SINERGI Vol. 26, No. 2, June 2022: 173-184
http://publikasi.mercubuana.ac.id/index.php/sinergi
http://doi.org/10.22441/sinergi.2022.2.006

Experimental investigation of course stability on a barge during damaged conditions

Suandar Baso*
Department of Naval Architecture, Faculty of Engineering, Hasanuddin University, Indonesia

Abstract
The paper presents an experimental investigation of course stability on the barge due to the damage conditions of one or more adjacent void tanks. The effects of various towline lengths and load conditions on the course stability of the barge were taken into account and incorporated with trim and heel conditions. The sway motion, defined as the towline's motion, was captured using the camera, and the yaw motion was measured using the Euler compass. The investigation results revealed that increased towline lengths, flooding locations, and load conditions affect the barge's course stability. The smallest value is the increased sway and yaw amplitudes affected by the flooded condition of one or adjacent two void tanks on the amidship part. The overall sway amplitude on the port side or starboard side increases significantly high, affected by towline length from 1L to 1.5L. Also, the overall yaw amplitude on the port side or starboard side increases significantly high, affected by towline length from 1.5L to 2L. The difference in the increased sway amplitude based on the flooding locations between stern, amidship, and bow parts is less than 10% on the port side and 2% on the starboard side. The difference in the increased yaw amplitude is less than 5% on the port side and 5% on the starboard side. The number of longitudinal bulkheads on the port side and starboard side must be considered for the reduction of the oscillation of the water mass inside the tank to reduce the degradation of the course stability.

Keywords:
Barge;
Course stability;
Flooded tank;
Sway motion;
Yaw motion;

Article History:
Received: July 30, 2021
Revised: November 12, 2021
Accepted: December 9, 2021
Published: June 1, 2022

Corresponding Author:
Suandar Baso,
Department of Naval Architecture, Faculty of Engineering, Hasanuddin University, Indonesia,
Email: s.baso@eng.unhas.ac.id

INTRODUCTION

Sea transportation of a tug and barge has been still very reliable and feasible to transport mining materials and other cargoes. However, during the operation for this kind of transportation, the safety of the towing operations requires good course stability of the barge. As known, a barge has a high vertical center of gravity, shallow draft, and low freeboard [1], and those characteristics affect its performance. Also, waves and severe weather in sailing conditions can disrupt a barges' performance. Therefore, to ensure the safety of the barge during sailing and towing operations, a transport method for a barge must be properly planned or arranged.

Numerous studies have investigated the aspects that affect operational safety concerning the transportation method. The dynamic response of the barge in a random sea was investigated by [2]. The course stability of a barge with skegs fitted at both sides of the stern was studied by [3] to improve its course stability performance. The course stability performance of the barge in the wide beam and shallow draft of the model tested in a towing tank was investigated by [4]. Also, the experimental investigation was carried out to obtain the effect of skegs on the barge hull's hydrodynamic derivatives. The full-scale barge motions measurement and comparison with a model test were presented by [5]. The towrope of unsuitable length would induce hazardous responses in operations and make it impossible to keep a barge in an equilibrium position [6].

Moreover, the methodology of the stability and motion analysis for practical problems of barge transportation was developed and implemented by [7]. However, this applied to barge transportation with zero forward speed. The experiment was conducted to investigate the effect of sway motion with different tow rope lengths and arrangements for a towed ship in calm water [8][9]. The coupled dynamics of a tug-towline-towed barge based on the multiple-element model of the towline were simulated by [10]. The effects of an unstable towed ship and a stable towed ship were investigated numerically at various angles and velocities of wind [11]. The rolling of a transport barge in irregular seas was investigated by [12]. The towing characteristics of a transportation barge during the multi-tug operation were studied by [13]. However, this research was focused on the parameters of towline tension. The slewing motion of the barge can be decreased by decreasing the towline lengths, which is greater when a bridle is connected to the towline [14]. The course stability of a towed ship using Computational Fluid Dynamics (Flow3D) was investigated by [15], where the effects of different towline lengths and towing's velocity on sway and yaw motions were investigated. The sway and yaw motions and towline tension of a ship towing system in calm water incorporated with symmetrical and asymmetrical bridle towline configurations were investigated by using the CFD simulation [16, 17, 18]. Furthermore, the hydrodynamic force acting on the towed vessel was modelled as a modular-type hull force model, including the linear and nonlinear (third-order) damping forces in sway and yawing directions [19, 20, 21] and the towing characteristics of the barge considering wind force were studied by [22].

The studies that have been explained previously show the course stability of the barge to be a function of towing's speed, barge hull geometry, skeg, water depth, wave condition, and towing system incorporated with the towline type, length, and tension. In the studies, the investigation of the course stability of the barge was in intact condition. However, a barge sometimes experiences a damaged condition at sea, and it is possible to a dangerous. Although barge collision accidents less occur, the studies of course stability of the barge in damaged conditions are rarely conducted. The accident of the towing tug (TB Mitra Jaya XXI) in Jawa sea-Indonesia was reported by [23, 24, 25] wherein the towing tug experienced a collision during towing the barge (Makmur Abadi 5) with another ship (KM Tanto Bersinar). The TB Mitra Jaya XXI sank in this accident, and the barge Makmur Abadi 5 suffered a torn hull and leakage. In the leakage condition, the barge must be towed to its destination. In this case, the course stability of a barge during damage conditions is an important matter. Therefore, the course stability of the barge due to the damage conditions of tanks must be investigated.

This study presents an experimental investigation on the course stability of the barge in the damage conditions. The effects of the damage conditions of the tank incorporated with towline length and load conditions on the barge's course stability have been taken into consideration. Several scenarios of the damage conditions of the void tank have been considered into one, adjacent two, and adjacent three flooded tanks. The lengthened towlines have been defined based on the barge's length. Also, the load condition of the barge has been considered in the draft of 100% and 75%. From the investigation results, the behaviors of the barge have been interpreted accordingly. This interpretation can guide the towing operations of a barge that experiences the flooded tanks.

METHOD

In this presented study, the investigation of the course stability of the barge model in calm water during flooded conditions has been carried out through experimental work. In the following, the ship model and experimental setup are discussed. The experiment was conducted at the towing tank of the Ship Hydrodynamics Laboratory, Department of Naval Architecture, Hasanuddin University. The towing tank dimension is 60 m in length, 4 m in width, 6 m in depth, and 3.80 m in water depth. The speed of the towing carriage is a maximum of 4 m/s.

The main dimensions of the barge and the body lines plan are shown in Table 1 and Figure 1, respectively. For the geometric scale, the barge model is scaled 1:50, considering the towing tank size to avoid some disturbances during the experiment. The ship model was made of fiberglass combined with thin wood, as shown in Figure 2, wherein the barge model was completed with the number of the void tanks (38 tanks) based on the tank arrangement and equipped with a skeg, as shown in Figure 3. The deck of the barge model was made of acrylic material, and its purpose was to easily control water volume and level inside a void tank due to a leaking condition.

Table 1. Main Dimension of the Actual Barge and Model

Dimension	Actual barge	Model
Length overall/LOA (m)	91.44	1.83
Breadth/B (m)	24.38	0.49
Depth/D (m)	6.09	0.12
Draft/d (m)	5.18	0.10

The schematic of the experiment is shown in Figure 4. The barge model was towed by the tugboat model using the towline. The towing post of the carriage is connected vertically with the towing tug model. The velocity of towing is sometimes 5 knots on the working operation. For a damage condition of a barge, the velocity of towing is assumed here to be around 2.5 knots. Therefore, by using the Froude similarity in the experiment, the speed of the towing carriage was the same as the tug's speed set at 0.18 m/s related to the Froude number (Fr) 0.042.

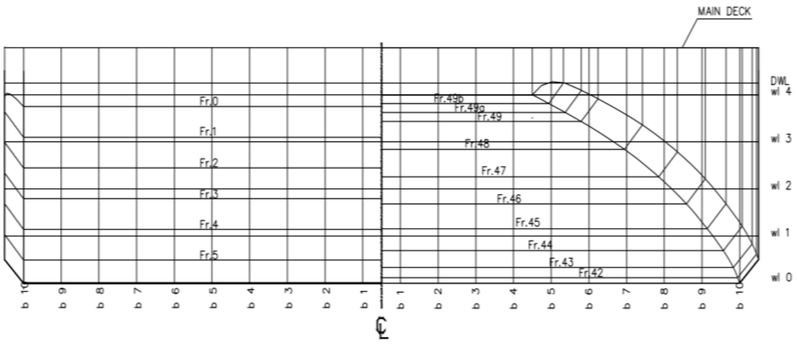


Figure 1. Body Lines Plan of Barge

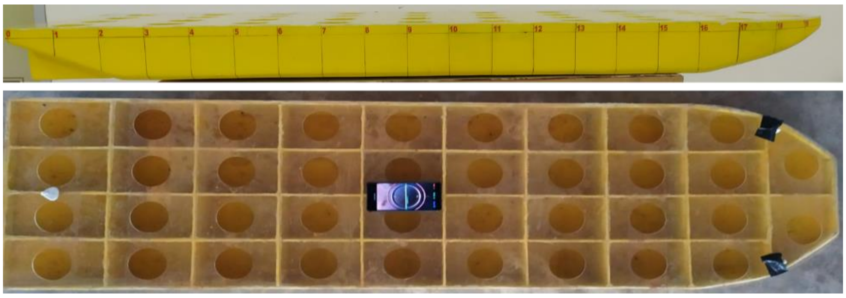


Figure 2. Model of Barge

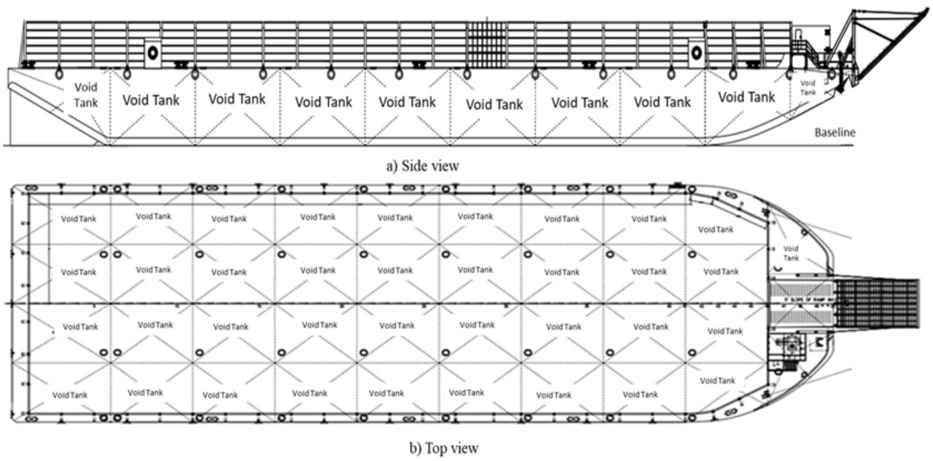


Figure 3. Void Tank Arrangement of Barge

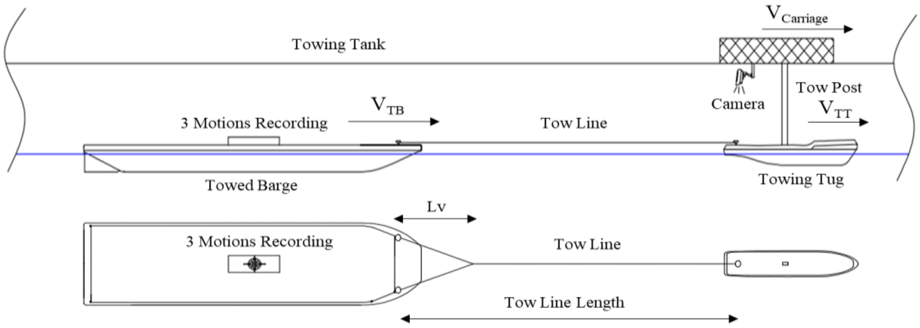


Figure 4. Schematic of Course Stability Experiment

A barge is sometimes not fully loaded when sailing at sea in the actual condition. Therefore, this condition is considered in this experiment. The loading conditions of the barge model were assumed into 75% draft (*d1*) and 100% draft (*d2*). Besides the loading condition, the length and type of towline are also considered. The tow rope was connected to the two models of tug and barge, wherein the towline is straight-tow with V-tow connected to the barge model, as shown in Figure 4. The V-tow type refers to [21], and the straight-tow refers to [6] [22]. The towline length is normalized with the barge model length (LOA or L) configured into 1L, 1.5L, and 2L, as shown in Table 2, wherein L is LOA. The towline length includes the straight-tow with V-tow (*Lv*), and the V-tow has various towline lengths based on the configuration of the towline length. The V-tow (*Lv*) length is connected to two points in the barge. The diameter of the tow rope is 5 mm, and its material is thermoplastic silky material (nylon). In the experimental study, the effect of tow rope tension stability is ignored on course stability.

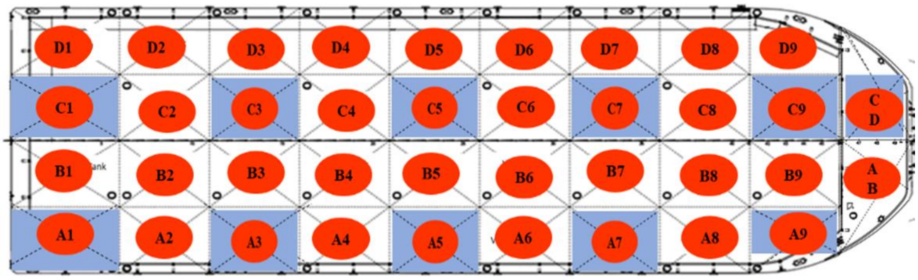
Moreover, the scenario of the flooded condition is assumed that a barge is experienced progressive flooding (external) caused by the leaked void tank and through the down flooding point. The damage is penetrated on the combination of the longitudinal and transverse subdivisions. Here, the permeability is assumed for flooded spaces due to the flooded condition, and its value for the void tank is 0.95 based on IACS Rec. 2009/Rev.1 2010.

Table 2. Towline Length and Configuration

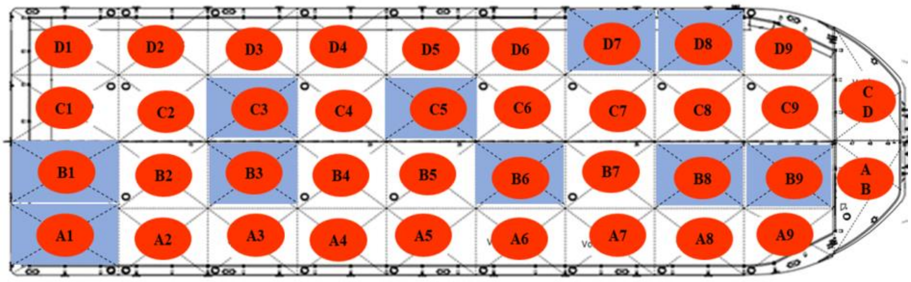
Towline length configuration	Length (m)	V-tow length (m)
1L	1.83	0.28
1.5L	2.74	0.35
2L	3.66	0.40

By this assumption, the total water volume of the void tank due to the flooded condition is 95% of the void tank space. Nevertheless, the water level inside the void tank is the same as the water outside the barge. On the other assumption, the opening (manhole or others) connects between the void tanks, and this opening is taken into account that can cause flooding on an adjacent void tank. Therefore, in this presented study, the number of adjacent flooded zones is considered one to three void tanks or simultaneous flooded two and three void tanks based on Resolution MSC.429(98).

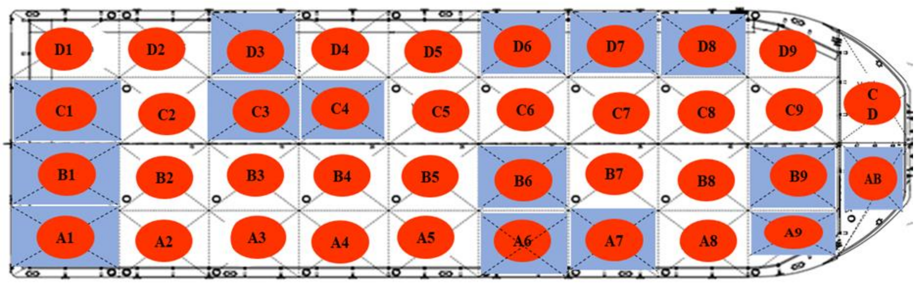
The symmetrical and unsymmetrical flooded conditions affect the trim and heel on the barge. One flooded void tank is an unsymmetrical condition, adjacent two flooded void tanks can be a possible symmetrical or unsymmetrical condition, and all three flooded void tanks are unsymmetrical conditions. The illustrations of the example of one (A1, C1, A3, C3, A5, C5, or CD, etc.), two (adjacent A1 and B1, adjacent C and B3, or adjacent B8 and B9, etc.), and three damaged void tanks (adjacent A1, B1, and C1, or adjacent D3, C3, and C4, etc.) is depicted in Figure 5. The flooding event of the void tank on the port side is the same as that experienced on the starboard side. Therefore, the measurement of flooding based on the scenario is conducted only once a time with a similar scenario. The barge's coupled trim and heeling conditions affected by the void tank's flooding were measured for the hydrostatic parameters. The barge's attitude was captured using the image (camera) and then was drawn through computer-aided design (CAD) to obtain the barge's draft. The extreme conditions of the barge are based on the highest trim and heel conditions. The extreme trim conditions were conducted on the course stability experiment.



(a) One Flooded Tank (Condition A)



(b) Adjacent Two Flooded Tanks (Condition B)



(c) Adjacent Three Flooded Tanks (Condition C)

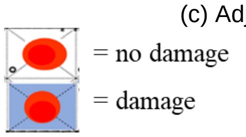
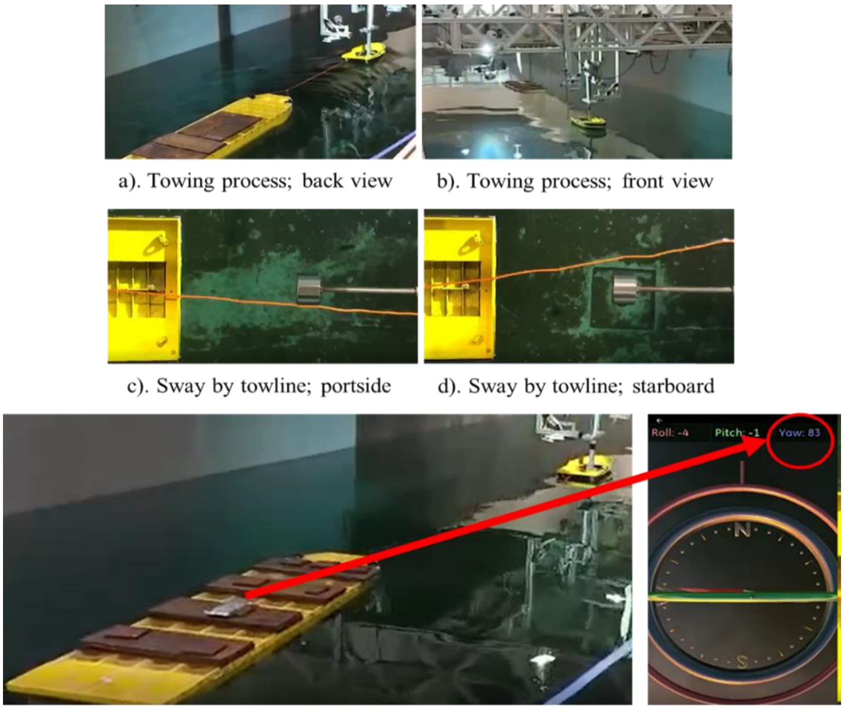


Figure 5. The Example of the Flooding Possibility of One (a), Adjacent Two (b), and Adjacent Three Flooded Tanks (c)

Regarding the course stability experiment of the barge due to damage conditions on the extreme conditions (the highest trim by bow or stern and heeling condition), the motions of the barge were measured, namely coupled sway and yaw. The sway motion was defined as the motion of the towline captured by using the camera to measure the motions of the barge model due to damage conditions. The camera was placed above the towline vertically and attached to the carriage structure. The angle of the towline movement at each second could be captured during the towing process using the camera. Based on this way, the sway motion was analyzed as assumed on the towline movement and the amidship point's translational movement and then using the Pythagorean theorem with an isosceles triangle. In addition, the yaw motion was measured at the same point as the sway motion captured by using the device with the application of the Euler compass that can measure and record the three rotational movements (pitch, heave, and yaw) per second.

The photograph of the course stability of the barge due to flooded conditions conducted in the towing tank is depicted in Figure 6; towing process (Figure 6a and Figure 6b), sway motion based on towline movements (Figure 6c and Figure 6d), and yaw motion recorded by the Euler compass (Figure 6f).



a). Towing process; back view b). Towing process; front view

c). Sway by towline; portside d). Sway by towline; starboard

f). Yaw motion recording

Figure 6. The Course Stability Experiment of the Barge Due to Flooded Void Tank

RESULTS AND DISCUSSION

The course stability analysis of the barge in calm water has been performed successfully through the experimental model test at the towing tank, where results are accordingly obtained. In addition, this experimental investigation of the course stability due to the damaged tanks is appropriately discussed.

Hydrostatic parameter of the barge due to damage tank

The trim by bow and stern on the barge due to the flooded conditions of void tanks was measured on the draft of 100% (full load). The void tank in rows A (starboard) and B are in the same position (symmetrical position) as the void tank in D and C, as shown in Figure 5. For this reason, the measurement of trim due to the flooded void tanks with a symmetrical position was conducted only on one side. Here, the flooded tank position was on the port side. The photograph during the experimental process of the draft measurement due to the flooded void tank is shown in Figure 7.

Nineteen void tanks were flooded and measured for Condition A and 68 various void tanks for Condition B in the experiment. The measurement results showed that the flooded void tank of D2 and D8 affected the highest trim by stern and bow, respectively. For the flooded void tank C4, the trim showed small in the flooded void tank around the amidship. The drats due to the flooded void tank of D2, C4, and D8 on the port side and starboard side are shown in Table 3. The difference in draft between on port and starboard sides affected the healing conditions. The heel magnitude at amidship was obtained at 1.40 degrees for D2, 2.39 degrees for D8, and 0.70 degrees for C4. Due to condition A, the heel magnitude is smaller on the amidship part than on the bow or stern part.

Condition B and Condition C's draft measurement on the bow and stern. On the measurement, the water level surface by trim and heeling conditions due to load 100% was over the deck level for all Conditions B and C. Therefore, these scenarios were not considered further performed on the experiment of the course stability. Regardless of the condition of the barge on draft 100% due to the flooded conditions of Condition B, the surface of water level by trim and heeling conditions remained under deck level for 75% draft. On the other hand, the water level was affected by Condition C were remain over deck level on the 75% draft of a barge. Therefore, the trim measurement due to the flooded conditions of Condition C was not conducted for experimental investigation of course stability.

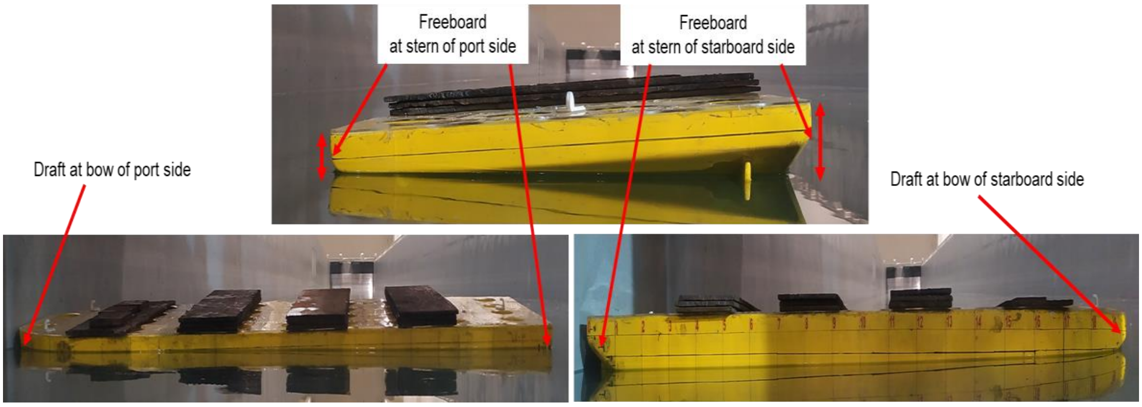


Figure 7. The Course Stability Experiment of the Barge Due to Flooded Void Tank

Table 3. Draft by Bow and Stern on Draft 100% Due to Condition A

Flooded void tank	Trim condition			
	Draft on the port side (cm)		Draft on the starboard side (cm)	
	Bow	Stern	Bow	Stern draft
D2	10.80	11.90	9.50	10.80
C4	10.80	11.50	10.30	10.80
D8	12.20	11.50	10.50	9.10

Table 4. Draft by Bow and Stern on Draft 75% Due to Condition B

Adjacent two flooded void tank	Trim condition			
	Draft on the port side (cm)		Draft on the starboard side (cm)	
	Bow	Stern	Bow	Stern
D2-D3	8.50	11.20	6.50	7.80
B4-C4	8.30	8.80	7.70	8.20
D7- D8	10.50	9.50	7.90	6.10

Table 4 shows the trim by bow and stern due to the flooded conditions of Condition B. Condition B of D2-D3 and D7-D8 affected the highest trim by stern and trim by bow, respectively. Based on Table 4, the heel magnitude affected by the flooded tanks of D2-D3 and D7-D8 is 3.15 degrees and 3.50 degrees, respectively. For the flooding conditions represented in the amidship part of the barge, Condition B of B4-C4 were considered to be performed in the experiment.

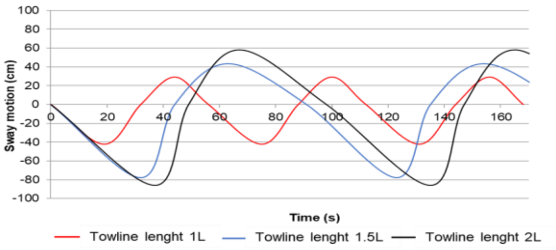
Course stability behaviors of the barge due to flooded void tank

The Condition A of D2, C4, and D8 and Condition B of D2-D3, D7-D8, and B4-C4, was performed in the experimental investigation of course stability.

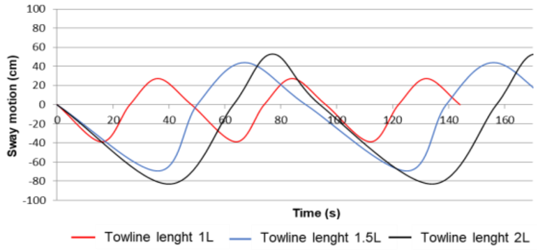
Figure 8 shows the time history of the sway motion of the barge in calm water due to Condition A. The sway motions due to the Condition A of D2 (Figure 8a), C4 (Figure 8b), and D8 (Figure 8c) show sufficient stable conditions. Although the sway motion has shown stable condition, the motion amplitude tends to move large to the port side of the barge. This tendency means the barge drifted to the port side caused by the oscillation of the water mass inside the flooding tank that occurred on the port side. The sway amplitude tends to increase in increasing the lengths of the towline, wherein the sway amplitude has the smallest value affected by the towline 1L for all of Condition A. For Condition B, the behavior of sway motion is similar to Condition A.

The average increased sway amplitude in increasing the towline lengths due to the Condition A of D2, C4, and D8 on the port side is 27.73%, 30.17%, and 28.47%, respectively. On the starboard side, the average increased sway amplitude in increasing the towline length due to D2, C4, and D8 on the starboard side is 28.17%, 27.81%, and 27.75%, respectively. The difference of the increasing sway motion due to the flooded location between stern (D2), amidship (C4), and bow parts (D8) is a small magnitude, wherein it is less than 7.41% on the port side and 1.0% on the starboard side, respectively.

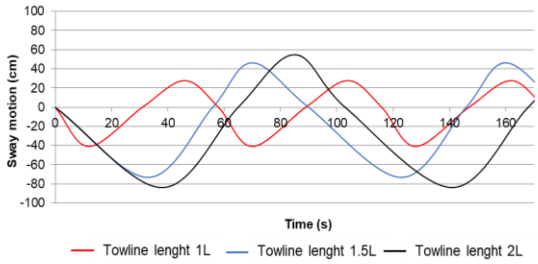
On the other hand, the average increased sway amplitude in increasing the towline lengths due to the Condition B of D2-D3, B4-C4, and D7-D8 on the rotational speed to the port side is 17.69%, 19.87%, and 18.64%, and it in starboard side is 26.64%, 27.55%, and 27.91%, respectively. The difference in the increased sway amplitude seems small based on the leaked location between stern, amidship and bow parts, wherein it is less than 9.47% on the port side and 1.05% on the starboard side. Therefore, the increased sway amplitude affected by Condition A or Condition B on the amidship part has the smallest value. Table 5 listed the average sway amplitude of the barge due to the Conditions A and B.



a). Flooded void tank of D2

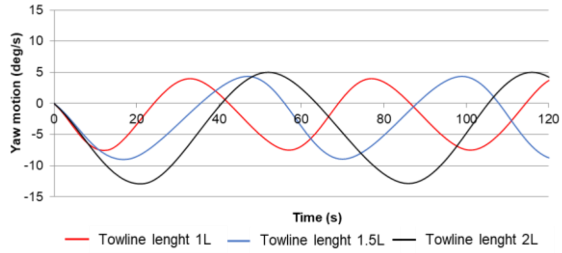


b). Flooded void tank of C4

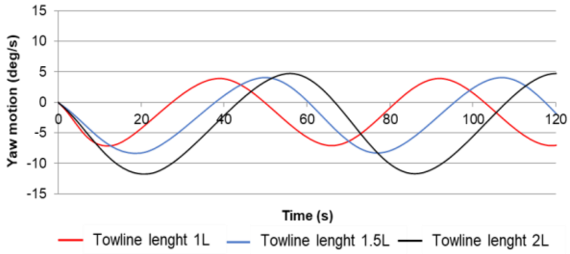


c). Flooded void tank of D8

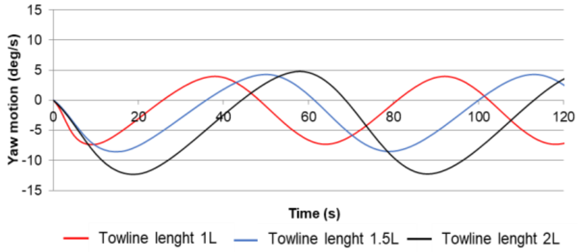
Figure 8. Time History of Sway Motion of Barge Due to Condition A.



a). Flooded void tank of D2



b). Flooded void tank of C4



c). Flooded void tank of D8

Figure 9. Time History of Yaw Motion of Barge Due to Condition A

Figure 9 shows the time history of the yaw motion of the barge in calm water due to Condition A. Regarding the yaw response, the yaw motion due to the Condition A of D2 based on Figure 9a affects the highest trim by stern.

The yaw amplitude is highest when the towline length is 2L, and the yaw amplitude is lowest affected by the towline of 1L. Also, the yaw motion increases by increasing the towline lengths. In addition, the yaw motion due to the Condition A of C4 and D8 is shown in Figure 9b and 9c, wherein the flooded void tank of C4 and D8 represent the flooded conditions on the amidship part and the bow part (highest trim by bow), respectively.

The tendency of yaw motion due to those flooded void tanks of C4 and D8 has the same behavior as the yaw motion of the Condition A of D2. Therefore, the behavior of the yaw motion is affected by the towline length, wherein the yaw motion becomes large in increasing the towline lengths. The average yaw amplitude due to conditions A and B is shown in Table 6.

Based on Table 6, the yaw amplitudes on the port side for both Condition A and B flooded conditions are higher than on the starboard side. The average increased yaw amplitude increases the towline lengths due to the Condition A of D2, C4, and D8 on the port side is 23.11%, 21.73%, and 22.36%. On the starboard side, the average increased yaw amplitude due to D2, C4, and D8 is 10.21%, 9.57%, and 9.90%. The difference in the increased yaw amplitude seems small based on the flooding location between the stern, amidship and bow parts, wherein it is less than 4.39% on the port side and 4.77% on the starboard side.

Meanwhile, the average increased yaw amplitude in increasing the towline lengths due to the Condition B of D2-D3, B4-C4, and D7-D8 on the rotational speed to the port side is 15.63%, 15.50%, and 16.37%, and it in starboard side is 12.40%, 12.31, and 12.33% respectively. The difference of the increased yaw amplitude in increasing the towline length seems small based on the leaked location between the stern, amidship, and bow parts.

The difference in the increased yaw amplitude seems small based on the leakage locations between the stern, amidship, and bow parts, wherein it is less than 3.07% on the port side and 1.0% on the starboard side. Also, the increased yaw amplitude has the smallest value on the amidship part for both flooded conditions of Condition A and B.

Figure 10 shows the tendency of sway amplitude of barge in increasing the towline lengths due to conditions A and B. The sway amplitude due to both of those flooded conditions seems to have the same tendency. Although the difference of increased sway amplitude that has been stated previously is a small value, the overall sway amplitude increases significantly high affected by towline lengths from 1L to 1.5L on both port side and starboard side.

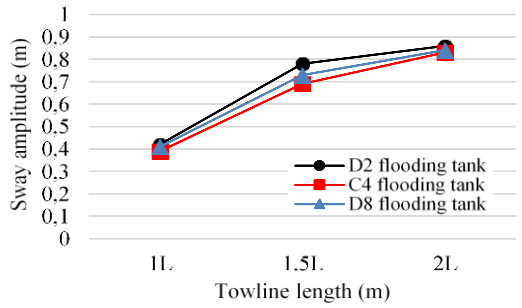
Figure 11 shows the barge's yaw amplitude tendency in increasing the towline lengths due to conditions A and B. On the contrary to the increased sway amplitude, the overall yaw amplitude increases significantly, affected by towline lengths from 1.5L to 2L on the port side and starboard side. Also, the tendency of sway amplitude due to Condition A is the same as Condition B.

Table 5. The Average Sway Amplitude of Barge Due to the Conditions A and B

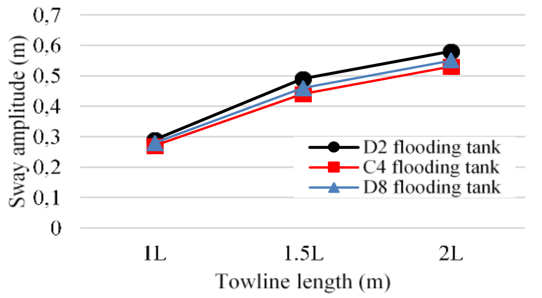
Condition	Flooded void tank	Towline length	Sway amplitude (m)	
			Port side (-)	Starboard side (+)
Condition A	D2	1L	0.42	0.29
		1.5L	0.78	0.49
		2L	0.86	0.58
	C4	1	0.39	0.27
		1.5L	0.69	0.44
		2L	0.83	0.53
	D8	1L	0.41	0.28
		1.5L	0.73	0.46
		2L	0.84	0.55
Condition B	D2-D3	1	0.37	0.20
		1.5L	0.49	0.32
		2L	0.55	0.38
	B4-C4	1L	0.31	0.17
		1.5L	0.44	0.30
		2L	0.49	0.34
	D7-D8	1L	0.34	0.18
		1.5L	0.47	0.31
		2L	0.52	0.36

Table 6. The Average Yaw Amplitude of Barge Due to the Conditions A and B

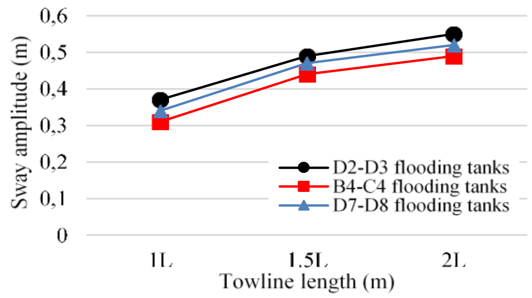
Condition	Flooded void tank	Towline length	Yaw amplitude (deg/s)	
			Port side (-)	Starboard side (+)
Condition A	D2	1L	7.52	4.02
		1.5L	8.92	4.36
		2L	12.84	4.99
	C4	1L	7.13	3.83
		1.5L	8.30	4.09
		2L	11.75	4.69
	D8	1L	7.34	3.91
		1.5L	8.56	4.23
		2L	12.31	4.82
Condition B	D2-D3	1L	3.08	2.39
		1.5L	3.21	2.62
		2L	4.41	3.12
	B4-C4	1L	2.82	2.30
		1.5L	3.00	2.43
		2L	4.00	3.01
	D7-D8	1L	2.91	3.35
		1L	3.11	2.52
		2L	4.22	3.07



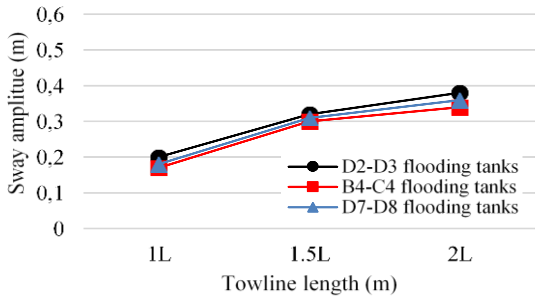
(a) Sway amplitude in port side.



(b) Sway amplitude in starboard side.

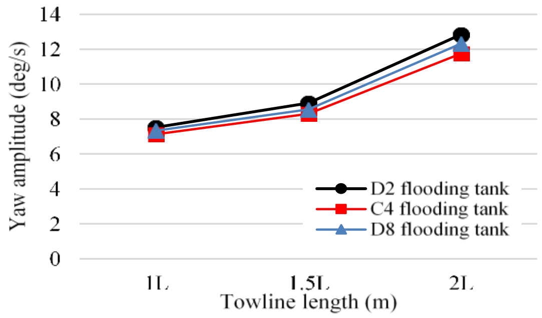


(c) Sway amplitude in port side.

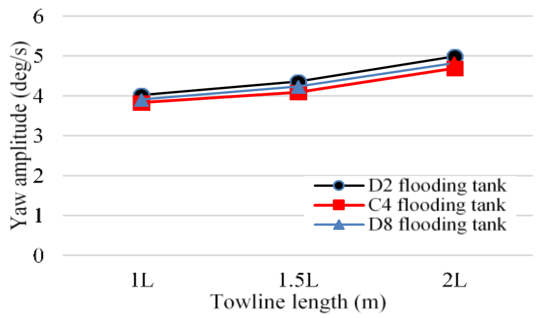


(d) Sway amplitude in starboard side.

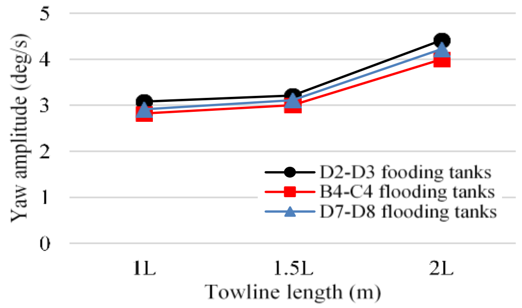
Figure 10. The Tendency of Sway Amplitude of Barge Due to Condition A (a and b), and Condition B (c and d)



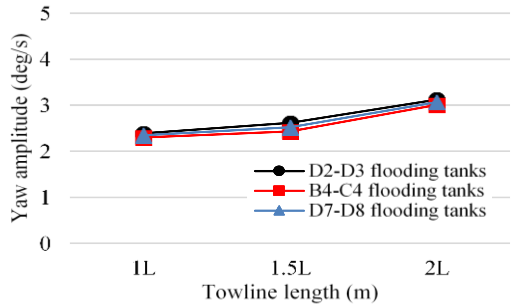
(a) Yaw amplitude in port side.



(b) Yaw amplitude in starboard side.



(c) Yaw amplitude in port side.



(d) Yaw amplitude in starboard side.

Figure 11. The Tendency of Yaw Amplitude of Barge Due to Condition A (a and b), and Condition B (c and d)

CONCLUSION

The experimental investigation of course stability of the barge due to the flooded conditions of one (Condition A) or adjacent two void tanks (Condition B) was conducted successfully. The various towline lengths and load conditions were also considered in this investigation. On the other hand, the flooded conditions on the adjacent two and three void tanks (Condition C) caused the extreme trim by bow or stern and the extreme heeling for full load condition wherein the water levels were over the deck. For this matter, the barge must be considered for adding the longitudinal bulkheads on both sides of the port and starboard to reduce the oscillation of the water mass inside the flooding tank and increase course stability.

The sway and yaw motion amplitude tends to move large to the experienced flooding part. This is caused by the oscillation of the water mass inside the flooding tank. The smallest value is the increased sway and yaw amplitudes affected by the flooded condition of one or adjacent two void tanks on the amidship part. The overall sway and yaw amplitude increases significantly, influenced by the increase of the towline length from 1L to 2L. The average increased sway and yaw amplitude increases the towline lengths due to one flooded void tank is 28.35% and 16.15%, respectively. For the adjacent two flooded void tanks, the average increased sway and yaw amplitude in increasing the towline lengths due to one flooded void tank is 23.05% and 14.09%, respectively.

ACKNOWLEDGMENT

The author would like to thank Ersya Chaeradha Bakhri, Andi Izarman Sutarya, and Hasrul for their kind help in experimenting. They have been a member of Ship Hydrodynamic Labo-based.

REFERENCES

[1] A. H. Magnuson, "Analysis of transport barge nonlinear roll motions in a seaway using an equivalent linearization procedure," in *Proceeding of the ASME 29th International Conference on Ocean, Offshore and Arctic Engineering,* Shanghai, China, June, 2010

[2] N. Starsmore, M. G. Halliday, and W. A. Ewers, "Barge motions and towline tensions measured during a North Sea tow," in *International Symposium on Ocean Engineering Ship Handling*, Gothenburg, Sweden, 1980.

[3] S. Inoue, K. Kijima, M. Murakami, K. Sakata, and S. Lim, "Some study of the course stability of towed ships systems," *Improvement of Barge Towing: Translations of Selected Japanese and Russian Technical Articles*, pp. 20-9, 1980.

[4] M. Tanaka, "Experimental study on the course stability of a towed barge,", *Improvement of Barge Towing: Translations of Selected Japanese and Russian Technical Articles*, pp. 38-46, 1980.

[5] F. Debord, J. Purl, J. Mlady, D.Wisch, and P. Zahn, "Measurement of full-scale motions and comparison with model test and mathematical model predictions," *SNAME Transactions*, vol. 95, pp. 319-35, 1987.

[6] M. L. Lee, "Dynamic stability of nonlinear barge-towing system," *Applied Mathematical Modelling,* vol. 13, no. 12, pp. 693-701, 1989.

[7] S. Dhavalikar, A. Negi, and R. Doshi, "Stability and motion analysis for barges," In *National Conference on Computer Aided Modelling and Simulation in Computational Mechanics, CAMSCM 09*, Itanagar, Arunachal Pradesh, India, 2009, pp. 1-13.

[8] U. I. Zan, H. Yasukawa, K. K. Koh, and A. Fitriadhy, "Model experimental study of a towed ship's motion," in *the 6th Asia-Pacific Workshop on Marine Hydrodynamics-APH Hydro*, Johor Bahru, Malaysia, September 2012.

[9] O. Yendri, "Effect of Water on Flow Fluctuation in River Flow," Journal of Integrated and Advanced Engineering (JIAE), vol. 2, no. 1, pp. 1-10, 2022, doi: 10.51662/jiae.v2i1.23

[10] H. K. Yoon and Y. G. Kim, "Coupled dynamic simulation of a tug-towline-towed barge based on the multiple element model of towline," *Journal of Navigation and Port Research*, vol. 36, no. 9, pp. 707-14, 2012, doi: 10.5394/KINPR.2012.36.9.707

[11] A. Fitriadhy, H. Yasukawa, and K. K. Koh, "Course stability of a ship towing system," *Ocean Engineering*, vol. 64, pp. 135-45, 2013, doi: 10.1016/j.oceaneng.2013.02.001

[12] A. Natskar and S. Steen, "Rolling of a transport barge in irregular seas, a comparison of motion analyses and model tests," *Marine Systems and Ocean Technology*, vol. 8, no. 1, pp. 5-19, 2013, doi: 10.1007/BF03449266

[13] B. W. Nam, S. Y. Hong, Y. M. Choi, I. B. Park, and D. Y. Lee, "A study on towing characteristics of a transport barge during multi-tug operation," in *Proceeding of 24th International Ocean and Polar Engineering Conference, Shanghai*, China, 2014.

[14] S. Lee and S. M. Lee, "Experimental study on the towing stability of barges based on bow shape," *Journal of the Korean Society of Marine Environment and Safety*, vol. 22, no. 7, pp. 800-6, 2016, doi: 10.7837/ kosomes.2016.22.7.800

[15] A. Fitriadhy, M. K. Aswad, N. A. Aldin, N. A. Mansor, A. A. Bakar, and W. B. Wan Nik, "Computational fluid dynamics analysis on the course stability of a towed ship," *Journal of Mechanical Engineering and Sciences*, pp. 2919-29, 2017, doi: 10.15282/jmes. 11.3.2017.12.0263

[16] A. Fitriadhy, N. A. Aldin, and N. A. Mansor, "CFD analysis on course stability of a towed ship incorporated with symmetrical bridle towline," *CFD Letters*, vol. 11, no. 12, pp. 88-98, 2019.

[17] A. Fitriadhy, N. A. Mansor, N. A. Aldin, and A. Maimun, "CFD analysis on course stability of an asymmetrical bridle towline model of a towed ship", *CFD Letters*, vol 11, no. 12, pp. 43-52, 2019.

[18] A. Fitriadhy, N. A. Aldin, and N. A. Mansor, "CFD analysis on course stability of a towed ship in calm water," *Journal of Sustainability Science and Management*, vol. 14, no. 4, pp. 130-8, 2019.

[19] A. Fitriadhy, N. A. Adam, N. Amalina, S. A. Azmi, "Seakeeping prediction of deep-v high speed catamaran using Computational Fluid Dynamics approach," *SINERGI*, vol. 22, no. 3, pp. 139-148, 2018, doi: 10.22441/ sinergi.2018.3.001

[20] A. Fitriadhy, N. A. Adam, CJ. Quah, "Computational prediction of a propeller performance in open water condition," *SINERGI*, vol. 24, no. 2, pp. 163-170, 2020, doi: 10.22441/sinergi.2020.2.010

[21] B. W. Nam, "Numerical investigation on nonlinear dynamic responses of a towed vessel in calm water," *Journal Marine Science and Engineering*, 8, 219, 2020, doi: 10.3390/jmse8030219

[22] B. W. Nam, Y. M. Choi, and S. Y. Hong, "A study on towing characteristics of barge considering wind force', *Journal Ocean Engineering and Technology*, vol. 29, no. 4, pp. 283–90, 2015, doi: 10.5574/KSOE. 2015.29.4.283

[23] iNewsJatim.id, "Ditabrak kapal motor tugboat pembawa tongkang tenggelam 8 ABK hilang", [Online]. Available: https://jatim.inews.id/berita/ditabrak-kapal-motor-tug-boat-pembawa-tongkang-tenggelam-8-abk-hilang [January 23, 2021].

[24] J. Nelson, "Yaw control of towed barge," *Patents*, No. 521137-13 claims (CI. 114-234), August 22, 1967.

[25] L. J. Yang, B. G. Hong, K. Inoue, and H. Sadakane, "Experimental study on braking force characteristic of tugboat," *Journal of Hydrodynamic*, vol. 22, no. 1, pp. 332-37, 2010, doi: 10.1016/S1001-6058(09)60216-X