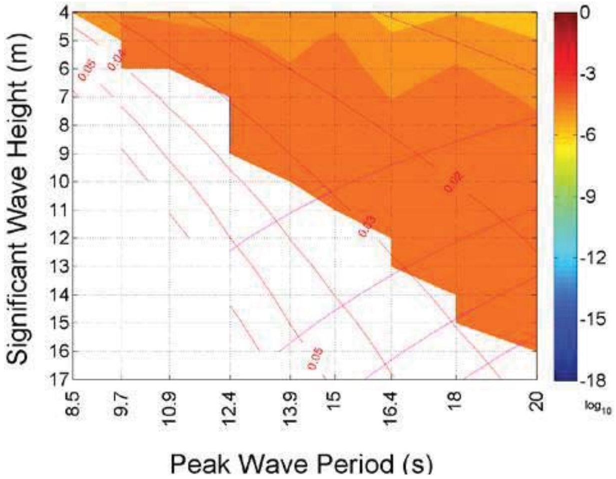

Figure 2. Maximum O(PECRA-VB) by Wave Height and Period – Phase 1 Load Condition 6.

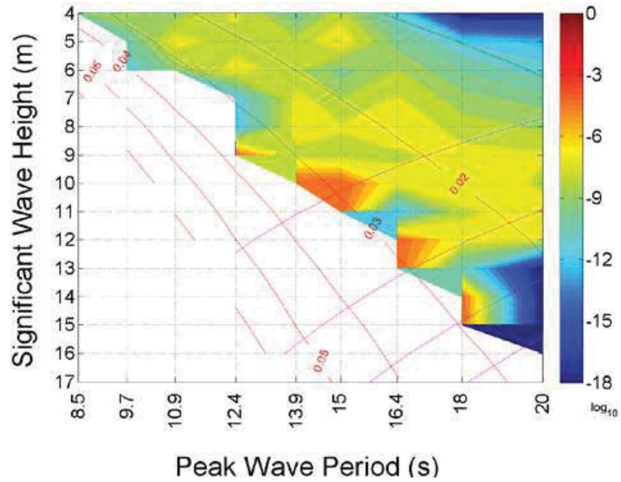

Figure 3. Maximum O(PECRA-VB) by Wave Height and Period – Phase 2 Load Condition 6.

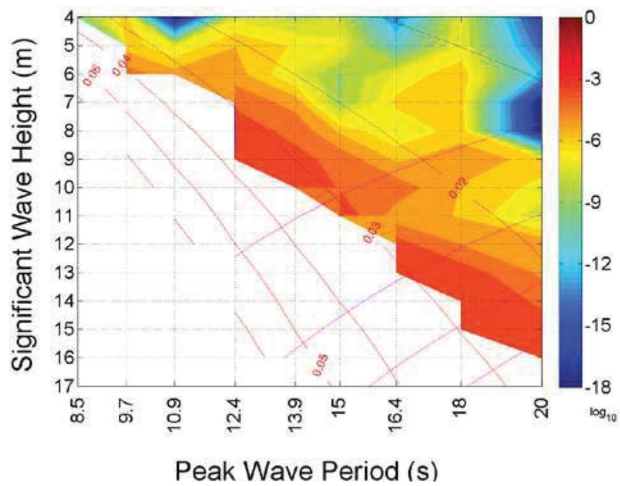

Figure 4. Maximum O(PECRA-VB) by Wave Height and Period – Phase 3 Load Condition 6.

3. SHIP GEOMETRY

The study looked at three forms of geometry:

1. A binary factor defining appendages
    a. Single vs double rudders
    b. Presence vs absence of skeg
    c. Presence vs absence of stabilizing fins
2. Dimensional geometry
3. Non-dimensional geometry

Scatter plots of TPECRA are used to investigate the effects of ship geometry.

3.1 Appendages

Within the set of ships simulated there are vessels with a skeg and/or fins, and some ships have a single rudder rather than twin rudders. The set of ships can be partitioned into groups having the various features:

Skeg Exclusively: ship(s) with skegs and double rudders, but no fins vs. all ships with a single rudder and/or fins and/or no skeg.

Fins Exclusively: ship(s) with fins and double rudders, but no skeg vs. all ships with a single rudder and/or a skeg and/or no fins.

Single Rudder Exclusively: ship(s) with a single rudder, but no skeg or fins vs all ships with a skeg and/or fins and/or double rudders.

Skeg Inclusive: ship(s) with skegs, with or without double rudders and/or fins vs. all ships without a skeg.

Fins Inclusive: ship(s) with fins, with or without double rudders and/or a skeg vs. all ships without fins.

Single Rudder Inclusive: ship(s) with a single rudder, with or without a skeg and/or fins vs. all ships with double rudders.

Skeg and Fins and Single Rudder: ship(s) with a skeg, fins, and double rudders vs. all ships not having all three features.

Other partitions are possible, but either the ship subsets already exist in the partitions above, or the ships used do not support them; i.e., one of the partitions is a null set and the other is the set of all ships.

Figure 5 shows a typical result. The filled markers in this figure indicate the load conditions of those ships with a single rudder only, but no fins, and no skeg, while the unfilled markers represent load conditions of all other ships. Although all the load conditions for the single-rudder ships are in one corner of the grouping, there is no definitive distinction between the filled and unfilled markers, at least in terms of the KG and O(TPECRA). Figure 6 shows that when ships with single rudders and fins or skegs are included, there is even less distinction. Figures 7 and 8 show the same thing when O(TPECRA) is plotted against the draft of the ship.

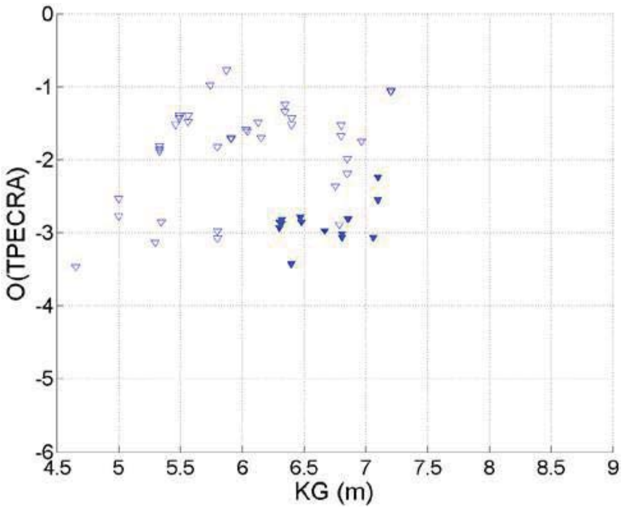

Figure 5. O(TPECRA) for each KG grouped by Single Rudder Exclusively (Phase 2).

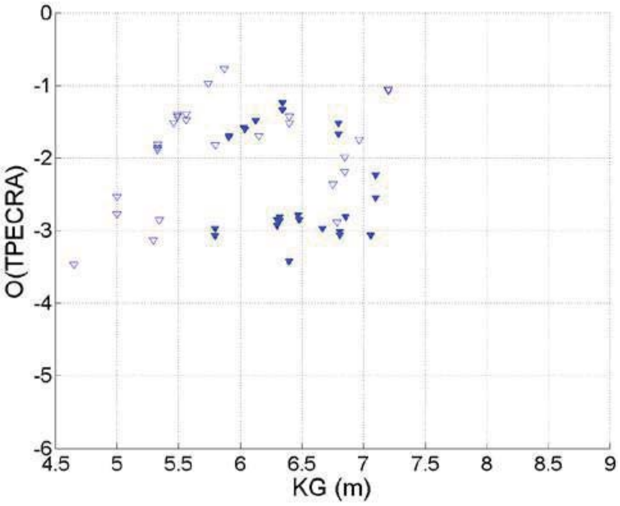

Figure 6. O(TPECRA) for each KG grouped by Single Rudder Inclusively (Phase 2).

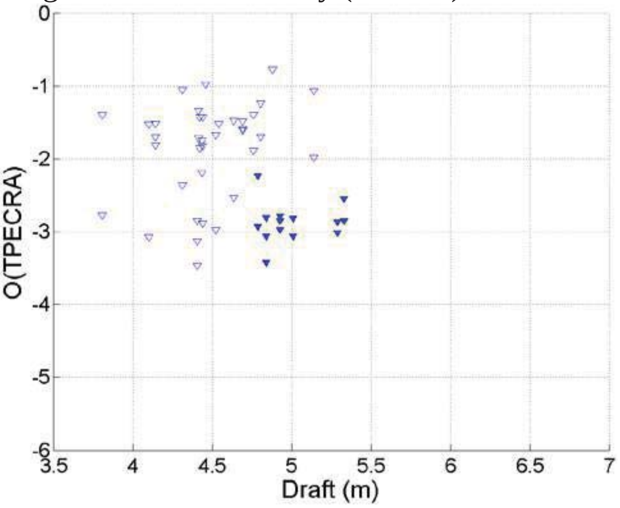

Figure 7. O(TPECRA) for each Draft grouped by Single Rudder Exclusively (Phase 2).

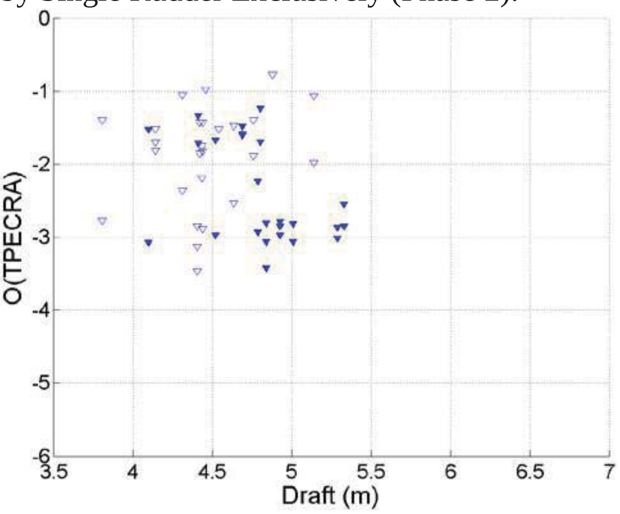

Figure 8. O(TPECRA) for each Draft grouped by Single Rudder Inclusively (Phase 2).

3.2 Dimensional Geometry

Dimensional measures of lengths, areas, and volumes were also examined to find any trends in the probability data. For some typical measures it is possible to look at the fore-aft differences as well.

LWL:	Length along waterline[2], L_{WL}.
BMSWL:	Beam at midships on the waterline.
BmaxWL:	Maximum beam on the waterline[3]
TMS:	Draft at midships.
AMS:	Area of the (immersed) midship section.
AWP:	Area of the waterplane.
VDisp:	Volume of displacement, ∇.

The length (LWL), waterplane area (AWP) and volume of displacement (VDisp) can be examined for fore-aft variations. The following postscripts are added to distinguish each case:

FWDMS/AFTMS:	Forward/aft of midships.
FWDLCF/AFTLCF:	Forward/aft of the center of flotation.
FWDLCB/AFTLCB:	Forward/aft of the center of buoyancy.

Midships (MS) represents a division in two based on ship length; the longitudinal center of floatation (LCF) represents division on the basis of waterplane area; and the longitudinal center of buoyancy (LCB) represents a division in two on the basis of volume.

The relationships between dimensional geometry (lengths, areas, volumes) are very similar to those for non-dimensional geometry, with lengths behaving like the ratios and

[2] The waterline is at the draft associated with the specific load condition, which is not necessarily the design draft.
[3] Because the maximum beam typically exists for some distance along the length of a ship, rather than only at a single, specific point, it is not suitable for dividing the ship into clear fore and aft parts.

coefficients in Figures 9 through 12, and areas and volumes more like Figure 13.

3.3 Non-Dimensional Geometry

Non-dimensional measures are ratios of dimensional measures, including classical form coefficients.

LWLoverTMS: Length to draft ratio.
LWLoverBMSWL: Length to beam ratio.
BMSWLoverTMS: Beam to draft ratio.
CM: Midship coefficient AMS/(BMSWL*TMS).
CW: Waterplane coefficient AWP/(LWL*BMSWL).
CB: Block coefficient Vdisp/(LWL*BMSWL*TMS).
CLP: (Longitudinal) prismatic coefficient Vdisp/(AMS*LWL) = CB/CM.
CVP: Vertical prismatic coefficient Vdisp/(AWP*TMS = CB/CW.

Length over beam, length over draft, the waterplane area coefficient, the block coefficient, and both prismatic coefficients allow for fore-aft versions, which are delineated by the same suffixes as the dimensional measures.

The O(TPECRA) was plotted against each of the geometry parameters to look for obvious trends. Figure 9 shows both forms of the typical results. On the left, the L/B ratios are tight-banded, while the more wide-banded data are like those of the B/T data on the right. None of the geometry parameters show a trend with the O(TPECRA); they were all vertical bands like those in Figure 9.

Figure 10 shows that the most common form coefficients do not have a meaningful relationship with O(TPECRA) either.

Figure 11 and Figure 12 show the situation is not changed by splitting the coefficients into fore and aft measures at midships (equal length halves). The results for division at the LCF (equal area halves) and the LCB (equal volume halves) show the same (lack of) trend.

Finally the freeboard is examined via the volume of reserve of buoyancy in Figure 13. It does not show any clear trend with O(TPECRA) either.

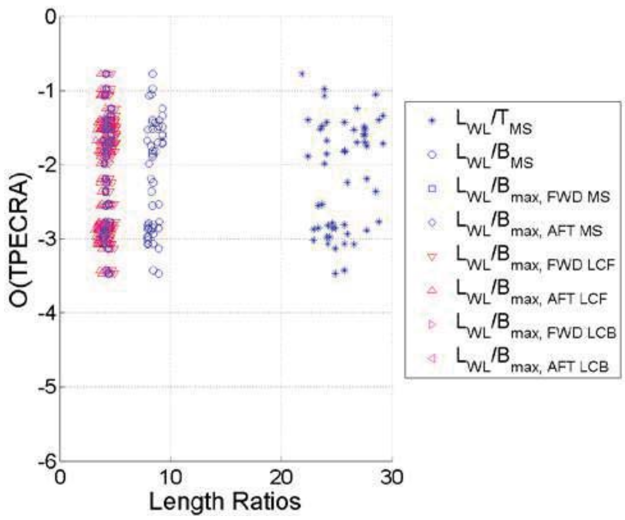

Figure 9. O(TPECRA) vs. Non-Dimensional Length (Beam) Ratios

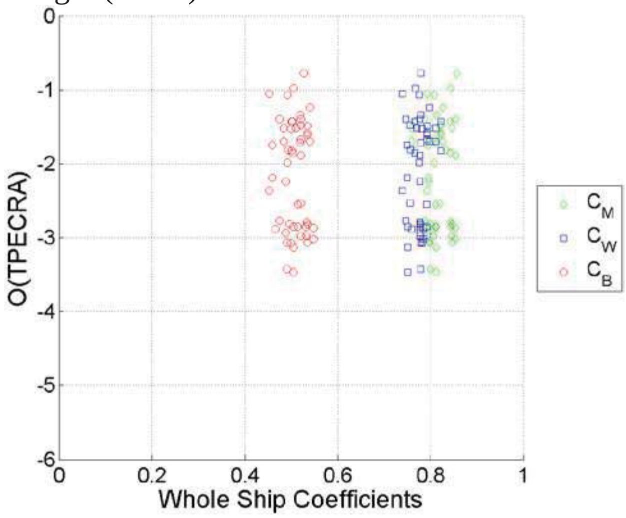

Figure 10. O(TPECRA) vs. Coefficients of Form for the Ship as a Whole.

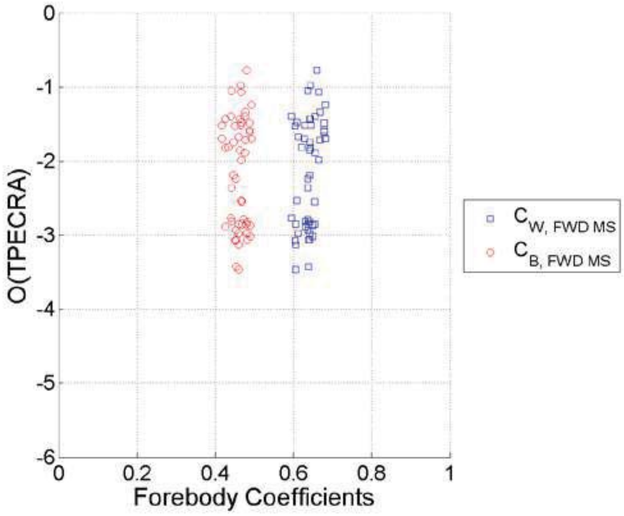

Figure 11. O(TPECRA) vs. Coefficients of Form for the Fore Body.

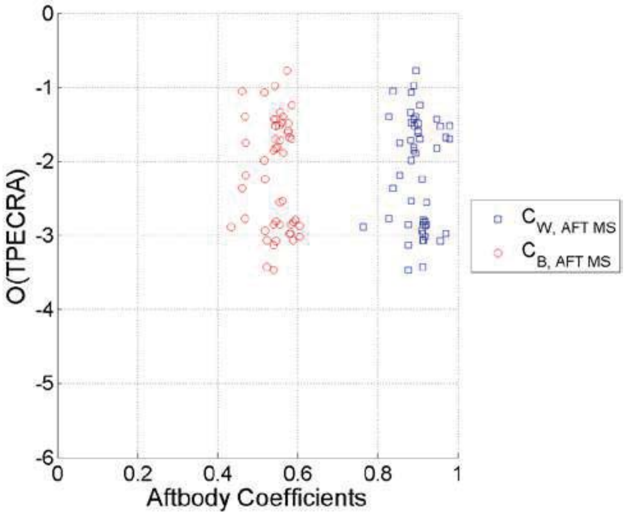

Figure 12. O(TPECRA) vs. Coefficients of Form for the Aft Body.

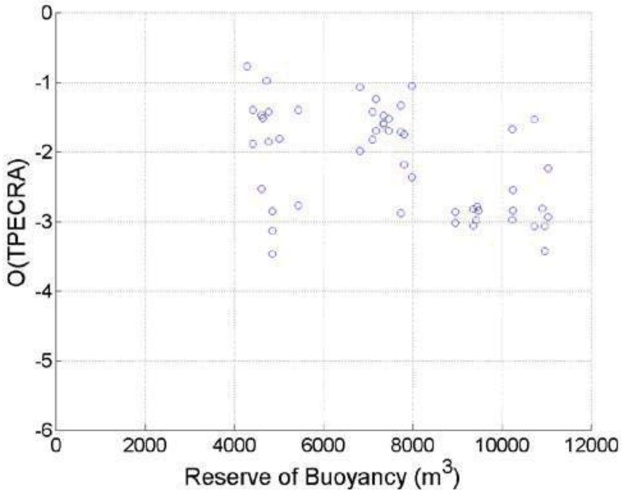

Figure 13. O(TPECRA) vs. Volume Reserve of Buoyancy

4. LOADING CONDITIONS, OPERATING POINTS, AND ENVIRONMENTAL CONDITIONS

In Phases 1 and 2, the loading conditions were picked such that for each ship at least four T-KG combinations constituted a matrix where two KG were simulated at two (or more) values of draft. This was not the case in Phase 3.

Contour plots over environmental conditions have been generated where the order of magnitude of the highest PECRA for all speeds and headings are shown for each height-period combination. For example, see Figure 14. Note that these plots show maxima results rather than marginal summations. Examination of contour plots for each loading condition of a ship will show that there can be a wide variation in the TPECRA for different loading conditions. Typically the effect of change in KG is more pronounced than that of a change in draft; however, this is not always true. Arguably, the expected outcome within each matrix is that the combination of the highest T and lowest KG would have the least O(PECRA), while the lowest T and the highest KG would have the greatest O(PECRA), with the other two combinations between the two extremes. Out of 8 ships, only 2 showed the expected outcome.

Contour plots over operating points were also generated where the order of magnitude of the highest PECRA for all heights and periods are shown for each speed-heading combination. Out of 8 ships, only 1 ship shows the expected outcome described above. These results indicate that the relationship between O(PECRA) and the draft and KG is complex and likely is affected by other factors, including the environmental conditions and the ship operating point.

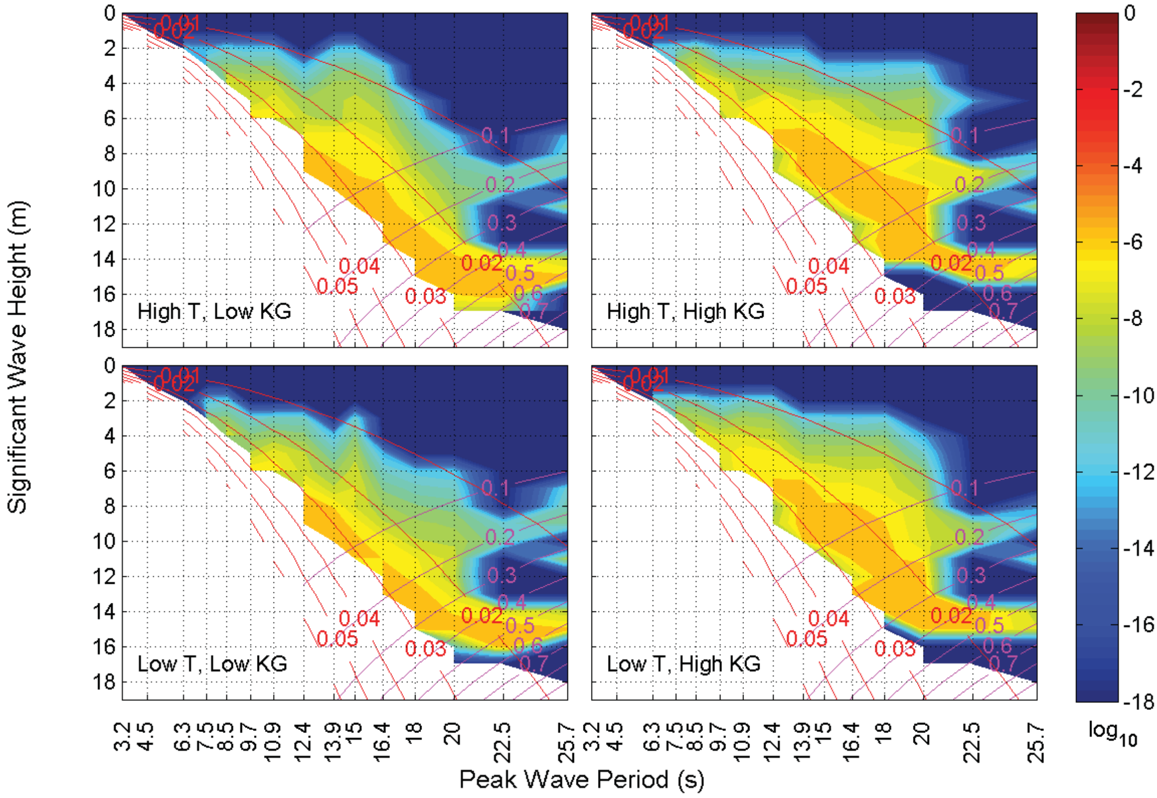

Figure 14. Typical Set of Environmental Relationships for Matrix of Load Conditions.

5. RANGE AND RESOLUTION OF INPUT CONTROL VARIABLES

The amount of data generated for each ship loading condition is sizeable, such that it is an onerous task to examine it all. It would be useful to reduce the number of conditions/points that need to be simulated. On the other hand, it is necessary to ensure that a sufficient number of conditions/points are simulated that an accurate characterization of the ship's behaviour is captured.

The idea of reduced data sets suggests that fewer simulations can be run to obtain the needed results. This was in fact practiced for the Phase 3 study, based on an educated guess of the new ranges of ship speed, and wave height and period. The question naturally arises as to whether or not the guess is reasonable, and further, how far the variable ranges can be reduced before the characterization of extreme roll probability is significantly affected.

Before either of these questions can be answered "significant" must be quantified. As stated above, when dealing with probabilities it is reasonable to speak in terms of orders of magnitude, and "significantly affected" can be thought of in terms of the difference between the order of magnitude of the sum of probabilities (TPECRA) for the reduced range and that for the full range. Five levels of significance have been examined in this study: 0.01, 0.05, 0.1, 0.5, and 1.0. These values represent approximately 2%, 12%, 26%, 300%, and 1000% changes respectively. The first level is very demanding, while the last level allows a 10x difference, and should be considered to be at or near the limit of acceptable difference, and in some cases may be too much of a difference.

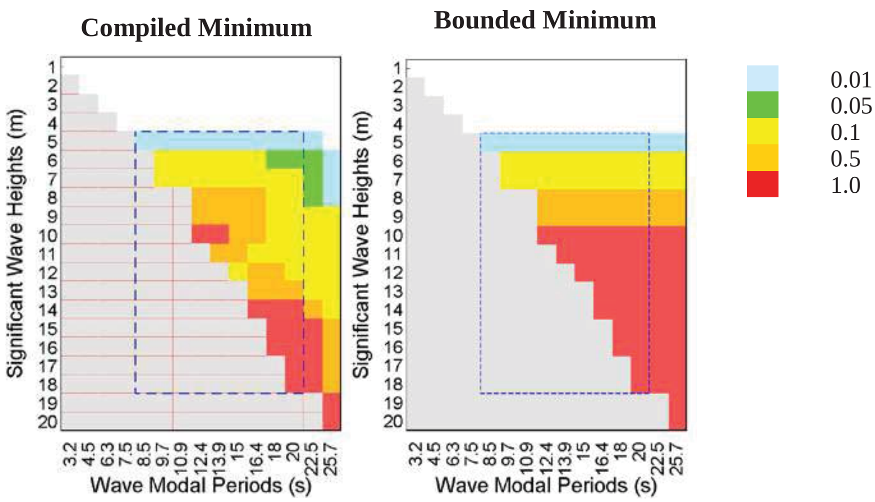

Figure 15. Minimum ranges of Wave Height and Period.

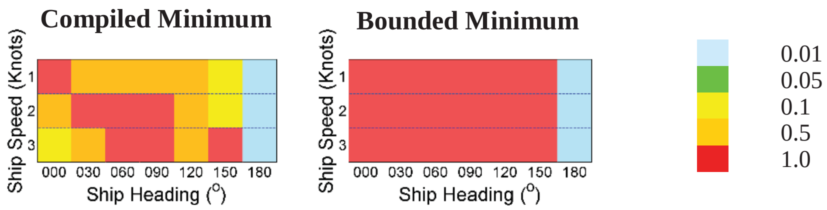

Figure 16. Minimum ranges of Ship Speeds and Headings.

The effect of reducing the range of the variables was investigated via a set of systematic reductions of the marginal sums over every possible range of the input control variables, leading to range-specific PECRA (RPECRA).

Figure 15 shows a compilation of results of the minimum-height-period-range search for all ship load conditions in Phase 2. The figure shows two wave height-period tables, each with all the possible wave conditions as non-greyed-out cells. The left-hand table shows the actual compilation of ranges; i.e., the minimum required range of environmental conditions for each load condition of all ships is included in the same figure, with the ranges corresponding to the less demanding levels of significance overlaid on the more demanding levels. Each level of significance is depicted in a different colour, with blue as the most demanding level and red as the least demanding level; the blue cells show the ranges of conditions required to provide a probability of exceeding the critical roll angle with an order of magnitude within 0.01, while the green cells represent a difference in the order of magnitudes of 0.05, the yellow cells a difference of 0.1 order of magnitude, the orange cells represent a difference in the order of magnitudes of 0.5, and the red cells a difference of 1 order of magnitude. The right-hand side shows the single contiguous range for each level needed to capture all the individual load condition ranges indicated in the left-hand side. These contiguous ranges represent the number of simulations that would be required if there was no prior knowledge of the individual constituent ranges. The blue dashed lines indicate the range of speeds and headings in the P3E (reduced) set.

Figure 15 shows that as the margin of difference is reduced, the ranges of conditions must increase. It also indicates that, based on the compilation of results from all ship load conditions, the range of wave heights go from 4 to 20 m and the range of wave periods is from 8.5 to 25.7 s to ensure that extreme roll probability is within 0.01 order of magnitude of the full-table value. The range of wave heights go from 10 to 20 m and the range of wave periods is from 12.4 to 25.7 s to ensure that extreme roll probability is within 1 order of magnitude of the full-table value.

Figure 16 shows a compilation of results of the minimum-speed-heading-range search. At the 0.01 level of significance, the whole range of speeds and headings are necessary, while at levels of significance of 0.05 and greater all speeds and most headings are still required. Note that a heading of 0° represents the ship in following seas.

Figures 15 and 16 indicate that the Phase 3 range reductions are somewhat reasonable in terms of wave height and period, but are not appropriate for ship speed. The results in Figures 15 and 16 do not necessarily reflect the characteristics of the individual ships used in the compilation.

Table 1 summarizes the check on the validity of reducing the ranges of ship speeds and wave heights and periods as done in Phase 3. The table shows that the reduction in wave conditions will still give results within half an order of magnitude of the full table, for most ships. However, reducing the range of speeds will lead to a difference in extreme roll probability of up to an order of magnitude for most ships, and greater for some ships.

Table 1. Adequacy of Phase 2 data when ranges reduced to those of Phase 3.

	Reduced Environmental Profile			Reduced Operational Profile		
	0.1	0.5	1.0	0.1	0.5	1.0
Ship A	✗	✓	✓	✗	✗	✓
Ship B	✗	✓	✓	✗	✗	✓
Ship C	✗	✓	✓	✗	✗	✓
Ship D	✓	✓	✓	✗	✗	✓
Ship E	✗	✓	✓	✗	✗	✓
Ship F	✗	✓	✓	✗	✗	✓
Ship G	✗	✗	✗	✗	✗	✗
Ship H	✗	✓	✓	✗	✗	✓

The ranges of environmental conditions and operating points are not the only determining factors for ensuring coverage of the phenomena that accurately characterizes the ship behaviour. The number of simulations required is also dependent on the resolution of the environmental condition and operating point sets. The resolution for the operating points was arbitrarily assigned by the NSSWG. The resolution of the environmental conditions is that of the Bales scattergram.

Figure 17 is an example of a Phase 2 contour plot over environmental conditions. Figure 18 shows the data cropped to the Phase-3-Equivalent range of wave headings and periods; that is, all the data is available but the axes scales are reduced to show only the ranges similar to the Phase 3 plots. Figure 19 shows the same data set when only the data from the heights and periods that are common to Phase 3 are kept. Figure 19 is different from Figure 18, indicating that the range and resolution of the data affects the plot. If the resolution were sufficient, the plots would be similar. Essentially, the contours are being affected by "far field" values. Better resolution would make it more difficult for the "far field" to affect the results.

6. OPERATIONAL OVERLAYS

Advice to the designer or operator would have to take into account the probabilities of being at each loading condition, operating point, and in each environment.

For the sake of the current work however, because summation across input variables required the use of probability distributions, the probabilities for the operating points and environmental conditions were taken as uniformly distributed over the ranges employed, while the probability of the load condition has not been considered. This was done to avoid obscuring relationships between the conditional probabilities and the conditions.

Naval Administrations can replace the uniform distributions with distributions more representative of their own particular pattern of use for the vessel. The replacement may require some interpolation. Any extrapolation must be limited to values very near the original data.

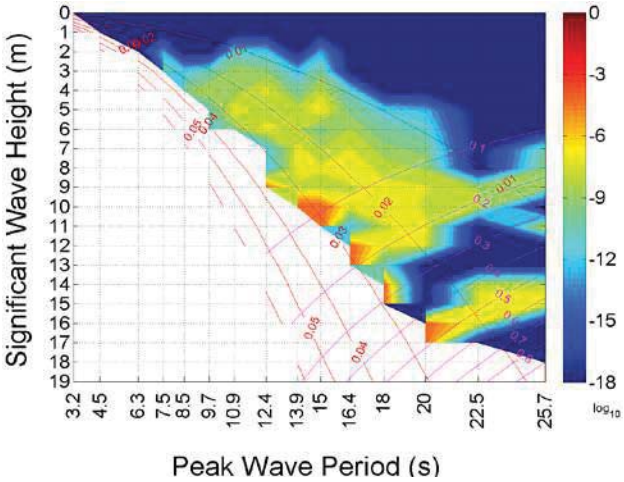

Figure 17. O(MPECRA-VB) by Wave Height and Period in Phase 2 Load Condition 6 (Full Range of Height and Period).

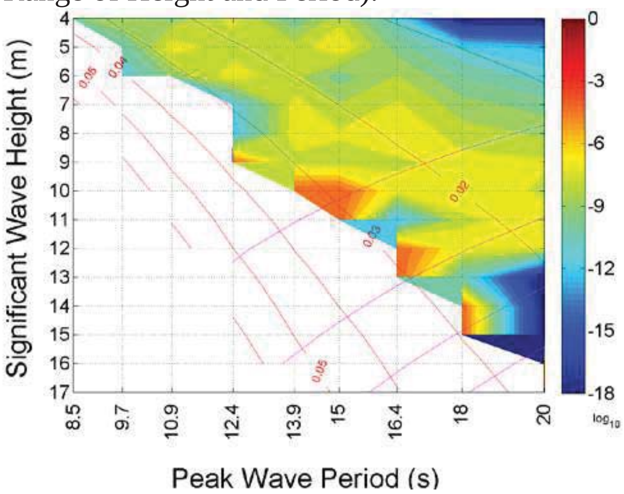

Figure 18. O(MPECRA-VB) by Wave Height and Period in Phase 2 Load Condition 6 (Full Range of Height and Period Cropped).

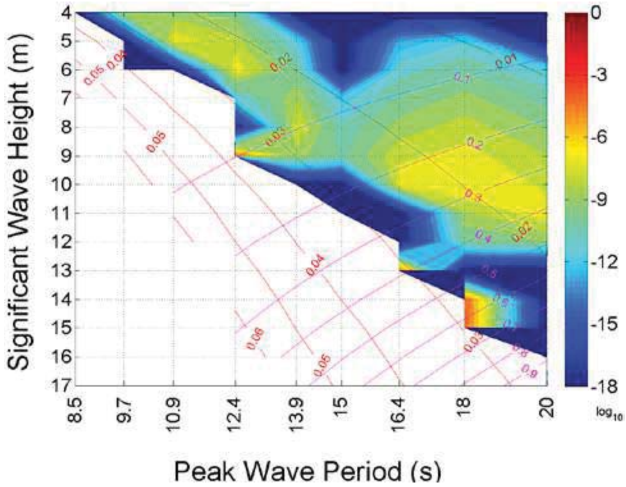

Figure 19. O(MPECRA-VB) by Wave Height and Period in Phase 2 Load Condition 6 (Phase 3 Equivalent Range of Height and Period).

For the main work of regression against stability parameters, the ships were assumed to be equally likely to take on any heading relative to the waves, but a generic 3-speed profile based on experience was agreed on and used (Phases 1 and 2; reduced to the most common speed for Phase 3). Further, the Bales' scattergram for the North Atlantic (see Bales, Lee, and Voelker [1981]) as modified by McTaggart and De Kat [2000] was used as the joint probability distribution of wave heights and periods.

Other options for operational overlays include the capability to use different wave height-and/or wave period distributions (e.g., the North Pacific scattergram) with the same underlying PECRA (via interpolation), and the ability to rule out certain environmental conditions based on restrictions due to design or change of vessel state. Operational overlays may also be used to account for operator influence, such as voluntary speed reductions and course changes in more severe seas.

7. CONCLUSIONS

This study has looked at probability data generated to investigate relationship between the probability of exceeding a critical roll angle (PECRA) and ship form and stability parameters. The probabilities were produced for several ships at a number of loading conditions, and for a standard set of operating points (speeds and headings) and environmental conditions (wave heights and periods).

Similar simulations were run for each of 3 phases which each had a different goal. There are notable differences in the results between the 3 phases of the intact stability project. Unfortunately, because of the number of changes in modelling capabilities and choices between the phases, it is not possible to attribute the changes to specific choices.

Within each phase, a careful examination of the probabilities for each ship did not provide any clear patterns related to the typical appendages, or due to geometric parameters, whether expressed in dimensional or non-dimensional form. However, the set of ships used represents a relatively small sample of closely related hull forms with similar features, and it is possible that a larger sample, using more divergent ship types may identify relationships between PECRA and geometry.

When differences between loading conditions for each ship were studied, there was clear evidence of the expected variation due to draft and, more strongly, vertical center of gravity, but these expected variations were not observed in all cases. This suggests greater complexity, and perhaps the influence of other factors. More investigation is warranted.

The study did not investigate the data at the level of each combination of control input variables, because the number of combinations is essentially too large to manually observe. Instead, marginal sums and maxima over operating points and/or environmental conditions provided the basis of analysis. It is possible that there may be some method to examine the large data set, but it is thought that such an investigation would be more suitable when a specific behaviour or anomaly is in view. It was noted that the O(PECRA) contours tended to align with wave steepness, indicating that future work with wave steepness and energy is needed.

The question of how to efficiently and accurately characterize PECRA was addressed by looking at the range and resolution pf the input control variables. It was found that the environmental conditions might be reduced in range, but probably need to be increased in resolution. It was also found that the both the range and resolution of the operating points may need to be increased, particularly in terms of the range of speeds. Further investigation is required.

Finally, the utility of Operational Overlays was introduced as a means of extending usefulness of underlying probability data for all users, from the designer to the operator.

8. REFERENCES

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