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Study on submerging operation design for heavy lift barges based on a real case analysis

Xin Wang* and Wei Jun Ko

Newcastle University, Newcastle upon Tyne, UK

* corresponding author, e-mail: xin.wang@newcastle.ac.uk

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Abstract

Semi-submersible heavy lift barges are widely used for transporting large offshore structures over long distances. The float on and float off operations of such vessels are considered as high-risk tasks even today. Improper flooding sequence may lead to accidents including loss of vessels and human lives. The main objective of the present study is to provide valuable findings and guidelines for the design of submerging operations based on the case study of an unsuccessful submerging sea trial. A quasi-static time-domain simulation was conducted to investigate the unsuccessful trial and design a new flooding sequence. Based on the simulation results, the causes of the unsuccessful trial have been identified. Moreover, a new flooding sequence is proposed after examining various options. Since the vessel's dimensions and ballast tank layout are typical and similar to many other heavy lift barges, general conclusions for the design of submerging operations are summarized.

Keywords: semi-submersible heavy lift vessel; quasi-static flooding simulation; unsymmetrical buoyancy tanks; sea trial; flooding sequence design.

1 Introduction

In the offshore oil and gas industry, the transportation of large offshore modules such as drilling rigs, jackets, topsides, bridge sections, and dredging equipment is considered as an important yet risky operation. There are two common transportation methods: rigs fixed onto a barge during the transportation, known as “dry tow,” or rigs floating on their own decks and towed by tugs, known as “wet tow.” Nowadays, as a safer and more efficient transportation mode, dry tows have become very popular, leading to an increasing demand of semi-submersible heavy lift vessels. There are several types of semi-submersible heavy lift vessels, and among those, one of the most economic choices is the nonself-propelled-type barge. As compared with others, nonself-propelled barges are cheaper to build, require less maintenance cost and crew, do not require annual survey for machineries, and do not require a safe manning certificate. Normally, barge-type semi-submersible heavy lift vessels have four buoyancy tanks located at the corners with a symmetric layout. However, when transporting large offshore structures so as to improve operation efficiency and reduce the risk of contact damage, it is possible to reduce the number of buoyancy tanks, resulting in an unsymmetrical layout out¹.

One of the most important functions of the heavy lift vessels is the capability of performing cargo loading and offloading also known as float on and float off operations. When conducting such tasks, it is required to submerge the vessel’s main deck to a certain draft below sea level by flooding the vessel’s ballast tanks. The submerging operation could be rather dangerous and must be conducted carefully because any mistake may result in the consequence of losing the vessel. There have been several reported accidents during the submerging operation that caused vessels to sink. During a float off operation that took place on December 6, 2006 near the port of Luanda, Angola, Mighty Servant 3 (a semi-submersible vessel) exceeded its design limit and eventually sank to the seabed². Another accident happened on July 18, 2014 in which a semi-submersible barge named “POSH Mogami” sank near the northeast of Skeupang, Batam, during a submerging trial³. According to the crew, only the repaired part of the vessel was submerged for testing. However, the ship still sank even when the crew tried to de-ballast the water to float her again. Similarly, accidents on ballast operations also occurred in floating docks. On March 18, 2012, a floating dock named

“Dry Dock #3” carrying a towing vessel capsized⁴. During the submerging process, the floating dock listed to the starboard side due to a faulty check valve at the discharge line of one of the tanks. Progressive flooding soon occurred through the open manholes into other tanks causing the floating dock to capsize.

The key to a successful submerging operation is to maintain adequate stability during the process, especially, when the vessel is under a temporary submerged condition. During the submerging operation, the floating state of the vessel is controlled by adjusting the ballast water load in tanks. Therefore, a well-designed flooding sequence is crucial for the success of submerging operations. There have been limited publications on the analysis and design of flooding sequences^{2;5-6}, and this field has not been thoroughly studied yet.

In the present paper, we focus on the analysis and design of the controlled flooding sequence based on a case study of an unsuccessful submerging sea trial of a 122-m semi-submersible barge. The vessel had an unsymmetrical floater arrangement. During the submerging sea trial, she experienced extreme heel and almost capsized. The incident was reconstructed by a quasi-static time-domain flooding simulation, and the possible causes were identified. Based on an analysis of the results, a new flooding sequence has been proposed. Valuable findings and general guidelines for submerging operation design have been then concluded.

2 Methodology

2.1 Numerical method

To analyze and simulate the submerging operation, the key is to calculate the flooding process during the operation. The numerical methods for the flooding simulation have been studied mainly for damaged ships in the past. The numerical approaches can be mainly divided into two categories. One approach is based on Bernoulli’s equation for the calculation of water flow through openings. Several simulation tools have been developed on the basis of this approach⁷⁻¹⁷. Although the transient dynamics of the internal flow are ignored and the influence of opening geometry and complex compartment internal layout may not be fully accounted, this approach is a very practical and efficient method to predict the progressive flooding phase and the

transient phase for vessels without large-scale damages. The other approach is based on computational fluid dynamics (CFD) method, mainly including the volume of fluid method¹⁸⁻²² and smooth particle hydrodynamics method²³⁻²⁴. Obviously, this approach can overcome the limitation of the first approach mentioned above; however, the high computational cost of the CFD approaches makes them not feasible for practical engineering usage yet.

In this study, the submerging operations of heavy lift vessels are considered as a steady flooding progression, where dynamical aspects are neglected. The key assumptions made for this simplified approach are discussed below.

A time-domain quasi-static approach was applied to simulate the flooding process during the submerging operation. The floating state of the vessel is updated instantly with the ballast water load change in all tanks at each time step. The floating state is obtained on the basis of hydrostatic calculation at each time step. This simplification is based on the fact that the submerging operation is normally conducted in calm weather conditions, so the dynamic loads due to wind and waves are small and motions of the body may be neglected.

The internal flow is assumed to settle down instantaneously with a flat surface that is parallel to the sea level. This assumption has been widely used for the flooding simulations of damaged ships whose sizes are significantly larger than the dimensions of the damage^{9,17,25}. During the submerging operations of heavy lift vessels, the flooding process is normally controlled at relatively low speed so that the transient phase of flooding toward equilibrium fades out quickly. Therefore, this assumption can also be justified for the submerging operations.

Another important assumption made in the present study is about the intake flow rate of each ballast tank. For a damaged ship, the flow between compartments is not known and needs to be accurately predicted with Bernoulli's equation or CFD approach. However, for heavy lift vessels, normally all ballast tanks are water tight, and the flow rate for each tank can be well controlled by adjusting its valve. Therefore, the actual intake flow rate for each tank can simply be used. In this study, a constant flow rate is applied for all tanks throughout the submerging operation. The flow rate applied is 1000 m³/h, which is the maximum capacity of the pump installed onboard

the vessel. This will cause a much faster submerging operation than reality. However, as the dynamic effects were neglected in this study and the real operations were conducted with a much slower speed to avoid significant dynamic effects, the selection of the flow rate will not affect the results and conclusions in this paper. The time step used was 1 min, which is small enough to capture the quasi-static intermediate phases when flooding each tank.

The air compression effects are also neglected in this study. The air compression effect may play an important role when the flooding rate is high and ventilation is restricted. Palazzi and de Kat²⁵ conducted model tests and numerical simulation on a damaged frigate to study its motion behavior with the effect of air flow. It was concluded that the air flow effects may introduce extra roll damping, and simulations considering the air flow effects showed clear improvement. Ruponen et al.²⁶ conducted full scale tests and numerical calculations to study the air compression effect inside a flooded tank. It was found that when the air pipe is relatively small, the air pressure inside the tank was increased significantly and the heeling angle of the vessel was also affected during the flooding process. In this paper, as the flooding process is controlled at a low speed, the ventilation can be considered as big enough for air to escape freely. The air compression effect is therefore neglected.

The numerical calculation in the present paper was conducted using the commercial software General Hydrostatics.

2.2 Stability rules and regulations for submerging operations

As a relatively new field, there are not many regulations on submerging operations of semi-submersible heavy lift vessels. The existing ones are “Rules on Offshore Service Vessels, Tugs, and Special Ships” by DNV GL²⁷ and “Guidelines for submersible pontoons handling cargo at sea” by Netherlands²⁸. The intact stability criteria by DNV GL require the following during the submerging operation:

- The transverse metacentric height GM_T at equilibrium should not be less than 0.3 m
- The heeling angle ϕ where maximum righting arm occurs should not be smaller than 7°

- The positive range of GZ (righting arm) curve should not be smaller than 15°
- The height of GZ curve should not be less than 0.1 m within the above range.

However, Netherlands requires the following during the submerging operation:

- The area under GZ curve should not be less than 0.075 m·rad
- Heeling angle should be less than 5° .

In this paper, the authors applied criteria that combine the conservative requirements of the above two documents. The criteria applied in the present paper is summarized in Table 1. When analyzing the sea trial and designing the new flooding sequence, these criteria were used to check the stability of the vessel throughout the operation.

The righting arm (GZ) curve was produced at every time step and compared with the stability criteria listed in Table 1. Free surface correction is included to account for the change of center of gravity when the vessel inclines. The classical naval architecture practice calculates the righting arm of a ship by taking the longitudinal axis as the heeling axis, where free trim is allowed. This practice was later expanded to offshore units with introduction of the critical axis. Recently, van Santen^{29,30} has pointed out that the free trim practice in combination with varying heeling axis may lead to incorrect interpretation. It was also found that the application of the lowest gain in potential energy can be used to define the critical axis. In the present study, as the vessel is a ship-like vessel, it is still sensible to use the free trim method with heeling axis fixed to be the longitudinal axis³⁰. Certainly, during the submerging operation, when the main deck is partially submerged, the critical axis will change. As the focus of the present study is on the design and analysis of controlled flooding sequences, this change is not considered in this paper. This may be further investigated as a future work.

3 Analysis of the unsuccessful sea trial

3.1 Vessel dimensions and flooding sequence

The vessel studied in this paper is a 122-m semi-submersible steel-deck heavy lift transport cargo barge designed for unrestricted ocean service. The vessel is an unmanned nonself-propelled barge with an unrestricted service notation. The principle

dimensions of the vessel are presented in Table 2. Layouts of the ballast and buoyancy tanks are shown in Fig. 1. The barge has three buoyancy tanks located at corners with unsymmetrical arrangement.

The sea trial was conducted at a designated anchorage area in Singapore water with a minimum water depth of 15 m. The requirement is to submerge the vessel's main deck 7 m below sea level. The anchor was released to ensure that the barge would not drift. During the trial, the flooding sequence in chronological orders is recorded as below. Descriptions of important events based on the crew members' statement are also listed.

- 1.) Ballast Tank 2P and 2S to 100% full.
- 2.) Ballast Tank 4P and 4S to 100% full.
- 3.) Ballast Tank 6P and 6S to 100% full.
- 4.) Ballast Tank 8P to 79.5% and 8S to 100% full.
- 5.) Ballast Tank 3P and 3S to 100% full.
- 6.) Ballast Tank 5P and 5S to 100% full.
- 7.) Ballast Tank 7P and 7S to 100% full.
- 8.) Ballast Tank 1P to 54.6% and 1S to 66.3% full.
- 9.) Ballast Tank 3C to 100% and 5C to 66% full.
- 10.) Ballast Tank 6C to 100% full.
- 11.) Ballast Tank 4C and 7C to 100% full.
- 12.) Ballast Tank 2C to 82.6% full.
 - Main deck was very close to sea level.
- 13.) Ballast Tank 1S to 100% and 8P to 89.5%.
- 14.) Ballast Tank 8C to 30.1% full.
 - After this step, the vessel was observed to trim toward aft significantly.
- 15.) De-ballast Tank 7P to 79.3% full.
 - Trimming the vessel toward the forward also led the vessel to heel extremely to the starboard.
- 16.) De-ballast Tank 8C to 20% full, and ballast Tank 1P to 90% and 7P to 95% full.
 - After this step, both trim and heel becomes small and the vessel was close to its upright position.
- 17.) Ballast Tank 5C to 80% full.

- Extreme heel was observed after flooding Tank 5C.

To summarize the sea trial, side tanks of the barge were first ballasted symmetrically to increase the draft of the vessel. Then, center tanks were ballasted to bring the main deck close to sea level until step 12. After that, the main deck started to be submerged. After step 14, the vessel trimmed to the aft significantly. As there was only little space left in the fore ballast tanks (Tank 1P and 2C), the captain was worried that the vessel may not be able to recover to its upright position. Therefore, he decided to de-ballast some tanks to reduce aft trim. Tank 7P was then de-ballasted to 79.3% to trim the vessel toward forward while a small aft trim angle is maintained to keep the control room (located at fore ship) as the highest point. However, this resulted in a much larger heeling angle toward the starboard. To bring the vessel back to even keel, Tank 8C was de-ballasted and Tank 1P and 7P were ballasted. The ship was very close to its upright position after this, and the captain decided to continue the submerging operation. However, after flooding Tank 5C to 80%, the vessel again heeled extremely to the starboard. Moreover, because almost all port tanks were already fully filled, it was impossible for the vessel to achieve even keel under this condition; thus, the trial was called off. The vessel was eventually safely de-ballasted to light ship and towed back to the shipyard.

3.2 Simulation validation

Following the above recorded sequence, a simulation was conducted to reconstruct the sea trial. Comparison between the sea trial and simulation results for the later stage of the operation are presented in Figure 2. In Figure 2, a vessel's floating states during sea trial are described on the basis of the statement of crew as explained in the previous section, and the simulation results are presented as a profile view or section view. At step 12 and 17, photos taken during the sea trial were available and hence also presented. From Figure 2, it can be inferred that the simulation results match well with the crews' description and photos taken during the sea trial. It can be concluded that the submerging trial has been properly reconstructed.

3.3 Sea trial analysis

Figure 3 presents the simulation results of the vessel's displacement, transverse metacentric height GM_T , and trim and heel angles. The results are presented at each step of the sea trial (Figure 3a) and in the time domain (Figure 3b). As shown in the figures and from step 12 to 14, when the main deck was being submerged and the displacement of the vessel was changing slowly, GM_T dropped very quickly to almost zero. It can be observed that after step 14, the heel angle became very sensitive and fluctuated largely. The rapid drop of metacentric height is dangerous, as it may cause unsteady movement of the vessel and makes it more difficult to control the vessel's heel angle as experienced in the sea trial.

Note that as per Figure 3b, the simulated submerging operation takes about 16.7 h. In the actual sea trial, the whole operation took roughly 24 h to complete. The simulated operation is much faster, as the intake flow rate was assumed to be the maximum capacity of the onboard pumps. As explained previously, this shall not affect the results and conclusions of this study.

When checking the vessel's stability against the criteria listed in Table 1, it has been found that the criteria were not satisfied first at step 14. Two criteria related with GZ curve were not satisfied, as presented in Table 3. This also coincides with captain's judgment to de-ballast tanks after step 14.

Based on the analysis of the simulation results, the authors concluded that there are three causes that may have contributed to the failure of the sea trial.

1. The strategy of the trial was to ballast the side tanks first to bring the main deck close to sea level and then ballast the center tanks to submerge the main deck. However, with side tanks fully filled in the beginning, it became more difficult to control the vessel's floating state, especially, the vessel's heel angle at a later stage of the operation.
2. When submerging the main deck, the drop of metacentric height was rather sudden instead of having a continuous and smooth change. This raises the uncertainty in the operation and the difficulty to control the vessel during later submerging operation stages.
3. When the vessel's main deck was submerged below sea level, the vessel experienced a large heel angle toward the starboard due to the unsymmetrical

layout of buoyancy tanks. At that stage, it was impossible to correct the heel angle as most of the side tanks were already full ballasted.

4 Design of a new flooding sequence

Based on the above analysis of the unsuccessful sea trial, authors designed a new controlled flooding sequence for the submerging operation. The new sequence is based on the below principles.

- The submerging operation starts with flooding the center tanks first, before the side tanks.
- When submerging the main deck, the decrease of water plane area should be as smooth as possible to avoid a sudden drop of the metacentric height.
- The stability criteria listed in Table 1 need to be satisfied throughout the whole operation. Careful consideration is required after the main deck is submerged because the buoyancy tanks have an unsymmetrical layout.

The submerging operation is divided into three stages.

- Stage I: flood center tanks to increase the draft of the vessel;
- Stage II: flood some of the side tanks to bring the main deck close to sea level;
- Stage III: submerge the main deck to required draft.

When flooding side tanks in Stage II, the tanks at amidships were first flooded to allow the fore and aft tanks to be used to adjust trim and heel at a later stage. In this case, the tanks to be flooded are Tank 3P, 3S, 4P, 4S, 5P, 5S, 6P, and 6S. Two flooding sequences have been considered (Table 4): symmetrical and antisymmetric flooding. The sea trial adopted the symmetrical sequence when flooding side tanks. As shown in Figure 4, although the change of metacentric height and heel angles are identical for both methods, the trim of the vessel during antisymmetric flooding is more stable; therefore, antisymmetric flooding is preferred.

At Stage III, the main deck is submerged below sea level to the required draft (14.62 m). The optimum final loading condition at which the vessel reaches the required draft needs to be first established. The design of the final loading condition is based on the principle to minimize the number of partially filled tanks to reduce the operational risk

caused by dynamic free surface movements. Another constraint was applied which requires the vessel to be floating upright with zero heel angle as its final status. For the present vessel, to achieve the required draft, it has been found that at least three tanks need to remain as partially filled. This leads to twenty possible combinations of partially filled tanks. All twenty combinations were examined and stability calculations were conducted to compare with the stability criteria in Table 1. The results showed that none of the combinations satisfied all criteria (particularly at the starboard side) if no heel angle is allowed.

Therefore, to satisfy all stability criteria, a non-zero heel angle must be allowed. After a trial and error process, it has been found that increasing the heel angle to the port side was beneficial for the vessel's stability. However, large heel angle is not favorable for the float-on/off operations and may increase the risk of capsizing. Thus, a minimum heel angle (1.18 degrees) was allowed in order to satisfy all stability criteria. The final loading condition was obtained by modifying one of the combinations whose stability is closest to the criteria. This final loading condition is listed in Table 5. The stability checks and draft under this final loading condition are presented in Table 6.

When designing the flooding sequence at this stage, the most important consideration is to submerge the main deck gradually to avoid a sudden decrease of the water plane area and metacentric height. Based on this principle, it was found that unsymmetrical flooding sequences allowed smoother submerging processes. The selected optimum flooding sequence is in general as aft port -> aft starboard -> forward starboard -> forward port -> aft port. The details of the flooding sequence are presented in Table 7.

Figure 5 presents a comparison of the waterline area and metacentric height between the failed sea trial and the new flooding sequence, focusing on the later stage of the operation. It is evident that with the new flooding sequence, the change of metacentric height is much more continuous and smooth. Figure 6 presents the heel and trim angles of the vessel. After the main deck is submerged, the heel angle could not be controlled during the sea trial although the new flooding sequence controls the heel angle well throughout the operation. Upon checking, all stability criteria in Table 1 were also satisfied at all steps of the new flooding sequence. It can be concluded that

the new flooding sequence is safer and more reliable as compared to the unsuccessful sea trial.

5 Conclusions

This paper focused on the design of controlled flooding sequences for submerging operations of heavy lift vessels. The research is based on the analysis of an unsuccessful sea trial of a semi-submersible heavy lift barge. A quasi-static time-domain approach was adopted to investigate the sea trial. The simulation results were validated by comparing with the crew members' statement and photos taken.

Based on the analysis of the simulation results, the causes of the failure have been identified and a new flooding sequence has been proposed. Following the proposed flooding sequence, the change of water plane area and metacentric height becomes more smooth and trim and heel angles are well controlled, which indicates a safer and reliable operation.

The findings from this study are based on a real case analysis of one vessel. However, as the vessel's dimensions and ballast tank layout are typical and similar to many other vessels, valuable insights and general guidelines for the design of submerging operations can be concluded as below.

1. The submerging operation may start with flooding center tanks before the side tanks. The side tanks shall be used to adjust the vessel's trim and heel at a later stage of the operation.
2. For vessels with unsymmetrical layout of buoyancy tanks, when flooding side tanks, an unsymmetrical flooding sequence is more favorable compared to a symmetric flooding sequence, as it allows a smoother submerging process.
3. For vessels with unsymmetrical layout of buoyancy tanks, it may be challenging to satisfy all stability requirements after the main deck is submerged. A minimum heel angle needs to be allowed at the final loading condition to satisfy all stability rules. For the submerging operations after the main deck is submerged, careful consideration also needs to be given to avoid large heel angles due to the unsymmetrical layout of buoyancy tanks.

References

1. Kojima R, Cho KR, Yang YT, et al. Float off operation of a semi-submersible barge with unsymmetrical floater arrangement. *The Kansai Society of Naval Architects* 2002; 237: 271-276.
2. Dankowski H, Dilger H. Investigation of the Mighty Servant 3 accident by a progressive flooding method. In: *Proc ASME 32nd Int Conf Ocean, Offshore Arct Eng*, Nantes, France, 9-14 June, 2013, paper no. OMAE2013-10342.
3. Suey, R. News! POSH Semi-Submersible Barge Sinks – Three Dead, <http://www.rolfsuey.com/2014/07/news-posh-semi-submersible-barge-sinks.html> (2014, Accessed: 9 January 2017).
4. National Transportation Safety Board. Dockside capsizing and sinking of towing vessel invader and Dry Dock #3. *Marine Accident Brief* 2012; MAB-13-16.
5. Sun W, Zhang D, Fan Z. Transportation of floating structures by using newly built heavy lifting semi vessel HYSY278. *China Ocean Engineering* 2012; 27(3):299-312.
6. Dankowski H, Hatecke H. Stability evaluations of semi-submersible heavy transport vessels by a progressive flooding simulation tool. *Proc ASME 31st Int Conf Ocean, Offshore Arct Eng*, Rio de Janeiro, Brazil, 2012.
7. Spanos D, Papanikolaou A. On the stability of fishing vessels with trapped water on Deck. *Ship Technol Res—Schiffstechnik* 2001; 48:124–133.
8. Jasionowski A. *An Integrated Approach to Damage Ship Survivability Assessment* (Ph.D. thesis). University of Strathclyde, 2001.
9. Ruponen P. Pressure-correction method for simulation of progressive flooding and internal airflows. *Ship Technol Res—Schiffstechnik* 2006; 53:63–73.
10. Ruponen P. *Progressive flooding of a damaged passenger ship* (dissertation for the degree of doctor of science in technology). TKK Dissertations 94, 2007, p. 124.
11. Ruponen, P. Adaptive time step in simulation of progressive flooding, *Ocean Engineering* 2014; 78:35-44.
12. Santos TA, Guides Soares C. 2009. Numerical assessment of factors affecting the survivability of damaged ro-ro ships in wave. *Ocean Eng* 2009; 36(11):797–809.

13. Ypma E, Turner T. An approach to the validation of ship flooding simulation models. In: *Proceedings of the 11th International Ship Stability Workshop*, Wageningen, The Netherlands, 2010.
14. Schreuder M, Hogström P, Ringsberg JW, et al. A method for assessment of the survival time of a ship damaged by collision. *J Ship Res* 2011;55(2):86–99.
15. Dankowski H. An explicit progressive flooding simulation method. In: *Proceedings of the 11th International Conference on Stability of Ships and Offshore Structures*, STAB 2012, Athens, Greece, p. 411–423.
16. Dankowski H. *A Fast and explicit method for simulating flooding and sinkage scenarios of ships* (Doctoral Dissertation). Technischen Universität Hamburg-Harburg, Hamburg, Germany, 2013, p. 107.
17. Rodrigues JM, Guedes Soares C. A generalized adaptive mesh pressure integration technique applied to progressive flooding of floating bodies in still water. *Ocean Engineering* 2015; 110:140–151.
18. Cho SK, Hong SY, Kim YH, et al. Investigation of dynamic characteristics of the flooding water of the damaged compartment of an ITTC RO-RO Passenger Ship. In: *Proceedings of the 8th International Ship Stability Workshop*, Istanbul, 2005.
19. Woodburn P, Gallagher P, Letizia L. Fundamentals of damage ship survivability. *Trans R Inst Nav Archit – RINA* 2002; 144:143–163.
20. Gao Z, Vassalos D, Gao Q. Numerical simulation of water flooding into a damaged vessel's compartment by volume of fluid method. *Ocean Eng* 2010; 37:1428–1442.
21. Gao Z, Gao Q, Vassalos D. Numerical simulation of flooding of a damaged ship. *Ocean Eng.* 2011; 38:1649–1662.
22. Gao Z, Gao Q, Vassalos D. 2013. Numerical study of damaged ship flooding in beam seas. *Ocean Eng.* 2013; 61:77–87.
23. González V, Talens M, Riola JM, et al. Numerical prediction of the dynamic behaviour of a ro-ro ship after a hull side damage. In: *Proceedings of the 8th International Conference on Stability of Ships and Ocean Vehicles*, Madrid, 2003, p. 215–227.
24. Skaar D, Vassalos D, Jasionowski A. The use of a meshless CFD method in modelling progressive flooding and damaged stability of ships. In: *Proceedings*

- of the 9th International Conference on Stability of Ships and Ocean Vehicles, Rio de Janeiro, Brazil, 2006, 2, p. 625–632.*
25. Palazzi L, De Kat J. Model experiments and simulations of a damaged ship with air flow taken into account. *Marine Tech.* 2004; 41(1):38-44.
 26. Ruponen P, Kurvinen P, Saisto I, Harras J. Air compression in a flooded tank of a damaged ship. *Ocean Eng.* 2013; 57: 64-71.
 27. DNV GL. *Offshore service vessels, tugs and special ships*, 2013.
 28. Netherlands. *Guidelines for submersible Pontoon handling cargo at sea*, 2000.
 29. Van Santen J. The use of energy build up to identify the most critical heeling axis direction for stability calculations for floating offshore structures. In: *Proceedings of the 10th International Stability of Ships and Ocean Vehicles*, 2009, p. 65-76.
 30. Van Santen J. Problems met in stability calculations of offshore rigs and how to deal with them. In: *Proceedings of the 13th International Ship Stability Workshop*, Brest, 2013.

Table 1 Summary of criteria applied in the present study

Requirements	
1	GM_T at equilibrium > 0.3 m
2	GZ_{max} at $\phi > 7^\circ$
3	Positive GZ range > 15°
4	Height of GZ curve > 0.1 m
5	Area under the GZ curve > 0.075 m·rad
6	Heeling angle < 5°

Table 2 Principle particulars of the 122-m heavy lift vessel

Principle particulars	Values	
Lightship	5045.16 tons	
L _{OA}	122	m
B _M	36.58	m
D _M	7.62	m
Summer load line	5.89	m
Required draft	14.62	m

L_{OA}: Length overall

B_M: Beam at ship midsection

D_M: Depth at ship midsection

Table 3 Summary of stability check at step 14

Requirements	Attained
1 GM_T at equilibrium > 0.3 m	1.115
2 GZ_{max} at $\phi > 7^\circ$	16.90
3 Positive GZ range > 15°	17.00
4 Height of GZ curve > 0.1 m	0.099
5 Area under the GZ curve > 0.075 m·rad	0.022
6 Heeling angle < 5°	1.9

**Bold values highlight the two values that do not satisfy the requirements*

Table 4 Symmetrical and antisymmetric flooding of side tanks (Stage II)

Step	Symmetrical flooding
1	Ballast Tank 5P and 5S to 100% full.
2	Ballast Tank 4P and 4S to 100% full.
3	Ballast Tank 6P and 6S to 100% full.
4	Ballast Tank 3P and 3S to 100% full.

Step	Antisymmetric flooding
1	Ballast Tank 5P and 4S to 100% full.
2	Ballast Tank 4P and 5S to 100% full.
3	Ballast Tank 6P and 3S to 100% full.
4	Ballast Tank 3P and 6S to 100% full.

Table 5 Optimum final loading condition

Tank	Filling ratio (%)
1P	100
1S	64.5
2P	100
2S	100
7P	100
7S	100
8P	22.5
8S	12.5
Other tanks	100

Table 6 Stability under the final loading condition

Criteria	Requirements	Starboard	Port
1	>0.3	0.97	0.97
2	>7°	8.07	21.97
3	>15°	121°	112°
4	>0.1 m	0.11	0.10
5	>0.075 m·rad	0.10	0.15
6	<5°	1.18 (port)	
Draft	14.62 m	14.62	

Table 7 Definition of flooding sequence for Stage III

Step Flooding sequence	
1	2P, 2S
2	7P, 8P
3	8S
4	7S
5	1P, 1S
6	7P
7	1S

Figure 1 Arrangement of ballast and buoyancy tanks

Figure 2 Comparison of sea trial and simulation results

Figure 3 Simulated characteristic stability values of the trial

a) Results in steps

b) Results in the time domain

Figure 4 Comparison of symmetrical and antisymmetric flooding (Stage II)

Figure 5 Comparison of waterline area and metacentric height between sea trial and the proposed flooding sequence

Figure 6 Comparison of trim and heel between sea trial and the proposed flooding sequence