Scientific Journals
of the Maritime University of Szczecin

Zeszyty Naukowe
Akademii Morskiej w Szczecinie

2018, 56 (128), 63–70
ISSN 1733-8670 (Printed)
ISSN 2392-0378 (Online)
DOI: 10.17402/315

Received: 23.09.2018
Accepted: 26.11.2018
Published: 17.12.2018

The impact of LNG carrier transit on fairway capacity

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Key words: waterborne transportation, liquefied natural gas (LNG) ship, approach channel capacity, vessel traffic control, fairway capacity, LNG Port

Abstract

Liquefied natural gas (LNG), as one of the main sources of clean energy, has witnessed great growth in marine transportation in recent years. Due to the potential catastrophic consequences in case of a vessel traffic accident, the guidelines of the design of an LNG Port and the regulation of traffic management require that a mobile safety zone be set up for the transit of an LNG carrier, that is, a moving safety area around the carrier that excludes other ship traffic. To study the impact of a safety zone on channel capacity, this paper has presented a mathematical model to calculate the impact ratio of a large LNG ship on channel capacity considering different speeds and sailing modes. As a case study, an approach channel to a new LNG port that was developed in Yueqing bay, Zhejiang province, East China, has been analyzed during the concept design of the port with the aim of receiving ships with a capacity of 145,000 m^3. Based on the model, the impact ratio on the whole channel and the segmented channel when a carrier arrives at and leaves the berth has been calculated. The methodology can support the job of port design and vessel traffic management to improve the capacity, efficiency and safety of a waterway.

Introduction

Natural gas supplies are critical for societies that are dependent on its use for industrial production and electricity generation; roughly 40 percent is used for industrial purposes (Berle, Norstad & Asbjørnslett, 2013). The US Energy Information Agency (EIA, 2010) expects that 36 percent of all electricity generation in 2035 will use natural gas. A growing share of traded natural gas is being transported on ships in the form of liquefied natural gas (LNG). The EIA anticipates that shipped LNG volumes will increase 2.4 times, from 226 billion m^3 to 538 billion m^3 from 2007 and 2035. The shipment capacity of LNG increased from 5 m^3 in 1980 to 35 million m^3 in 2007 and was expected to reach 55 million m^3 by 2010 – but the total traded volume reached 483 million m^3 in 2010.

China is one of the countries which imports LNG from overseas, and the biggest market share of the LNG is transported on special ships. China's energy planners are paying great attention to the use of domestic and imported natural gas recently, in order to achieve a sustainable balance between strong economic growth and environmental protection (Shi et al., 2010). This has contributed to the recent dramatic growth of the LNG trade in mainland China. Imports of LNG soared from 483 tons in 2005 to about 3.5 million tons (Mt) in 2009 (Xinhua Net, 2010). It has been predicted that China will import 46 Mt of LNG in 2020 (Sethuraman, 2010). Along with the increased import capacity, China's LNG industry is burgeoning and booming.

In recent years, there are a growing number of LNG terminals that have been constructed in the coastal ports of China. With the rapid construction and expansion of infrastructure such as ports and berths, especially the completion and operation of large-scale LNG terminals, the through capacity of the waterways has become one of the main factors that affect the development and service level of the ports. In addition, it is prescribed in the design specification of Liquefied Natural Gas Ports and Jetties in China that when LNG ships enter and leave the harbor, a mobile safety zone should be set up. For large LNG ships, traffic control shall also be carried out, and escort ships shall be provided. All these regulations for the design of LNG terminals have improved the safety status of the waterways. However, these regulations may also impede the normal operation of the waterways and have some influence on the channel's capacity, especially when an LNG ship is transiting the waterway. To improve the channel's capacity and enhance the safety of waterway transportation from the perspective of vessel traffic arrangement and control, according to the detailed influence on specific routes of an LNG ship, it is of great significance to analyze the influence of channel capacity on a large LNG ship's navigation for different speeds and sailing modes.

To improve seaport channel capacity, many researchers have dedicated great effort to this area. For example, Ning et al. (Ning et al., 2008) proposed the tentative construction standard of a two-way traffic channel and tried to see if it could improve the waterway's capacity; Guo et al. (Guo et al., 2010) and Wang et al. (Wang et al., 2015) gave the definition of a seaport's channel capacity and analyzed the influence of a port's service level or safety level on channel capacity, respectively; Liu et al. (Liu et al., 2016) proposed a dynamic ship domain model that takes into consideration the waterways' navigation condition, ship behaviors, ship types and sizes and operators' skill, to estimate the capacity of restricted water channels. Zhang et al. (Zhang et al., 2017) developed a typical capacity estimation model based on ship domain theory and analyzed various physical characteristics, such as weather conditions, and vessel characteristics in order to derive the related impacts of each on the overall capacity of a bifurcated estuary; Wang et al. (Wang et al., 2017) analyzed the impact of three kinds of key influencing factors, including various rules of ships entering and leaving port, multiple navigation rules of ships going through waterways and different scales of inner anchorages, on improving the channel capacity of ports. How much each kind of influencing factor could improve the capacity was also quantitatively obtained.

The above references have introduced various aspects of each study on promotion measures of channel capacity, which have provided a strong foundation for further studies. However, there has been little research that involved the influence analysis of a large LNG ship's navigation on channel capacity.

To improve the channel capacity and enhance the safety of waterway transportation from the perspective of vessel traffic arrangement and control, this paper has analyzed the influence of a large LNG ship's navigation on channel capacity for different speeds and sailing modes. Aimed at ships with a volume of 145,000 m^3, the impact ratio on both the whole channel and the segmented channel has been calculated.

Research area

In this paper, the channel to an LNG terminal in Taizhou city of Zhejiang province in China was taken as the research area. The volume of the LNG ship used in this study was about 145,000 m^3, and the ship was 292 meters long and 46 meters wide.

The details of the study area and the ship routes have been shown in Figure 1. LNG ships travel along the Yueqing Bay channel, from the entrance of the channel (point A), sail to point B, and then turn 45 degrees to point C, arrive at point C, and then turn about 79 degrees towards point D, then arrive at point D, turn about 49 degrees, and arrive at point E (the LNG terminal). For the convenience of this research, the waterway in this paper mainly refers to the channel from A to D.

Mathematical model to calculate the impact ratio on channel capacity

Based on the ship domain and ship safety distance theory, in order to maintain the safety of navigation, every ship should keep a certain distance from other vessels. The channel capacity in this paper has been defined as the maximum number of ships that the channel can accommodate.

The influence of ships on channel capacity is strongly related to the length of the channel, density of ship traffic, ship dimensions and so on. It was assumed that the length of the channel was L^i_{ch}, the average length of the vessels was L^i_{sh}, the average speed of the vessels was V^i_{ch}, the mean time interval of the vessels was T^i_{int}, the average length of an LNG ship was L_{LNG}, the average speed of an LNG ship was V^i_{LNG}, and the safety zone of an LNG ship was Z_{saf} long.

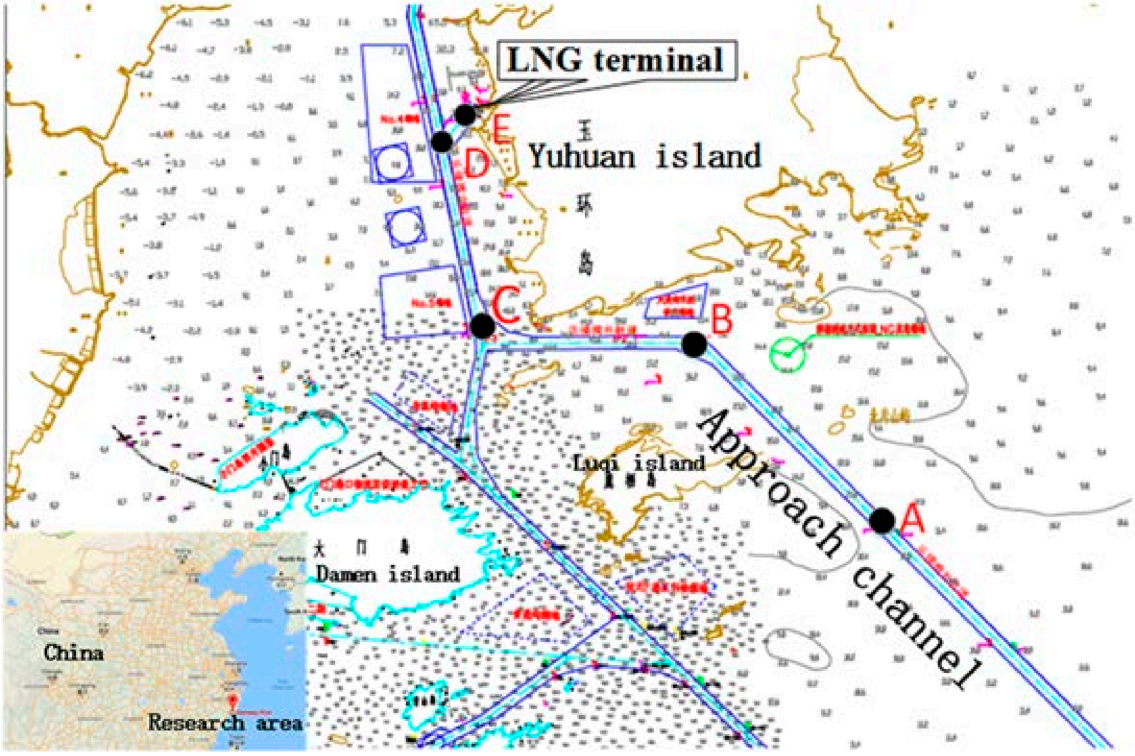

Figure. 1. Research area

As for the two-way navigable channel, when an LNG ship uses it as a one-way navigable channel, other vessels need to wait at anchorage or in their berth. The distance between the waiting point and the channel is supposed to be S_{wait}; Considering the safety of navigation, it is impossible for an LNG ship to be just at the entrance of the channel when the channel is clear, but there should be a safe distance, taken as S_{LNG}; In addition, when clearing the channel, there may be some vessels that have just set off towards the channel but have not yet entered it. These vessels may also have some influence on the time needed to clear the channel. Therefore, some extra distance should be considered as the supplement to the time needed to clear the channel, taken as S_{clear}.

LNG ships passing through the channel as a non-exclusive mode

The non-exclusive mode means that the LNG ships can pass through a one-way navigable channel or pass through a two-way navigable channel with other vessels. In this mode, the impact quantity of an LNG ship on the channel capacity for every transit was taken as N^i_s, which can be calculated from formula (1):

$$N_s^i = \frac{Z_{\text{saf}} + L_{\text{LNG}}}{V_{\text{LNG}}^i T_{\text{int}}^i} \tag{1}$$

The impact ratio is the proportion of the impact quantity on one day's waterway throughput capacity, which was taken as η^i_{one} and can be calculated from formula (2):

$$\eta_{\text{one}}^i = \frac{N_s^i}{\dfrac{24 \cdot 3600}{T_{\text{int}}^i}} = \frac{Z_{\text{LNG}} + L_{\text{LNG}}}{24 \cdot 3600 \cdot V_{\text{LNG}}^i} \tag{2}$$

LNG ships passing through a channel as an exclusive mode

The exclusive mode means that the LNG ships use the two-way navigable channel as a one-way navigable channel, and another vessel cannot navigate in it at the same time. In this sailing mode, the influence of an LNG ship's navigation on the traffic flow differs from the same direction and opposite direction. The impact quantity of an LNG ship on channel capacity with the traffic flow in the same direction at every transit was taken as N_d^{same}, which can be calculated from formula (3):

$$N_d^{\text{same}} = \frac{L_{ch}^i + L_{sh}^i + S_{\text{clear}}}{V_{ch}^i T_{\text{int}}^i} + \frac{S_{\text{LNG}} + Z_{\text{saf}} + L_{\text{LNG}}}{V_{\text{LNG}}^i T_{\text{int}}^i} + \\ + \frac{S_{\text{wait}}}{V_{ch}^i T_{\text{int}}^i} \tag{3}$$

The impact quantity of an LNG ship on channel capacity with the traffic flow in the opposite direction at every transit was taken as N_d^{verse}, which can be calculated from formula (4):

$$N_d^{\text{verse}} = \left(\frac{L_{ch}^i + L_{sh}^i + S_{\text{clear}}}{V_{ch}^i} + \frac{S_{\text{LNG}} + Z_{\text{saf}} + L_{\text{LNG}}}{V_{\text{LNG}}^i} + \frac{S_{\text{wait}}}{V_{ch}^i} + \frac{L_{ch}^i}{V_{\text{LNG}}^i} \right) \cdot \frac{1}{T_{\text{int}}^i} \tag{4}$$

The impact ratios on one day's waterway throughput capacity with the traffic flow in the same or opposite direction were taken as $\eta_{\text{two}}^{\text{same}}$ and $\eta_{\text{two}}^{\text{verse}}$ respectively, which can be calculated from formulas (5) and (6):

$$\eta_{\text{two}}^{\text{same}} = \frac{\dfrac{N_d^{\text{same}}}{24 \cdot 3600}}{T_{\text{int}}^i} = \frac{L_{ch}^i + L_{sh}^i + S_{\text{clear}} + S_{\text{wait}}}{24 \cdot 3600 \cdot V_{ch}^i} + \frac{Z_{\text{saf}} + L_{\text{LNG}} + S_{\text{LNG}}}{24 \cdot 3600 \cdot V_{\text{LNG}}^i} \tag{5}$$

$$\eta_{\text{two}}^{\text{verse}} = \frac{\dfrac{N_d^{\text{verse}}}{24 \cdot 3600}}{T_{\text{int}}^i} = \frac{L_{ch}^i + L_{sh}^i + S_{\text{clear}} + S_{\text{wait}}}{24 \cdot 3600 \cdot V_{ch}^i} + \frac{L_{ch}^i + Z_{\text{saf}} + L_{\text{LNG}} + S_{\text{LNG}}}{24 \cdot 3600 \cdot V_{\text{LNG}}^i} \tag{6}$$

Case study

The impact ratio on different sub-channels

When LNG ships enter or leave the channel, the most affected channel is AD (see Figure 1). Therefore, only the impact ratio in sub-channel AD has been analyzed. According to the actual situation of the research area, the calculation parameters involved in this study have been listed in Table 1. Combined with the proposed mathematical model, the result of the impact ratio for different sub-channels can be seen in Figures 2–4 and Table 2.

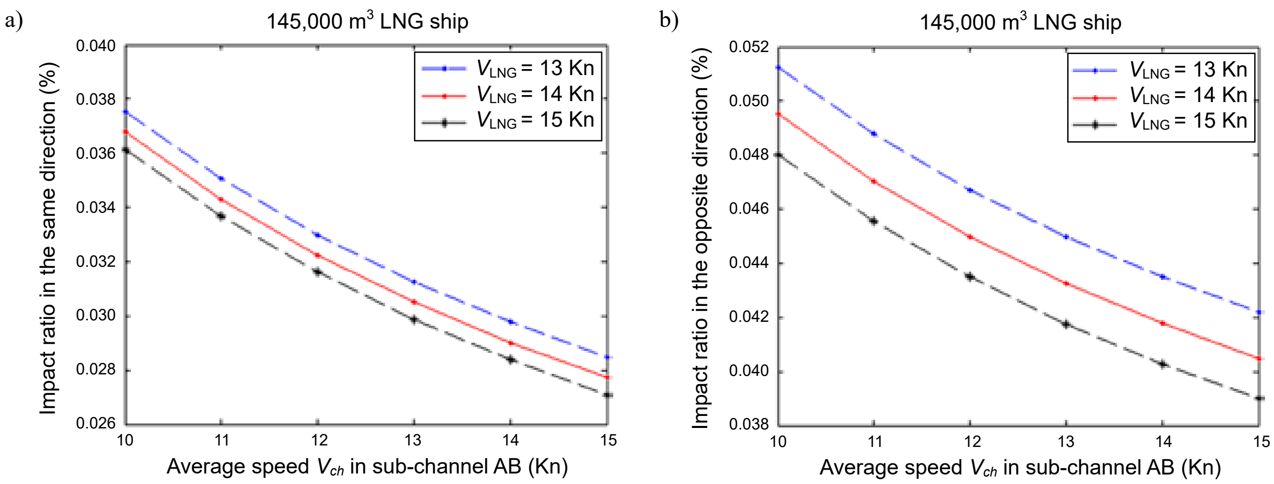

Figure 2. The impact ratio on sub-channel AB, a) Impact ratio in the same direction, b) Impact ratio in the opposite direction

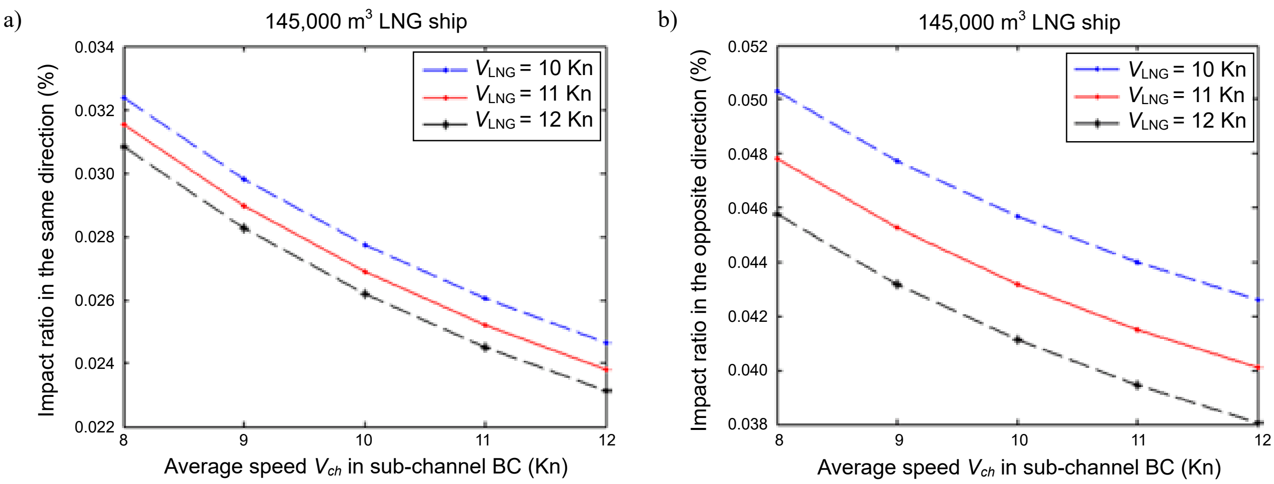

Figure 3. The impact ratio on sub-channel BC, a) Impact ratio in the same direction, b) Impact ratio in the opposite direction

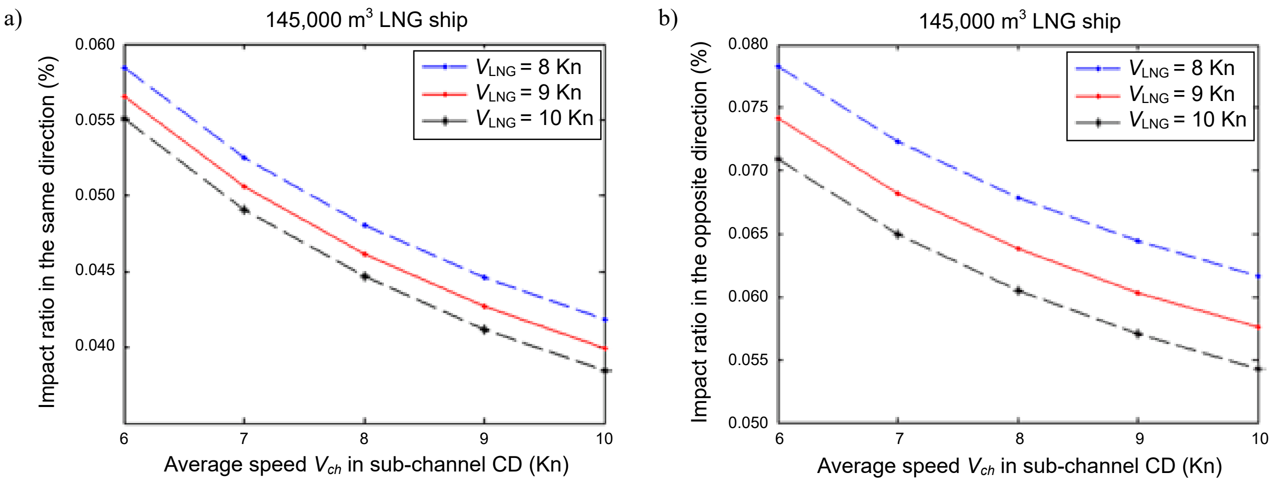

Figure 4. The impact ratio on sub-channel CD, a) Impact ratio in the same direction, b) Impact ratio in the opposite direction

Table 1. Calculation parameters for different sub-channels

Parameter	Unit	Value		
		Sub-channel AB	Sub-channel BC	Sub-channel CD
L^i_{ch}	nm	4.16	4.18	3.7
L^i_{sh}	m	300	250	200
V^i_{ch}	kn	10 ~ 15	8 ~ 12	6 ~ 10
L_{LNG}	m		292	
V^i_{LNG}	kn	13 ~ 15	10 ~ 12	8 ~ 10
Z_{saf}	n mile	2	2	2
S_{wait}	n mile	1	0	1
S_{LNG}	n mile	1	0	1
S_{clear}	n mile	1	0	1

Table 2. The impact ratio on different sub-channels

Sub-channel	V_{LNG}/kn	Impact ratio in the same direction/%	Impact ratio in the opposite direction /%
AB	13	2.82 ~ 3.73	4.21 ~ 5.15
	14	2.78 ~ 3.62	4.08 ~ 4.93
	15	2.69 ~ 3.58	3.91 ~ 4.79
BC	10	2.47 ~ 3.24	4.23 ~ 5.03
	11	2.38 ~ 3.16	4.02 ~ 4.78
	12	2.31 ~ 3.08	3.82 ~ 4.57
CD	8	4.26 ~ 5.64	6.18 ~ 7.72
	9	4.15 ~ 5.43	5.71 ~ 7.41
	10	3.78 ~ 5.49	5.46 ~ 7.18

The impact ratio on the whole channel

In order to calculate the impact ratio of an LNG ship's navigation on the whole channel, the calculation parameters involved in this study have been listed in the Table 3. Based on the proposed mathematical model, the result of the impact ratio in the whole channel can be seen in Figure 5 and Table 4.

(1) The impact ratio in the same and opposite direction for different lengths of an LNG ship in the channel.

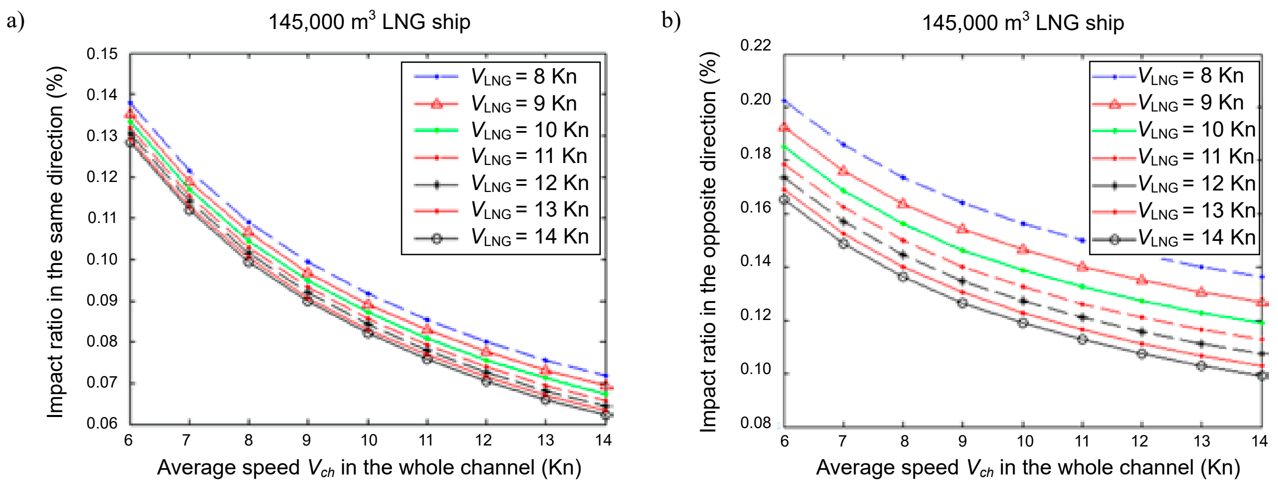

Figure 5. The impact ratio on the whole channel, a) Impact ratio in the same direction, b) Impact ratio in the opposite direction

Table 3. Calculation parameters for the whole channel

Parameter	Unit	Value
		Whole channel
L^i_{ch}	nm	12.04
L^i_{sh}	m	250 (average)
V^i_{ch}	kn	6 ~ 14
L_{LNG}	m	292
V^i_{LNG}	kn	8 ~ 14
Z_{saf}	n mile	2
S_{wait}	n mile	2
S_{LNG}	n mile	2
S_{clear}	n mile	2

According to Figures 6 and 7, it was easy to see that as the length of an LNG ship increased, its impact ratio on the capacity of the channel also increased, and its influence rate on a ship facing the ship was the same as that of the ship. The impact ratio of the ship was slightly larger.

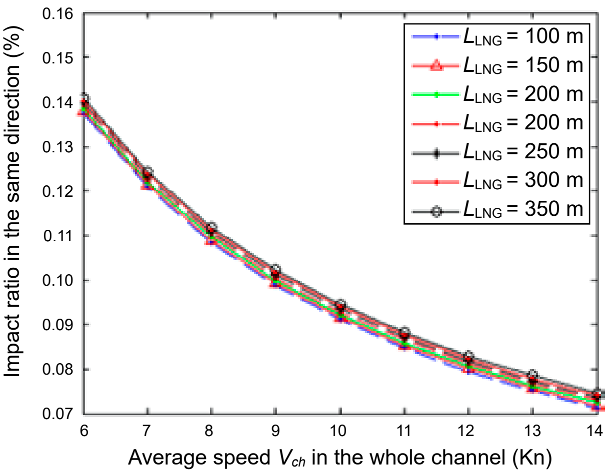

Figure 6. The impact ratio in the same direction for different lengths of an LNG ship

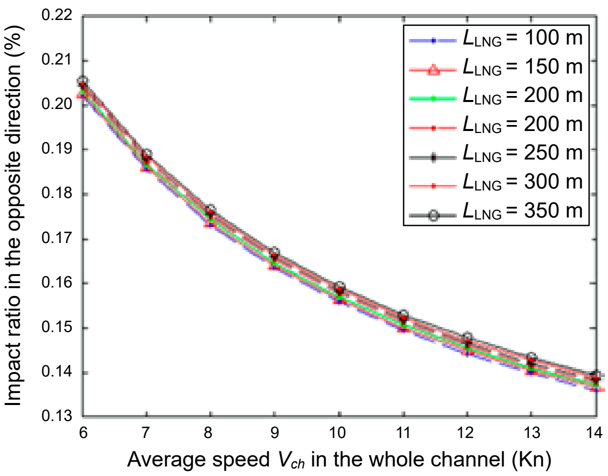

Figure 7. The impact ratio in the opposite direction for different lengths of an LNG ship

Table 4. The impact ratio on different sub-channels

Channel	V_{LNG}/kn	Impact ratio in the same direction/%	Impact ratio in the opposite direction /%
Whole channel	8	7.2 ~ 13.8	13.8 ~ 20.1
	10	6.8 ~ 13.2	11.9 ~ 18.8
	12	6.4 ~ 12.8	10.8 ~ 17.6
	14	6.2 ~ 12.7	10.2 ~ 16.2

(2) The impact ratio in the same and the opposite direction for an LNG ship's safety zone in the channel.

According to Figures 8 and 9, it could be seen that as the length of the safety zone increased, its impact rate on the capacity of the channel also increased, and its impact ratio on a ship that was opposite to the ship was the same as that of the ship. The impact ratio of the ship was slightly larger.

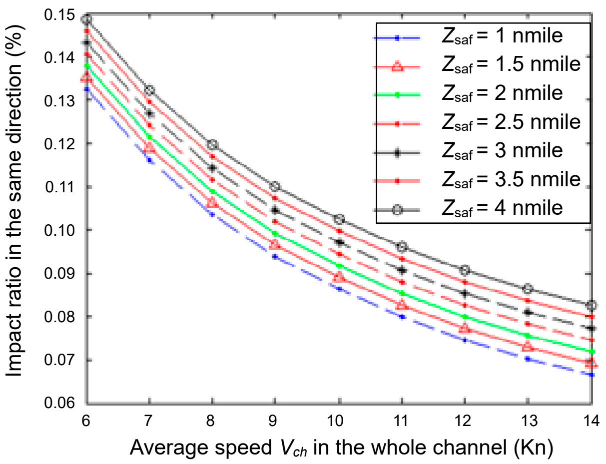

Figure 8. The impact ratio in the same direction for an LNG ship's safety zone

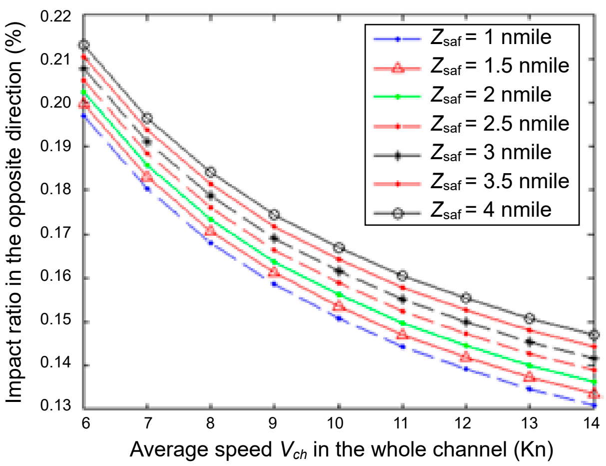

Figure 9. The impact ratio in the opposite direction for an LNG ship's safety zone

Result and discussion

From formula (5) and formula (6), the influence of an LNG ship's exclusive passage on the channel capacity was mainly related to the speed of the ship and the size of the ship's safety zone.

(1) The sub-channel AB was about 4.16 NM long, and there were about 15 ships passing through the channel every day. Therefore, in this sub-channel, the average ship speed was taken as 10 knots ~ 15 knots. When LNG ships passed through the channel in an exclusive mode, the length of the safety zone was taken as 2 NM, the average speed of an LNG ship was taken as 13 ~ 15 knots. In this case, the impact ratio of LNG ships on the throughput capacity of sub-channel AB in one day was between 2.69% ~ 5.15%, which was relatively small.

(2) The sub-channel BC was about 4.18 NM long, and there were about 13 ships passing through the channel every day. Therefore, in this sub-channel, the average ship speed was taken as 8 knots ~ 10 knots. When LNG ships passed through the channel in an exclusive mode, the average speed of an LNG ship was taken as 10 ~ 12 knots. In this case, the impact ratio of LNG ships on the throughput capacity of sub-channel BC in one day was between 2.31% ~ 5.03%, which meant that this had a limited influence on sub-channel BC.

(3) The sub-channel CD was about 3.7 NM long, and the vessel traffic was rather busy in this area every day. Therefore, in this sub-channel, the average ship speed was taken as 6 knots ~ 10 knots. When LNG ships passed through the channel in an exclusive mode, the average speed of an LNG ship was taken as 8 ~ 10 knots. In this case, the impact ratio of LNG ships on the throughput capacity of sub-channel CD in one day was between 3.78% ~ 7.72%, which was relatively higher compared to sub-channels AB and BC.

(4) According to the current situation of the channel in Yueqing bay, Taizhou city of Zhejiang province in China, and with consideration to the requirements that the channel will be one-way navigable when an LNG ship passes through, it was found that the throughput capacity of each sub-channel in one day decreased by a different degree when an LNG ship entered or left the channel (Table 2). As for the whole channel, the maximum impact ratio in the same direction and the opposite direction was 13.8% and 20.1% respectively (Table 4).

To reduce the influence of an LNG ship on the channel capacity and enhance the safety of marine traffic, some corresponding suggestions have been recommended as follows:

(1) When an LNG ship enters or leaves the port, pilotage with a qualified pilot shall be compulsory. The maritime administration shall broadcast navigational warning information and implement temporary traffic control. During the traffic control, no vessel shall impede the normal navigation of an LNG ship; Vessels navigating in the main channel or crossing the main channel shall remain outside the safety alert zone of an LNG ship, and no vessel shall enter the safety zone except for the escort ship;

(2) To keep abreast of the arrival of an LNG ship, a reporting system to the port shall be established; and to guarantee the safety of the port when an LNG ship enters or leaves the channel, the competent authorities shall make reasonable arrangements for other vessels entering or leaving the port according to the detailed impact ratio on different channels at different times.

(3) To ensure the safety of the port area when LNG ships are entering and leaving the port, the mobile safety zone shall be set up, and its specific dimensions shall be determined based on thematic analysis.

Conclusions

In order analyze the influence of a large LNG ship's navigation on channel capacity this paper has taken the channel to the LNG terminal in Taizhou city of Zhejiang province in China as a case study. Based on the proposed mathematical model, the impact ratio on both the whole channel and the segmented channel when LNG ships passed through the channel with different speeds and navigational modes has been calculated. It was found that the navigation of an LNG ship in the channel will influence the channel capacity to a certain degree and pose some risk to the safety of marine traffic, especially when LNG ships pass through the channel in an exclusive way.

Acknowledgments

The work presented in this paper is financially supported by the National Natural Science Foundation China (Grant number 51579201), Independent innovation fund for graduate students of Wuhan University of Technology (Grant number 175212004) and the Open Foundation of Nation Water Transportation Safety Engineering Technical Center (Grant number: 185212007).

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