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The Scheme of Re-floating a Grounded Vessel and Risk Analysis Based on M.V. EVER GIVEN

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Abstract: Ship grounding is a major maritime accident, and also the cause of ship capsizing, total loss, serious pollution and etc.. The harm caused by ship grounding is extremely serious, especially for those grounding case in canal or important channels. Some of the grounding cases have brought great impacts to the shipping allover the world. On 23 March 2021, Motor vessel EVER GIVEN, one of the largest container ships in the world with a length of 400 meters, a width of 59 meters, and a gross tonnage of 219,000 tons, ran aground when it was passing through the Suez Canal after its hull went off course, becoming an insurmountable wall across the narrow Suez Canal. The blockage of the Suez Canal, one of the world's most important shipping lanes, has left global supply chains "stuck in their throats" for more 6 days, and has brought huge influence to world shipping. This paper analyzes the concept of confined waters in terms of relative water depth and relative width, the main hazards of large ships navigating in confined waters, such as the impact on the maneuverability and under keel clearance of the vessel, the bank effects and so on. In this paper, we also analyze the main re-floating scheme against the background of the accident of the EVER GIVEN in the confined waters, and provide operational solutions to refloat the grounded vessels to give reference for navigators on board a ship and salvage operators in shipping industry.

Keywords: Ship, Grounding, Marine Salvage, Re-floating Scheme, Confined Waters, Risk Analysis

1. Introduction

Clogged arteries in the human body are an essential problem of life, just as "clogged arteries" in shipping are a disruption to cargo. Motor vessel EVER GIVEN, one of the largest cargo ships in the world with a length of 400 meters, a width of 59 meters, and a gross tonnage of 219,000 tons, ran aground on 23 March 2021 when it was passing through the Suez Canal after its hull went off course, becoming an insurmountable wall across the narrow Suez Canal. Following six days of emergency rescue, the EVER GIVEN was successfully floated on 29 March 2021 and the Suez Canal, a key passage, was finally restored to navigation. Ship grounding is a major maritime accident, and also the cause of ship capsizing, total loss, serious pollution and etc.. The harm caused by ship grounding is extremely serious, especially for those grounding case in canal or important channels. Some of the grounding cases have brought great impacts to the shipping allover the world. [1] Ship grounding/stranding events leading to significant losses are not rare. For another example, on March 6, 1978, the Liberian supertanker AMOCO CADIZ hit a reef due to damage of steering gear in The Waters off The Coast of Brithari, France, resulting in hull breaking, spilling 220,000 tons of crude oil and polluting the coast of France for 250km, resulting in direct economic losses of 300 million DOLLARS and incalculable indirect losses. What caused worldwide concern was the damage that the grounding cases such as EVER GIVEN, inflicted not only on the normal operation of the canal but also on the delays caused to other ships passing through the canal and huge amount of economic losses. As a result, the hazards of navigating large ships through confined waters and the option of re-floating are significant perspectives for every ship navigators. Based on above, this paper analyzes the concept of confined waters in terms of relative water depth and relative width, the main hazards of large ships navigating in confined waters, such as the impact on the maneuverability and under keel clearance of the vessel, the bank effects and so on. In this paper, the main re-floating scheme are also discussed against the background of the accident of the EVER GIVEN in the Suez Canal, and operational solutions to refloat the grounded vessels in confined waters are provided to give reference for navigators on board a ship and salvage operators in shipping industry.

2. The Definition of Confined Waters

Confined waters constitute a relative concept, primarily for ships of different drafts and widths. Water with relatively shallow water depths and narrow channel widths are referred to as confined waters, in which ships either lack the freedom to change direction and speed, and other operations, or suffer from restrictions on changing direction and speed [2]. In common cases, approach channels, narrow waterways, anchorages, narrow canals, bridge areas, etc. may become confined waters.

Vessel motion when operating in confined waters has phenomena and characteristics that differ from those of wide deep water, including shallow water effects and wall effects. Ships are often subject to both the shallow water effect and the sidewall effect, collectively referred to as the confined water effect (restricted water effect or confined water effect). No specific confined water method is prescribed, yet a few reference standards exist in the industry, mainly based on the depth and width of navigable waters. Hooft [3], a Dutch scholar, divided the confined water according to the effect of relative depth (H/D) on the resistance of the ship's hull as it moves forward, arguing that the low-speed ship when H/D≤4 and the high-speed ship when H/D≤10 can be considered shallow water, and when H/D≤2.5, they can be regarded as shallow water in terms of the influence of the current on the lateral movement of the ship [4].

Table 1. *The delineation criteria of relative water depth.*

Relative Water Depth (H - Height, D - Draft)	Definition of confined water
H/D ≥ 3	Deep Water
1.5 ≤ H/D < 3	Medium Water
1.2 ≤ H/D < 1.5	Shallow Water
H/D < 1.2	Very Shallow Water

The water width is usually judged by the ratio of the effective width W of the channel to the length L of the vessel, as shown in Table 2. The effective width W refers to the minimum width in the channel, not the width of the water visible to the driver's eye.

Table 2. *The delineation criteria of relative width.*

Relative Width (W–Effective Width, L- length of Vessel)	Definition of confined water
W/L ≤ 2	Narrow waters, Bank effects may occur
W/L ≤ 1	Confined waters have a clear impact on the maneuverability of ships

3. Major Hazards of Confined Waters

3.1. The Effect of Confined Water Depth on Vessel Handling

Ever Given had a draft of 15.7 m at the time of the accident and the section was approximately 25 m deep with a relative water depth of 1.59. Without considering the factors such as speed, displacement and external wind currents, the water was in an area of moderate depth and the vessel was actually in shallow water as the vessel was travelling at 13.5 kn [5].

3.1.1. Increment of Additional Mass of the Ship and Additional Moment of Inertia

A vessel's additional mass and additional moment of inertia increase as the relative water depth H/D decreases. Such increase is more pronounced when H/D ≤ 2, while the multiplication of this increase will increase sharply when H/D ≤ 1.5. Meanwhile, the wider the hull, the faster the ship, the greater the additional mass and the additional moment of inertia, which will lead to difficulties in accelerating the ship and slowing down what has been expedited in shallow water, consequently, large ships taking variable speed operation in narrow waters will be greatly restricted to take variable speed operating in confined water.

3.1.2. Increase in Wave-Making Resistance

Once a ship enters shallow water, the water becomes turbid and the first dispersion wave becomes smaller while the towing wave increases under the flow of the fish-directing propeller at the stern and on both sides of the ship. At the same time, the trailing flow is stronger, the difference in thrust between the upper and lower propeller blades is more pronounced than in deeper water, and hull vibration increases.

3.1.3. Increase in Hull Sinking

If the fluid is maintained and the summation of the static and dynamic pressures is constant, according to the principles of hydrodynamics, the dynamic pressure increases relatively as the static pressure decreases. In the idle state, all weight of ship is supported by the static pressure, when the dynamic pressure is zero, while in motion, the dynamic pressure increases and the static pressure decreases because of the acceleration of water flow around the ship, causing the ship to sink. In the meantime, there is a tilting of the ship due to the change in the distribution of water pressure at the bow and stern [6].

The sinkage and trim of hull in deep water mainly depends on the ship type and its speed. The test results indicated that larger ships have more drastic changes in hull sinking and trimming, meaning that the faster the ship is speeding, the more drastic the changes in hull sinking and trimming. The main factor affecting the amount of hull sinkage is the speed, which is usually measured by the dimensionless number of the ship speed, Froude Number $F_r = \frac{v}{\sqrt{gL}}$ where the ship hull starts to sink when $F_r \approx 0.06$. [7]

The hull sinkage and trim in shallow water is sharper than that in deep water. Except the factors of the ship type and speed, it is also related to the water depth in terms of the water depth Froude number Froude number $F_{rh} = \frac{v_s}{\sqrt{gH}}$. According to the data of EVER GIVEN, the number of ships is about 0.86 and the vessel sinks worse, with the stern sinking more than that of the bow.

3.1.4. Decrease in Vessel Speed

Ships sailing in shallow water have a space constrained current around their hull so that the current accelerates, the hull will sink, draft and trim will increase, leading to increased frictional resistance. At the same time, the ship's wave resistance and vortex resistance increase in shallow water and the enhancement of vortex near the propeller will lead to a decrease in propeller efficiency. All of the above factors will result in the ship speed in shallow water being lower than in deep water at the same speed.

3.1.5. Decrease in Vessel Maneuverability

Steerability of a ship in shallow water is significantly weakened, mainly due to a sharp increase in slew resistance in shallow water and a decrease in the maneuverability index K/T [8].

3.2. Effect of Restricted Width on Vessel Operation

When EVER GIVEN ran aground, the length of the vessel was 400m, the water width of the section was 291m, the submerged width of the hull keel position was 200m, the width of the river bottom was 130m, and the W/L ratio was less than 1, indicating that the water width had an obvious effect on the operation of the vessel.

With limited water width, when the ship yaws close to the channel shore wall, the ship is prone to Bank effect, such as the whole ship being sucked towards the shore wall (Repulsion) while the bow turns towards the center of the channel (Suction or Attraction) due to the different hydrodynamic forces on both sides of the ship [9].

4. Methods of Re-floating a Grounded Vessel

Typically, with different measures, several re-floating methods are available, which can be divided into two main categories: self re-floating and external assistance re-floating. Different re-floating ways have their own characteristics and risks during operation. Generally speaking, for minor level groundings, a single solution is sufficient to refloat a vessel for minor horizontal groundings, while for severe and complex level groundings, such as the "Ever Given", multiple viable solutions need to be properly implemented in order to successfully refloat the vessel [10].

4.1. Develop a Re-floating Plan

Development of a refloat plan after a ship has run aground should be a top priority, regardless of the method used, and should be based on a full assessment of the ship's grounding condition, the surrounding environment and available rescue forces, and a strict control of all risks during the implementation of the plan to prevent further escalation of the incident.

In general, the factors that should be fully considered in developing a ship re-floating plan include:

(1) Basic information and circumstances of the aground ship, including the name, scale of ship, hydrostatic data, aground position, etc.

(2) Technical calculations include seabed forces, required re-floating forces, horizontal position of the ship's center of gravity, stability after stranding and re-floating, hull structure, damage areas, strength contact and tie-down points, overview of the fundamentals involved in selecting special outlets and floating techniques based on reliable re-floating practices. Hydrographic information including detailed data collected during hydrographic surveys to provide hazardous waters, bearings, areas and other nautical information for vessels and rubber vessels engaged in re-floating, including measures such as marking isolated hazards, setting tide gauges, setting nautical waters. [11]

(3) The impact of potential pollution control technologies, and the resource and pollution control on re-floating.

(4) Safety inspection results and recommendations of the person in charge of safety, detailing the special hazards identified and listing safety precautions.

4.2. Self Re-floating

This mainly includes tide-waiting method, shift-load method, discharge-load method, etc.

4.2.1. Tide-Waiting Method

If the time of grounding is not during high tide, and the damage assessment indicates that the ship will not deflect, sink or capsize, and there is sufficient water area and depth, the combination of main engine, rudder and anchor can be used to refloat at the next high tide, where the general practice is to use the main engine an hour before high tide and use the ship's main engine to reverse for re-floating. If full speed reversing is ineffective, combine with port and starboard full rudder swing the hull half an hour in advance and then carry out fast reversing the main engine back, or make full use of the strong grip of the anchor to help back to float. In the case of a muddy bottom substrate, attention should be paid to the buildup around the hull when reversing so as not to affect the capsize [12]. The tide height of "Ever Given" was the 1.56m, which was the high tide level of the day, but not the high tide period of the month. The tide height on 30th March was 2.14m, which provided a strong condition for the ship to come out of the water smoothly at the later stage of the accident.

Implementation risks and precautions for the combination of main engine, rudder and anchor in waiting tide re-floating.

1) When faced with the problem that the ship's sea chest may be blocked, it should be switched to a higher level sea chest to ensure normal operation of machinery and equipment.
2) When attempting self-reverse re-floating a vessel, the area of water behind of the vessel should be large enough to prevent the ship from sliding to the other side of the channel after re-floating and causing secondary grounding.
3) To take advantage of the minimum sea bed at high tide friction, the backing force of the main engine and anchor should be gradually increased to reach to the maximum 2 hours before high tide and maintain that backing force until the ship is pulled out of shallow water or when the tide starts to fall.

4.2.2. Shift-Load Method

Re-floating can be performed by internal transfer of ballast water, fresh water, fuel oil or cargo when the ship runs aground at one end or on the port or starboard side and there is sufficient water at the other end or on the other side. This requires an assessment of the stability and strength of the ship, otherwise, if transferred improperly, it may result in capsizing or making the ship break apart.

4.2.3. Discharge-Load Method

The principle of quick, easy and minimal damage should be considered when, after estimating and adjusting the trim, the combination of rudder and anchor does not work and re-floating by unloading can be used. Firstly, consideration should be given to squeezing the ballast water and unloading the excess fresh water. Secondly, consideration should be given to unloading fuel and less damaging cargo.

4.3. External Assistance Re-floating

To refloat the grounded vessel by external assistance mainly includes tugboat towing, dredging, etc.

External assistance refloat should be requested without hesitation if the propeller or main engine is damaged, or if the hull is so badly damaged that it has lost its ability to float, or if it is calculated that the pull force required to refloat the vessel after it has run aground is too great to do so, and the towing capacity of the tug, the number and power of the tug should be calculated in advance. [13]

4.3.1. Tugboat Towing to Re-floating

The following points should be noted when refloat a grounded vessel by tug towing:

1) The location and number of the tugs, length of the towing cable must be arranged in accordance with the following principles to give the most effective pulling power and to avoid interaction and distortion with the anchor cable.
2) The cable length of all tugs should be approximately the same to avoid tug and towing cable entanglement. When the towing cables are of the same length, tugs may come into contact with each other and collision may occur, so anti-collision pads should be set on the rescue vessel or tugboat to avoid damage when they come into contact. [14]
3) Generally, multiple tugs tow the aground ship along the fore and aft direction to the deep-water side at the same time to exert the maximum towing force of the tug, or tow the bow or stern of the aground ship to the positive horizontal direction in order to turn the aground ship.

Basically, when a ship runs aground, the direction of turning the ship's head is opposite to the ship's heading, the reason being that turning the ship's stern usually prevents damage to the rudder, propeller and other ancillary devices when they slide along the bottom of the ship. The optimum direction of re-floating is usually the opposite direction of the ship's grounding if the shoal is vertical or nearly vertical after the ship has run aground and there is no significant change in the direction of the bow. It is necessary to adjust the ship's heading. Adjustment of the heading to turn the ship requires a towing force of approximately one third of the towing force if the ship is deflected after running aground.

4.3.2. Turning the Grounded Vessel by Tugboat

Tug assistance in turning an aground ship helps to overcome seabed friction or to turn onto a heading that can be easily refloated. Tugboats need the flexibility to change their operation during towing in order to steer a rounding vessel. A tug with maximum horsepower should be used to turn the stranded ship. As soon as it starts to rotate, the tug assisting in the rotation should stop the rotation operation and quickly return to the course that provides the most power for the re-floating direction.

A certain amount of danger is involved when the tug is assisting in the refloat of a grounded vessel. Throughout the operation, the towing vessel's propellers are always at maximum speed or pitch until the tow is finished or the stranded vessel is moved, while the towing vessel itself is almost stationary and the operator is under high stress. Under such circumstances, in the event of an accident, the safety of the towing vessel or personnel may be endangered, for which reason, operations should be stopped immediately when the towing vessel or barge is in danger. [15]

4.3.3. Dredging of Sediment from Stranded Areas of Ships

Given that the aforementioned methods are unable to refloat the ship, dredging of the sediment at the bottom of the stranded part of the ship can be considered. Nevertheless, attention must be paid to the balance on both sides of the stranded part when dredging the sediment, or else it may cause the ship to tilt to one side and thus cause the ship to drift away.

5. Conclusion

Ship running aground is one of the common types of marine accidents. Crises are always with us when sailing at sea, but how to identify, control and resolve hazards has always been the primary subject of resource management on the bridge. The probability of accidents at sea will be greatly reduced by reducing human errors and increasing the crisis awareness and alertness of the pilot on duty with regards to this issue. Through the accident of "Ever Given" running aground, the safety management of the ship should be strengthened, and the situational awareness and team consciousness of the ship's pilot should be improved when ships are sailing into Suez Canal, the crucial point of world shipping. Duty officers should be on high alert, cooperate with each other and use all available bridge resources to deal with all kinds of unexpected situations to avoid accidents. It is the duty of every seafarer and the most basic professionalism to detect hidden dangers in a timely manner, control them, break the chain of human operational errors and snuff them out early to ensure the safety of human life, environment and property at sea.

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