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Simulation Study on the Influence of Tugboats Capacity on the Safety of Simultaneous Emergency Un-berthing

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ABSTRACT: This paper simulated a simultaneous un-berthing of two container ships. The simulation was intended to determine the number and capacity of tugboats considering an emergency situation in a port. A port provides the number and capacity of tugboats based on the regulation of the Transportation Ministry. In an emergency condition at the terminal and the maximum environmental conditions of wind, wave, and current, the vessel should be un-berthed simultaneously. In this study, two container ships are un-berthed simultaneously in eight scenarios. The available tugboats are simulated using the MMG model to pull the vessels from the jetty turn them in the approaching channel and pass the main channel to achieve the anchorage area. The trajectories of maneuvering using the existing tugs are compared to the normal passage using the appropriate capacity of tugboats. The number and capacity of the tugboat to comply with the safety criteria and avoid collision between the un-berthed ships is proposed.

1 INTRODUCTION

A port operator uses tugboats with a certain number and capacity for berthing and un-berthing vessel based on the requirements released by the regulator. The Indonesian Ministry of Transportation determined the tugboats based on the ships' length. The total number of tugboats and their bollard pull provided by the operator depends on the maximum number of vessels and their main dimensions handled at the same operation time. A high-risk corporation has considered providing tugboat capacity to accommodate emergency conditions where two ships should be un-berthed simultaneously at the maximum environment disturbance forces.

Hundreds of vessels avoid voyaging and staying in the anchorage area of Tanjung Perak Port in extreme wind, current, and wave conditions. In the other case, the vessel should immediately un-berth from the jetty in an emergency. Emergencies may occur due to a fire in the port area, a tsunami, or other incidents and natural disasters. The Indonesian Council of Meteorology, Climatology, and Geophysics predicted an earthquake of 8.7 R and a tsunami of 29 m could occur in East Java. The same disaster can crash West Java in Sunda Strait with about the same intensity, 8.7 R and 30 m. The impact of the disasters can reach the North Coast of Java Island, including Jakarta and Surabaya.

The safety of ship handling has been widely investigated by researchers. It is still an interesting topic of research that relates to several issues and regulations. A study using maneuvering simulation in heavy weather found that the safe ship-handling limit of the Energy Efficiency Design Index (EEDI) power ship is one level below the conventional engine power ship (Nishizaki et al., 2019). The criteria applied to determine the limit of the Beaufort scale were the speed course and trajectory.

Discrete distance was introduced by Inoue (Inoue et al., 2013) to evaluate the safety of berthing maneuvers in case the vessel should be turned before being berthed on the dock. Considering the correlation between the distance of the ship to the quay and the corresponding speed at the position, the study proposed that the threshold of the normal area for the turning maneuver is 0.56L, where L is the ship length. The effect of crosswind on the increasing number of tugboat capacities considering the potential area of water for maneuvering in the second berthing scheme, the scheme of turning before berthing (Inoue et al., 2013), has been found by using the Maneuvering Mathematical Modeling Group (MMG) (Hejun et al., 2021).

In this study, the authors evaluate the required number and capacity of tugboats to assist in the emergency un-berthing maneuver of container ships in the Container Terminal of Surabaya. Firstly, the simulation scenario involved un-berthing using the capacity of tugboats as required by regulation. Secondly, the simulation predicted the required capacity of tugboats under the maximum conditions of the environmental disturbance forces. The outcomes of the two simulations were analyzed and compared to determine the capacity of the tugboats if the maneuvering of two vessels was simultaneous. The simultaneous un-berthing consists of eight scenarios based on the disturbance directions and berthing positions.

2 METHODS

The un-berthing simulation developed in this study refers to the 3-Degrees of Freedom (3-DOF) Mathematical Maneuvering Group (MMG) model (Yasukawa and Yoshimura, 2015) and the hydrodynamic force database for maneuvering prediction of vessels with the block coefficient (CB) of between 0.51 and 0.65 (Yoshimura and Masumoto, 2011). The coefficient block of container ships is 0.57 to 0.66 (Charchalis, 2018). The model expressed in Equations 1 to 3 consists of environmental disturbances and tugboat assistance.

$$(m+m_x)\dot{u}-(m+m_y)v_m r-mx_G r^2 = X_H + X_P + X_R + X_A + X_T \tag{1}$$

$$(m+m_y)\dot{v}_m+(m+m_x)ur+mx_G\dot{r} = Y_H + Y_R + Y_A + Y_T \tag{2}$$

$$(I_{zz}+J_{zz}+mx_G^2)\dot{r}+mx_G(\dot{v}_m+ur) = N_H + N_R + N_A + N_T \tag{3}$$

In the equations, m is the ship's mass and I_{zz} is the moment of inertia for yawing motion. The added mass for surge and sway and added moment of inertia is represented by m_x, m_y, and J_{zz}, respectively. u, v_m, and r represent surging velocity, swaying velocity at the mid-ship, and yawing rate, respectively. The x_G is the longitudinal center of gravity of the ship from mid-ship. X, Y, and N denote surging force, swaying force, and the yawing moment around mid-ship, respectively. Subscript H, P, R, A, and T denote the ship's hull, propeller, rudder, wind, and tugs, respectively. β, δ, and ψ denote the drift angle, rudder angle, and the ship's true heading, respectively.

The hull forces and moments are calculated using Equations 4 to 6. This study adopts the approximation of the hydrodynamic derivatives based on the ship's main dimension published by Taimura (Taimuri et al., 2020), adopting the rapid estimation from several publications, including (Norrbin, 1970), (Kijima et al., 1990), (Brix, 1993) and (Yoshimura and Masumoto, 2011).

$$X_H = \frac{1}{2}\left(-R_0' + X_{vv}'v'^2 + X_{vr}'v_m'r' + X_{rr}'r'^2 + X_{vvvv}'v_m'^4\right)\rho LdU^2 \tag{4}$$

$$Y_H = \frac{1}{2}\left(Y_v'v_m' + Y_r'r' + Y_{vvv}'v_m'^3 + Y_{vvr}'v_m'^2 r' + Y_{vrr}'v_m'r'^2 + Y_{rrr}'r'^3\right)\rho LdU^2 \tag{5}$$

$$N_H = \frac{1}{2}\left(N_v'v_m' + N_r'r' + N_{vvv}'v_m'^3 + N_{vvr}'v_m'^2 r' + N_{vrr}'v_m'r'^2 + N_{rrr}'r'^3\right)\rho L^2 dU^2 \tag{6}$$

In equations 4 to 6, ρ denotes the water density, and L, d, and U denote the ship's length between perpendiculars, ship draft, and resultant speed, respectively. $\frac{1}{2}\rho LdU^2$ and $\frac{1}{2}\rho L^2 dU^2$ are non-dimensional force and non-dimensional moment, respectively.

The wind forces and moments acting on the ship and affecting the ship's maneuvering are calculated based on a constant and uniform wind (Yasukawa and Sakuno, 2020). This simulation used non-dimensional time-averaged wave-induced steady forces and a yaw moment. Forces and moments due to tugboats and currents are referred to in another paper (Putu Sindhu Asmara and Husodo, 2022).

3 RESULTS AND DISCUSSIONS

3.1 *Subject Ship*

The subject ship trained in the simulation is a container ship with a capacity of 4300 TEUs, as seen in Table 1. The vessel is the maximum capacity of the vessel berthed in the Surabaya Container Terminal derived from Automatic Identification System (AIS) data. The same dimension of the vessel is assumed to be un-berthed at the same time in the Jetty called Jetty 1 and Jetty 2.

Table 1. Ship Dimensions

LOA (m)	DWT (t)	Capacity (TEUs)	Beam (m)	Draught (m)	Block Coefficient
262.08	51693	4300	32.25	12	0.65

3.2 *Environmental Disturbances and Scenarios*

The water depth is 15 m, and according to data from the Meteorology, Climatology, and Geophysics Council in Tanjung Perak Station, the high current speed is up to 0.87 m/s, the low tide is -1.2 m, and the high tide is 0.6 m. Accordingly, the water depth at high tide is 15.6 m, and at low tide is 13.8 m. The maximum wind conditions for the un-berthing maneuver is 30 knots with a maximum wave height of 1.5 m for a period of 6 seconds, as seen in Table 2. The water depth of the turning basin is 15 m. The vessels were berthed in eight scenarios by the starboard side or port side and environmental condition 1 or condition 2, as seen in Table 3.

Table 2. Environmental Conditions

Environmental Condition	Condition 1	Condition 2
Maximum wind speed (knots)	30 (NW to SE)	30 (NW to SE)
Maximum wave	Hs: 1.5 m T: 6s	Hs: 1.5 m T: 6s
Maximum current velocity (m/s)	0.87 (East to West)	0.87 (West to East)
Maximum tidal (m)	0.6 (High Tide)	-1.2 (Low Tide)
Water Depth (m)	15	15

Table 3. Scenarios by Environmental and Ship Condition

Scenario	Environmental Condition	Ship and condition
1	Wind 30 knots from NW (315°)	Jetty 1: Starboard – 4300 TEUs – Laden Jetty 2: Starboard – 4300 TEUs – Laden
2	Wave 1.5m, 6s from NW (315°)	Jetty 1: Port Side – 4300 TEUs – Laden Jetty 2: Port Side – 4300 TEUs – Laden
3	Current 0.87 m/s to W (270°)	Jetty 1: Port Side – 4300 TEUs – Laden Jetty 2: Starboard – 4300 TEUs – Laden
4		Jetty 1: Starboard – 4300 TEUs – Laden Jetty 2: Port Side – 4300 TEUs – Laden
5	Wind 30 knots from NW (315°)	Jetty 1: Starboard – 4300 TEUs – Laden Jetty 2: Starboard – 4300 TEUs – Laden
6	Wave 1.5m, 6s from NW (315°)	Jetty 1: Port Side – 4300 TEUs – Laden Jetty 2: Port Side – 4300 TEUs – Laden
7	Current 0.87 m/s to E (95°)	Jetty 1: Port Side – 4300 TEUs – Laden Jetty 2: Starboard – 4300 TEUs – Laden
8		Jetty 1: Starboard – 4300 TEUs – Laden Jetty 2: Port Side – 4300 TEUs – Laden

3.3 *Acceptance Criteria*

The acceptance criteria for the success of the simulations are:

1. At the first stage of the un-berthing maneuver, the vessel should be pulled parallel to the jetty for a distance of at least 100 m. This is determined based on the discussion with a port pilot.
2. The vessels should not be out of the waterway to avoid collision in the anchorage area.
3. The distance between two vessels is not less than 0.89L, where L is the ship length (Inoue et al., 1994).

The status of maneuvering is successful if all criteria are fulfilled. If, in the first stage, all tugboats use out of full power (more than 85% of the maximum BP, Bollard Pull), the status is marginal, although all criteria are fulfilled.

3.4 *The Capacity of Tugboats*

Government regulation regarding the capacity of tugboats to serve berthing and un-berthing maneuver of the vessels having a length of more than 250 m is the total bollard pull of 125 t. In normal conditions, the vessel was served by 3 tugboats with a maximum of 45 tons of bollard pull, each.

3.5 *Maneuvering Steps*

The vessel should leave the port area through the West Part of the Surabaya Waterway. The centerline of the channel is presented as two straight lines as seen in Figure 1. The two red spot in the figure are the position of the red buoy as the boundary area and the separation between the channel and the anchorage area. In the case of berthing on the starboard side, the first step of the un-berthing maneuvering is to pull out the vessel parallel to the jetty. The second is to turn the vessel, and the third is to follow the waterway. In the case of berthing on the port side, the second step isn't applicable.

3.6 *Maneuvering Validation*

The maneuvering simulator was validated using the trajectories of Pure Car Carrier (PCC) having a coefficient block of 0.54 [I.P.S. Asmara, 2015]. In this paper, the simulation program is added by the force and moment generated by the bollard pull of tugboats. The surging force, swaying force, and yawing moment due to the tugboats are presented by XT, YT, and NT, respectively in equations 1 to 3.

3.7 *Simulation Outcomes*

In scenario 1, the vessel berths on the starboard side. Figure 1 shows the three tugboats with a capacity of 45 tons bollard pull succeed to pull out and turn the vessel, and avoid entering the anchorage area. The output of maneuvering is presented by figures plotting the vessel every 30 seconds, showing the position and the heading. The outcome of this scenario using 3 tugboats is marginal due to the capacity of all tugboats delivered to the vessel being 100% of the maximum bollard pull as presented in Table 4.

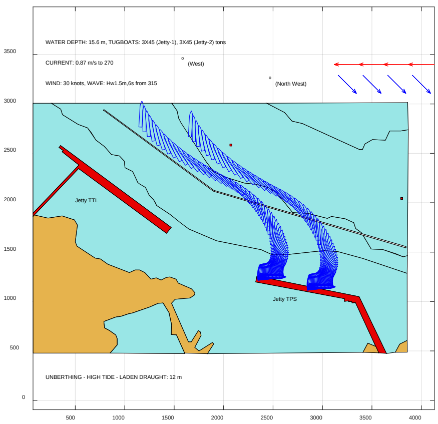

Figure 1. Un-berthing Trajectory of Scenario 1 using 3 Tugboats

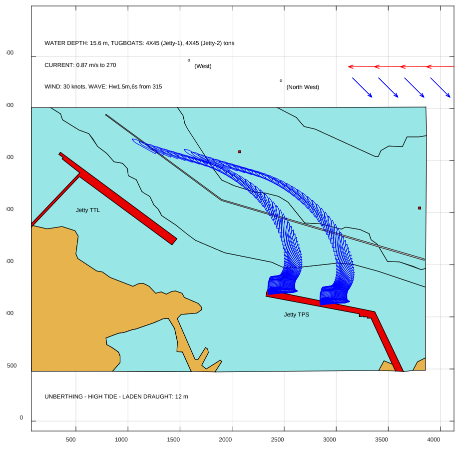

Figure 2. Un-berthing Trajectory of Scenario 1 using 4 Tugboats

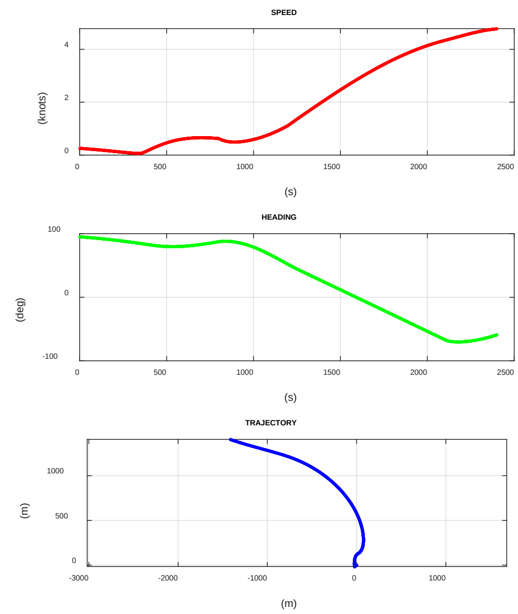

Figure 3. Berthing Speed, Heading, and Trajectory in Scenario 1 using 4 Tugboats

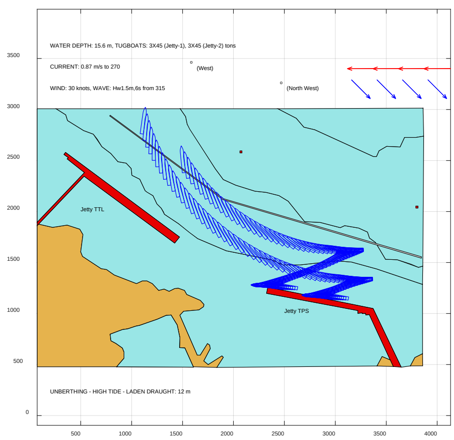

Figure 4. Un-berthing Trajectory of Scenario 2 using 3 Tugboats

Figure 3 shows the speed, heading, and trajectory of the vessel in this scenario using 4 tugboats. By using 4 tugboats, the outcomes are successful, as seen in Figure 2 and Table 5 which show the passage is in the waterway and the force delivered by the tugboats is 85%. The additional tugboat is able to result in the improvement of the heading of the vessel at the end stage of maneuvering.

In scenario 2, the vessel berths on the port side. Figure 4 shows the three tugboats able to pull out the vessel. The capacity of all tugboats delivered to the vessel is 100% of the maximum bollard pull as presented in Table 6. Table 6 shows the tugboat element for un-berthing from Jetty 2. The period of the first step is 900 s for Jetty 2 and 1200 s for Jetty 1. The interval of 300 s is intended to keep a safe distance between the vessels. The outcome of this scenario using 3 tugboats is marginal.

By using 4 tugboats, the passage of the vessel is closer to the centerline of the waterway, as seen in Figure 5. The figure shows the vessel drifted at the beginning of the maneuvering. The phenomenon can be avoided by releasing the mooring line after the tugboats are ready to pull out of the vessel. Table 7 shows the force delivered by the tugboats is 85%. The interval period between the maneuvering in Jetty 1 and Jetty 2 in the first step is 100 s.

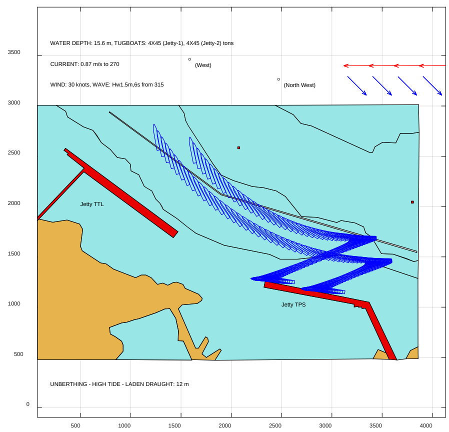

Figure 5. Un-berthing Trajectory of Scenario 2 using 4 Tugboats

In scenario 3, the vessel berths on the port side in Jetty 1 and on the starboard side in Jetty 2. The simultaneous un-berthing maneuver in this scenario leads to an accident of ship-to-ship collision, as seen in Figure 6. The tugboats should handle the un-berthing maneuver in a sequential method.

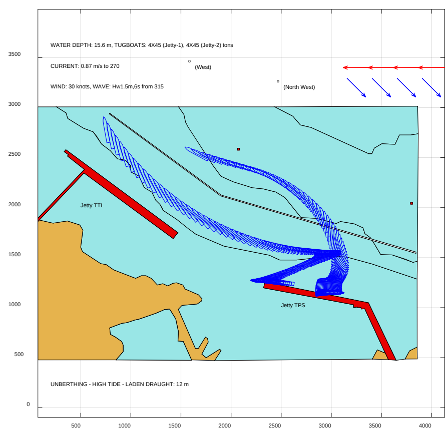

Figure 6. Un-berthing Trajectory of Scenario 3 using 4 Tugboats

Table 4. Tugboat Elements for Scenario 1 using 3 Tugboats

Step	Time (s)	Engine Status	Rudder Angle	Astern Tug 45 tons Bollard Pull		Mid-ship Tug 45 tons Bollard Pull		Forward Tug 45 tons Bollard Pull	
				Force	Direction	Force	Direction	Force	Direction
1	0–350	Slow	0°	-	-	-	-	-	-
2	350–800	Slow	0°	100%×45t	-85°	100%×45t	-85°	100%×45t	-85°
3	800–2100	Slow	0°	100%×45t	90°	100%×45t	90°	100%×45t	-90°
4	2100–2400	Slow	0°	100%×45t	-90°	100%×45t	-90°	100%×45t	90°

Table 5. Tugboat Elements for Scenario 1 using 4 Tugboats

Step	Time (s)	Engine Status	Rudder Angle	Astern Tug 45 tons Bollard Pull		Quarter Tug 45 tons Bollard Pull		Shoulder Tug 45 tons Bollard Pull		Forward Tug 45 tons Bollard Pull	
				Force	Direction	Force	Direction	Force	Direction	Force	Direction
1	0–350	Slow	0°	-	-	-	-	-	-	-	-
2	350–800	Slow	0°	85%×45t	-85°	85%×45t	-85°	85%×45 t	-85°	85%×45t	-85°
3	800–2100	Slow	0°	85%×45t	90°	85%×45t	90°	-	-	85%×45t	-90°
4	2100–2400	Slow	0°	85%×45t	-90°	85%×45t	-90°	-	-	85%×45t	90°

Table 6. Tugboat Elements for Scenario 1 using 4 Tugboats in Jetty 2

Step	Time (s)	Engine Status	Rudder Angle	Astern Tug 45 tons Bollard Pull		Mid-ship Tug 45 tons Bollard Pull		Forward Tug 45 tons Bollard Pull	
				Force	Direction	Force	Direction	Force	Direction
1	0–900	Off	0°	100%×45t	160°	100%×45t	160°	100%×45t	160°
2	900–3000	Slow	0°	85%×45t	-155°	-	-	85%×45t	25°

Table 7. Tugboat Elements for Scenario 2 using 4 Tugboats in Jetty 2

Step	Time (s)	Engine Status	Rudder Angle	Astern Tug 45 tons Bollard Pull		Quarter Tug 45 tons Bollard Pull		Shoulder Tug 45 tons Bollard Pull		Forward Tug 45 tons Bollard Pull	
				Force	Direction	Force	Direction	Force	Direction	Force	Direction
1	0–900	Off	0°	85%×45t	160°	85%×45t	160°	85%×45t	160°	85%×45t	160°
2	900–3000	Slow	0°	85%×45t	-155°	-	-	-	-	85%×45t	25°

Table 8. Tugboat Elements for Scenario 5 using 3 Tugboats

Step	Time (s)	Engine Status	Rudder Angle	Astern Tug 45 tons Bollard Pull		Mid-ship Tug 45 tons Bollard Pull		Forward Tug 45 tons Bollard Pull	
				Force	Direction	Force	Direction	Force	Direction
1	0–700	Off	0°	100%×45t	-160°	100%×45t	-160°	100%×45t	-160°
2	700–2700	Slow	0°	100%×45t	90°	100%×45t	0°	100%×45t	-90°

Table 9. Tugboat Elements for Scenario 6 using 3 Tugboats

Step	Time (s)	Engine Status	Rudder Angle	Astern Tug 45 tons Bollard Pull		Mid-ship Tug 45 tons Bollard Pull		Forward Tug 45 tons Bollard Pull	
				Force	Direction	Force	Direction	Force	Direction
1	0–600	Slow	0°	-	-	85%×45t	90°	85%×45t	30°
2	600–1600	Slow	0°	85%×45t	-160°	-	-	85%×45t	20°

Table 10. Summary of the Maneuvering Outcome

Scenario	Tug deployment	Outcome	Scenario summary
1	Jetty 1: 3x45 tons BP	Jetty 1: Marginal	Un-berthing from Jetty 1: Comply with all criteria
	Jetty 2: 3x45 tons BP	Jetty 2: Marginal	Un-berthing from Jetty 2: Comply with all criteria
2	Jetty 1: 3x45 tons BP	Jetty 1: Marginal	Un-berthing from Jetty 1: Comply with all criteria
	Jetty 2: 3x45 tons BP	Jetty 2: Marginal	Un-berthing from Jetty 2: Comply with all criteria
3	Jetty 1: 3x45 tons BP	Jetty 1: Failure	Un-berthing from Jetty 1: Not comply with criteria 3
	Jetty 2: 3x45 tons BP	Jetty 2: Failure	Un-berthing from Jetty 2: Not comply with criteria 3
4	Jetty 1: 3x45 tons BP	Jetty 1: Marginal	Un-berthing from Jetty 1: Comply with all criteria
	Jetty 2: 3x45 tons BP	Jetty 2: Marginal	Un-berthing from Jetty 2: Comply with all criteria
5	Jetty 1: 3x45 tons BP	Jetty 1: Marginal	Un-berthing from Jetty 1: Comply with all criteria
	Jetty 2: 3x45 tons BP	Jetty 2: Marginal	Un-berthing from Jetty 2: Comply with all criteria
6	Jetty 1: 3x45 tons BP	Jetty 1: Successful	Un-berthing from Jetty 1: Comply with all criteria
	Jetty 2: 3x45 tons BP	Jetty 2: Successful	Un-berthing from Jetty 2: Comply with all criteria
7	Jetty 1: 3x45 tons BP	Jetty 1: Marginal	Un-berthing from Jetty 1: Comply with all criteria
	Jetty 2: 3x45 tons BP	Jetty 2: Marginal	Un-berthing from Jetty 2: Comply with all criteria
8	Jetty 1: 3x45 tons BP	Jetty 1: Marginal	Un-berthing from Jetty 1: Comply with all criteria
	Jetty 2: 3x45 tons BP	Jetty 2: Marginal	Un-berthing from Jetty 2: Comply with all criteria

In scenario 4, the vessel berths on the starboard side in Jetty 1 and on the port side in Jetty 2. The simultaneous un-berthing maneuver in this scenario can be applied using 3 tugboats, as seen in Figure 6, but the force delivered by the tugboats is 100% of the maximum bollard pull.

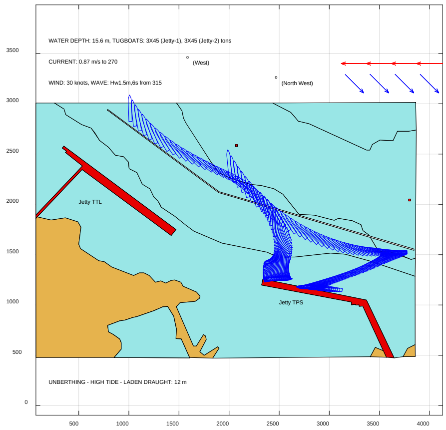

Figure 7. Un-berthing Trajectory of Scenario 4 using 3 Tugboats

Figure 8 shows the 3 tugboats able to serve the simultaneous maneuvering scenario 5. In the first step, the vessel tends to drift and succeeds in pulling out and turning to the West heading. The vessel is also not out of the waterway. Table 7 shows the tugboats delivered 100% of the maximum bollard pull.

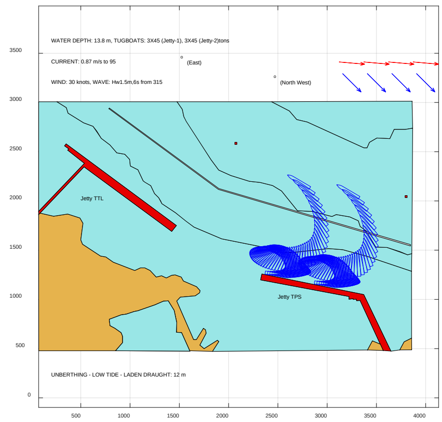

Figure 8. Un-berthing Trajectory of Scenario 5 using 3 Tugboats

In scenario 6, the existing tugboat successfully un-berth the 2 container ships simultaneously, as seen in Figure 9, and the force delivered by the tugboat is 85%, as presented in Table 9.

Scenario 7 and scenario 8 are a combination of scenario 5 and scenario 6. The maneuvers comply with all the criteria, but the bollard pull delivered to the vessel is more than 85%, so the outcomes of the maneuvers are marginal.

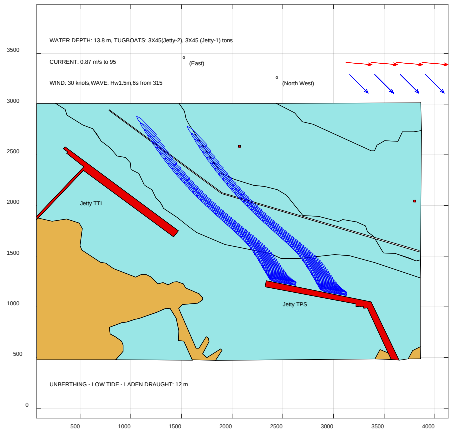

Figure 9. Un-berthing Trajectory of Scenario 6 using 3 Tugboats

Table 10 shows the summary of the outcome of the simulation for 8 scenarios. Based on the 8 scenarios, the probability of existing tugboats successfully or unsuccessfully performing the maneuvering simultaneously is 12.5%. The probability of marginal status is 75%, and this outcome can be improved by using four tugboats for each jetty. Based on the outcome summary, the government requirement on the number of tugboats is not appropriate to provide an emergency response to maritime transportation. One additional tugboat should be provided in the port.

4 CONCLUSIONS AND FUTURE WORKS

In this study, the authors conducted a simulation of the un-berthing using the MMG model in heavy weather. The number and capacity of tugboats required based on the regulation were applied in the simulation, and the probability of successfully un-berthing the vessel was determined based on a case study implemented in a container terminal using 8 scenarios. The study found that the probability of success or failure is the same, 12.5%, and the status of marginal is 75%. The probability of success can be improved up to 87.5% by using additional tugboats. The failure probability of simultaneous un-berthing is the potential of ship-to-ship collision. In this case study, the success status is for scenario 6 and the failure status is for scenario 3. The hazard of scenario 3 can be mitigated by implementing sequential un-berthing.

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