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RANKING OF SAILING ROUTES ACCORDING TO THE POTENTIAL NUMBER OF GROUNDINGS

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Abstract. The paper presents the selection of ship sailing routes in the coastal area according to the probability of grounding. Taking into consideration the dangers in the heading direction as well as the vicinity and length of the coastline parallel to the ship course, the paper will try to propose a model for choosing the sailing route with the smallest possibility of grounding. The estimation of the dangers on the routes will be based on the potential number of groundings; human factor will not be taken into account, assuming that a human error on each route will have the same probability of occurrence.

Keywords: ship; route; potential number of groundings; selection of sailing route; coastal navigation.

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Introduction

One of the most common causes of ship accidents is grounding. Groundings account for 18% of the total number of ship losses (World Casualty Statistics 2007). Also, groundings cause 35% of incidents with large oil spills (>7000 tons) (Causes of Spills 2010). Taking into account the proportion of groundings in the total number of all accidents, this percentage is even higher, especially in the areas with rugged coastline and relatively high traffic volume. The Adriatic Sea is such an example, especially its eastern coast (Fig. 1).

The largest number of groundings along the eastern coast of the Adriatic refers to smaller ships passing through the narrow passages between islands and between islands and the shore line. A significant number of large vessel groundings is caused by ships sailing to or from the main ports of the Eastern Adriatic and by those using coastal transit routes (longitudinal routes parallel to the coastline) (Fig. 2). Especially risky routes are those featuring dangers in heading direction and with small distance between planned wheel over position and the danger.

Most of these potentially dangerous routes lie within 10 nm of the coastline, while ships in the local traffic or those directed toward the Croatian ports often use routes within 5 nm of the coastline.

An analysis of plotting courses in coastal navigation by masters and officers onboard ships confirms almost the same. About 30% of them would plot courses within 5 nm from the coastline, just to shorten the time of travel (Lušić, Kos 2010).

In risk analysis of ship accidents, especially collisions, groundings (include grounding [impact with individual shoals and islands in the fairway], and strandings [impact with the coastline] (Kristiansen 2005)), in addition to statistical methods there are methods that are based on the calculation of the actual number of accidents from their potential number. The potential number of accidents over a time interval is the number that defines the frequency of dangers which may result in an accident if the crew does not intervene. At the basic level, the potential number of accidents, such as groundings, can be equated with the geometric probability, for example, ratio of the width of the danger and width of the fairway. The total number of groundings can be obtained from the product of the number of potential groundings and causation probability, i.e. ratio between ship groundings and situations when ship

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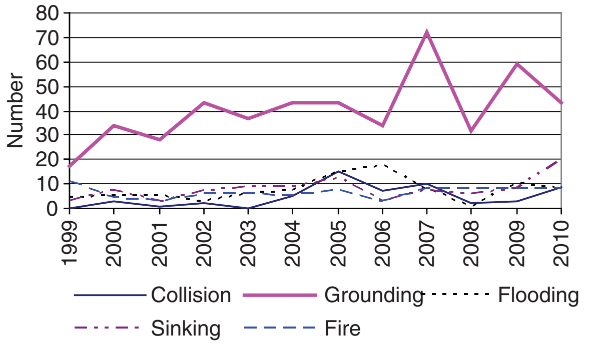

Fig. 1. Five main causes of ship accidents on the east coast of the Adriatic (Statistički Podaci SAR 2010)

is on a grounding course – models based on the researches carried out by Fujii (Oshima, Fujii 1974; Fujii *et al*. 1974; Fujii 1974; Fujii, Yamanouchi 1974) and Macduff (1974), see also researches carried out later by Friis-Hansen (2000), Friis-Hansen, Simonsen (2002) and Mazaheri 2009). In order to quantitatively determine the degree of danger of groundings on two or more alternative sailing routes between two ports (points), it should be sufficient to determine the potential number of groundings. Also it can be assumed that the expected error of the crew will be identical, and this eventually means that it is enough to compare the potential risks in order to select the safest sailing route.

The model in this paper, used for comparing sailing routes with regard to the possibility of groundings, will be based on the calculation of the potential number of groundings. Also, the model will take into account the following: the dangers related to the width on a sailing route, the distance to the danger in the direction of the course from the point of turning, and the length of sailing along the coast and the distance to the coast. The proposed model does not take into account oceanographic or meteorological factors and other external factors affecting the choice of sailing routes. Likewise, the model does not apply to maneuvering.

1. Potential number of groundings

The potential number of groundings may be based on (Simonsen 1997):

I. An assumed geometric distribution of the ship traffic over the waterway. If ships follow the ordinary, direct route at normal speed, accidents in this category are mainly due to human error or unexpected problems that occur in the vicinity of a fixed marine structure or shoal:

$$N_{(\mathrm{I})} = \sum_i P_{ci} \cdot Q_i \cdot \int_{z\,\min}^{z\,\max} f(z_i)dz_i, \tag{1}$$

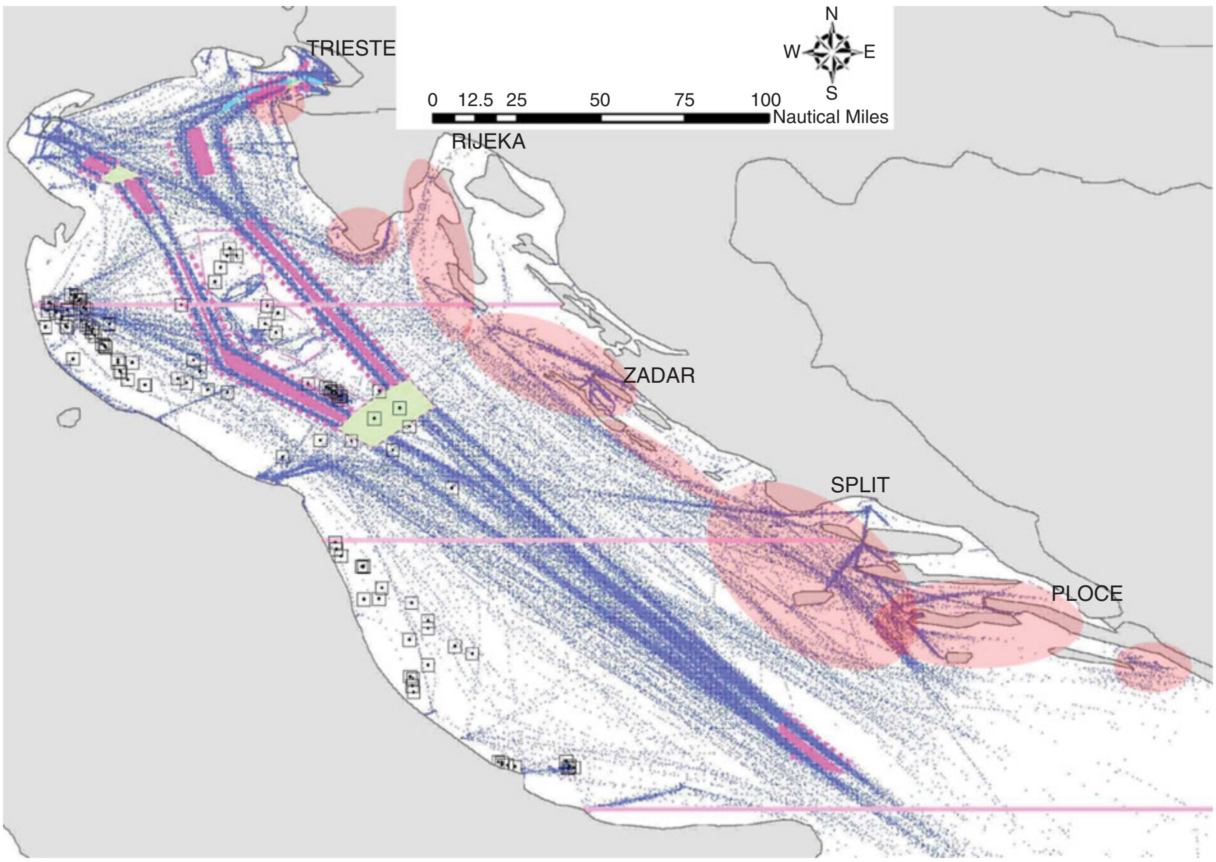

Fig. 2. AIS vessel plotting (2009) and areas of increased grounding risk, Adriatic Sea-Eastern part (Lušić *et al*. 2011)

where: $N_{(I)}$ – expected number of category I grounding events over a unit of time (because of the course overlapping with a danger); P_{ci} – causation probability, i.e. ratio between ships grounding and ships on grounding course; i – index for ship class; $f(z_i)$ – density function of the ship traffic in the transverse axis of the waterway; Q_i – number of ships in class i passing across the observed section of the route in a unit of time; z_{min}, z_{max} – transverse coordinates for an obstacle.

II. Ships that fail to alter their course at a given turning point near the obstacle:

$$N_{(II)} = \sum_i P_{ci} \cdot Q_i \cdot e^{-\frac{d}{a_i}} \cdot \int_{z\,min}^{z\,max} f(z_i)dz_i, \quad (2)$$

where: $N_{(II)}$ – expected number of category II grounding events in a unit of time, as a function of the number and position of the turning points; a_i – average distance between position checks by the navigator; d – distance from the obstacle to the bend in the navigation route.

III. Ships that take evasive action in the vicinity of the obstacle and, as a result, collide with a structure or ground on the shoal:

$$N_{(III)} = Q_i \cdot P'_{ci}, \quad (3)$$

where: $N_{(III)}$ – expected number of category III grounding events over a unit of time, as a result of taking evasive action near the obstacle; P'_{ci} – causation probability.

IV. All others situations that cannot be categorized under I, II, or III:

$$N_{(IV)} = Q_i \cdot P''_{ci}, \quad (4)$$

where: $N_{(IV)}$ – expected number of category IV grounding events in a unit of time; P_{ci} – causation probability.

Total expected number of groundings over a unit of time:

$$Ng = N_{(I)} + N_{(II)} + N_{(III)} + N_{(IV)}. \quad (5)$$

In the presented model for calculating the potential number of groundings, the impact of vicinity of the coastline parallel to the course is not taken into consideration. Other authors have similar approach to this problem (Mazaheri, Ylitalo 2010), i.e. they do not take into account the impact of proximity of the coastline parallel to the course on the potential number of groundings. A model which partially takes into account the danger of proximity of the coastline parallel to the course is presented by Kristiansen (2005):

$$P_i \approx 1 - \frac{2}{\pi} \cdot \frac{W}{D},$$

where: W – width of of the waterway; D – length of waterway.

Impact of proximity of the coastline parallel to the course is taken into calculation only within calculation of the volume of traffic passing too close to the coast in accordance with the transversal distribution of the ship traffic. However, in practice, a ship is never exactly on the ideal course, i.e. she tends to move to the left or the right side of the course when sailing between two positions so that there is a potential danger of impact with the coastline parallel to the course.

2. Potential number of groundings for courses parallel to the coastline

The potential danger of stranding in a limited waterway can be expressed as a relation of uncertainty area, defined by Dead Reckoning (DR) error and the available surface of waterway between two ships' positions. This relation can be described with the corresponding coefficient K_{ub} that will define the impact of the coastline vicinity on the potential number of groundings.

The fix expansion (Fig. 3) encompasses all the area in which the vessel could be located (as long as all sources of error are considered). All possible

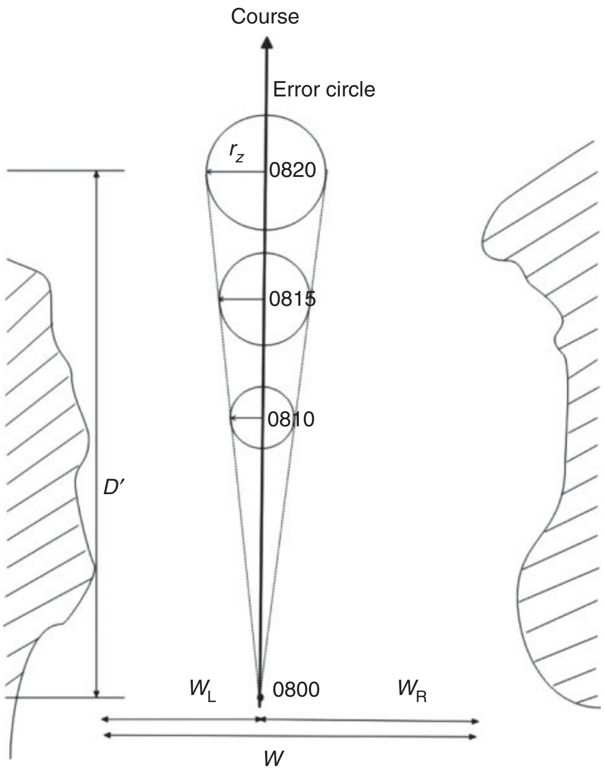

Fig. 3. Fix expansion and error circle around the DR plot

positions of the ship must lie between the lines tangent to the expanding circles (circle around the DR plot in which the vessel can be located).

Uncertainty area:

$$r_z \cdot v \cdot \Delta t = r_z \cdot D'.$$

Available surface of waterway between two ships' positions:

$$v \cdot \Delta t \cdot W = D' \cdot W.$$

K_{ub} for channel (course in the middle):

$$K_{ub} = \frac{r_z \cdot v \cdot \Delta t}{v \cdot \Delta t \cdot W} = \frac{r_z}{W}, \tag{6}$$

where: Δt – time between two ships' positions; v – speed of ship; W – width of the waterway; r_z – radius of circle around the DR plot in which the vessel can be located (error circle) ($r_z =$ approximately 5% of the distance between two positions in standard conditions of navigation (Benković *et al.* 1986). In addition to this error, for the purpose of determining the potential number of stranding, can be added the error of positioning, the beam of a ship, including the minimum size of the area for safe maneuvering. These errors can be expressed together as a maximal acceptable value of deviation from the course).

For sailing along one coastline, the area of uncertainty is one half of the area of uncertainty for a channel. Also, it can be assumed that probability of occurrence of the ship in this half is 50% (generally, the ship can deviate from the course to the port or starboard side).

Uncertainty area:

$$\frac{r_z \cdot v \cdot \Delta t}{2} \cdot \frac{1}{2}.$$

Available surface of waterway between two ship positions:

$$v \cdot \Delta t \cdot W.$$

Accordingly, K_{ub} for one coastline is:

$$K_{ub} = \frac{r_z}{4 \cdot W_L} \text{ or } K_{ub} = \frac{r_z}{4 \cdot W_R}. \tag{7}$$

For channel width W ($W = W_L + W_R$, where W_L and W_R are beams on the distance from the route to the left/right coast):

$$K_{ub} = \frac{r_z}{4 \cdot W_L} + \frac{r_z}{4 \cdot W_R} = \frac{r_z}{4} \cdot \left(\frac{1}{W_L} + \frac{1}{W_R} \right). \tag{8}$$

For $W_L = W_R = \frac{W}{2}$ (mid part of channel):

$$K_{ub} = \frac{r_z}{4 \cdot \frac{W}{2}} + \frac{r_z}{4 \cdot \frac{W}{2}} = \frac{r_z}{W}.$$

Suppose that a unit distance corresponds to the distance between two ships' positions (D'). It is assumed, when sailing along the coast, that the distance between the two positions corresponds to the length of travel along the danger, even though the length of travel along the danger may be less than the distance between the two positions. Also, suppose that the different unit distances D' are independent as each uncertainty ceases at the time of determining the position. The potential number of stranding Ng' in a channel having length $D = D'$ and traffic Q in a unit of time can be expressed as follows:

$$Ng' = \frac{r_z}{4} \cdot \left(\frac{1}{W_L} + \frac{1}{W_R} \right) \cdot Q. \tag{9}$$

For more ships of different class i, on the same course, with different r_z:

$$Ng' = \sum_i Q_i \cdot \frac{r_{zi}}{4} \cdot \left(\frac{1}{W_L} + \frac{1}{W_R} \right), \tag{10}$$

where: i – index for ship class; Q_i – number of ships in class i, in a unit of time; r_{zi} – radius of error circle, for ship class i.

For a ship in a channel of length D ($D > D'$):

$$Ng' = \sum_j \frac{r_{zj}}{4} \cdot \left(\frac{1}{W_{Lj}} + \frac{1}{W_{Rj}} \right), \tag{11}$$

where: j – index of the specific unit distance D', featuring different characteristics (W_{Lj} and W_{Rj}); r_{zj} – radius of error circle on the path D'; W_{Lj}, W_{Rj} – distance from the course to the left/right coast, on the path D'.

To obtain the actual number of groundings caused by Ng' one should take into account the causation probability, i.e. probability that the ship is outside the planned route and too close to the coastal line (danger) and that the person in charge does not choose an appropriate maneuver.

3. Method of calculation of potential groundings and its usefulness

The method of calculating the potential number of groundings is an alternative to standard statistical methods that are used for estimating the probability of ship groundings. Its main advantages, when compared to statistical methods, stem from linking the probability of groundings to the size of the area of navigation. Extending the existing models of calculation of potential groundings, by including the influence of coastline parallel to the ship's course, allows the navigational routes to be ranked according to spatial distribution of dangers. Each route can be observed and evaluated separately.

The safety degree of sailing routes can, therefore, be compared in accordance with the potential number of groundings. This means that it is necessary to be familiar with the proximity of dangers, traffic rate, types of ships, etc. The traffic rate is not only one of the key elements but also one of the elements that often remain unknown. Even so, it is possible to rank sailing routes with regard to the spatial distribution of dangers, the key elements being coefficient K_{ub} and expression $e^{(-d/a_i)}$ (in further text: coefficient K_{ik}). The sum of these elements for certain parts of the sailing route represents a part of total number of potential groundings. For two or more alternative routes (with the same starting and ending point) with unit (same) traffic this means: the higher sum of coefficient – the higher number of potential grounding.

Fig. 4 shows the changes of the coefficients K_{ub} and K_{ik} in the function of changes of the distance from the coast or the danger. Also, from Fig. 4, for selected examples, one can define critical distances within which the number of potential grounding begins to increase very rapidly. It is around 5 nm for courses parallel to the coastline and between 10 nm and 15 nm for dangers in heading direction (distance from a waypoint to the danger).

The following example will illustrate the influence of coastline parallel to the ship's course and the dangers in heading direction on the potential number of groundings.

It should be taken into account that this model is not suitable for the routes (or parts thereof) that are very close to the dangers, i.e. when navigation requires state of maneuvering. The main reason is impact of the causation probability, especially part caused by human errors. Accordingly, for the routes where navigation requires a state of maneuvering,

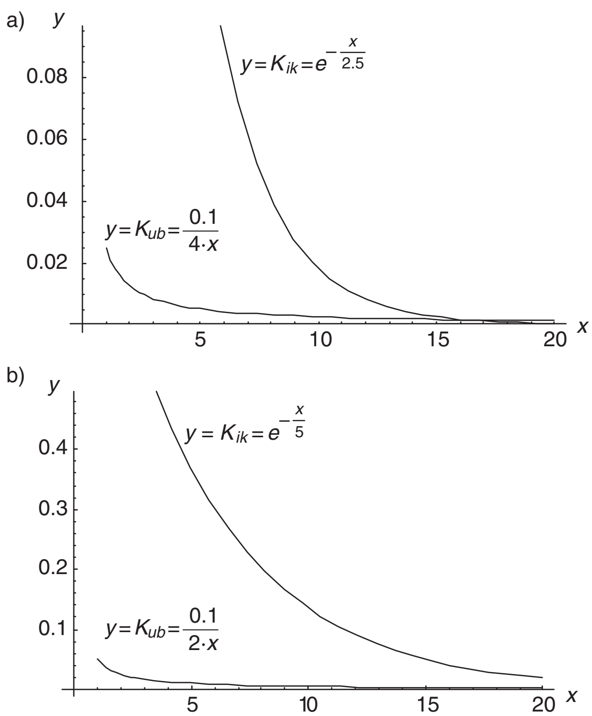

Fig. 4. Influence of coefficient K_{ub} and K_{ik} on potential number of groundings (x – distance to the coast in nm, $D = D'$): a – $r_z = 0.1$ nm, $a_i = 2.5$ nm; b – $r_z = 0.1$ nm, $a_i = 2.5$ nm

comparison of routes should be in accordance with the actual number of grounding, i.e. causation probability should be taken into consideration as well.

4. Example: ranking of two sailing routes as per potential number of groundings

Suppose that we want to compare two routes between two points, each route with the features according to the tables below (features: number and length of dangerous sectors, average distance to the coast/danger line – abeam to the course for each dangerous sector and distance to the coast/danger – from waypoint ahead) (Lušić 2010).

Expected speed of ship is 15 knots, positioning every 12 minutes.

The goal is to find a safer route, considering the possibility of grounding.

For all the above route parts: speed 15 kn, position every 12 min ($r_z = 0.038 \cdot D'$, $a_i = 3$ nm).

Route segmented as per dangerous parts, other parts (open sea) are not taken into consideration.

$K_{ub} = (D/D') \cdot r_z \cdot (1/4\,W_L + 1/4\,W_R)$ (from the expression 11 – if the all unit distances D' have the same features: W_L, W_R, r_z).

$$K_{ik} = e^{-(d/a_i)}.$$

Relations between the obtained sums should correspond to the relations of potential groundings.

According to the results (Tables 1 and 2) on the Route Number Two, the expected number of potential groundings is 2.6 times greater comparing to the route number one (for the same time between positions and unit traffic, also for the selected waypoints).

Conclusions

One of the key elements of passage planning and selecting the future ship route is the assessment of the safety degree on the waterway. Today, the assessment is largely based on the subjective assessment of the master who takes into account the spatial distribution of hazards, voyage distance, estimated travel costs, meteorological and oceanographic conditions, special cargo requirements, ship type and its maneuvering characteristics, etc. In most cases, the goal is to find the shortest route with a sufficient degree of safety. A more objective way to rank the sailing routes with regard to the spatial distribution of risk is provided by the models for calculating the potential number of groundings. The model proposed in this paper complements the existing models of calculation of potential number of groundings and introduces into calculation the influence of coastline parallel to the ship course, allowing the navigational routes to be ranked according to spatial distribution of dangers. The model is applicable to ranking of sailing routes because it can correlate

Table 1. Route I (257 nm)

Along the coastline		Dangerous sectors length (nm)	Coast ahead	
K_{ub}	Average distance to the coast/dangers line (nm) – abeam		K_{ik}	Distance to the coast (nm) – from waypoint ahead
0.0475 0.02262	10 (port) 7.0 (port), 3.0 (starb.)	50 5.0	– 0.13534	– 6
0.03166	6.0 (port.), 4.0 (starb.)	7.8	0.00047	23
0.04769	5.0 (starb.)	25.1	–	–
$\Sigma K_{ub} = 0.14947$			$\Sigma K_{ik} = 0.13581$	

Table 2. Route II (251 nm)

Along the coastline		Dangerous sectors length (nm)	Coast ahead	
K_{ub}	Average distance to the coast/dangers line (nm) – abeam		K_{ik}	Distance to the coast (nm) – from waypoint ahead
0.02794 0.005 0.01357	17 (port) 9.5 (starb.) 3.5 (starb.)	50 5 5	– – 0.05882	– – 8.5
0.05067	3.0 (port), 7.0 (starb)	11.2	0.22313	4.5
0.11671	4.0 (port), 2.5 (starb.)	18.9	–	–
0.03863	3.0 (starb.)	12.2	0.09697	7
0.0694	3.5 (port) 3.0 (starb.)	11.8	–	–
0.01425	2.0 (starb.)	3.0	0.03567	10
0.01767	5.0 (starb.)	9.3	–	–
$\Sigma K_{ub} = 0.335384$			$\Sigma K_{ik} = 0.41459$	

risks arising from the appropriate length of sailing along the coast (the line of danger) and the risk arising from changes in distance to the coast. On this basis, it is possible to objectively assess the risk of grounding. Also, the model can contribute to future improvement of electronic navigation systems (e.g. ECDIS, GPS, Chart plotters, etc.). These improvements are primarily related to additional highlighting of the dangers near the coast, improving the alarm systems, prevention of unnecessary approaching to the coast, and, ultimately, to automatic selection of routes.

It should be noted that the introduced model can be applied only to the comparison of similar sailing routes (alternative routes with small differences regarding distance, vicinity of coast, traffic, currents, etc.) due to the fact that it does not take into consideration human behavior, meteorological and oceanographic elements, and other external or internal factors affecting the selection of sailing routes. The impact of these elements can be subsequently estimated. However, this does not diminish the significance of the proposed model because the model assesses the risk of grounding on at a fundamental level.

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