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Optimizing Throughput of Restricted Tidal Waters: Composite Ship and Time Domain Model and Its Applications

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ABSTRACT:

The explosive economic growth in recent years in China has spurred interests in one of the oldest, most economic transportation mode, inland waterway transportation. As economic growth, logistic distributions, and passenger movements are demanding more and more transportation capacity, the need for maximizing throughput or optimizing operations along inland waterways, especially access to ports, becomes urgent.

This manuscript documents a heuristic approach based on ship domain theory and tidal water characteristics along the time domain to maximize the throughput for various waterway configurations. The proposed model not only incorporates physical properties of the navigation channel but also sets up parameters for regulation compliances, safety standards, and economic returns even the latter was not addressed in the current manuscript but has potential for future studies.

Applying the heuristic model to the operations of an inland waterway in the lower range of Yangtze River, Funan Channel, authors have compared the capacity of two possible navigation control modes with existing situations and demonstrated that the navigation control operations will not only increase the throughput measured in Cargo Load, but also improve safety of navigation and management of the channel.

KEY WORDS:

Inland waterway, capacity analysis, tidal waters, restricted channel, spatial model

WORD COUNT

4708 + 1 tables + 9 Figures = 7208

1. INTRODUCTION

Inland waterway transportation, one of the oldest and most economic transportation mode, has seen its resurgence in China in recent years due to the explosive economic growth and greater demand for all transportations. Along with the trend of increasing ship sizes, larger ports and terminals, and on-going standardization of navigation systems, inland waterway navigation should not be operated with random vessel flows. The urgent needs of developing operation plans, ensuring safety performance, and maximizing economic return require more efficient use of limited waterway condition. Compared with ocean bound containership movements, navigation in inland waterways, especially port access channels or restricted tidal waters, has garnered little attention and less research until recent alarms raised by congested channels, chaotic ports, and severe accidents in some locations (19).

Most inland water channels are formed by natural rivers which have various width, water depth, and curvatures at different locations, Compounding the complexities of the navigation channels. Furthermore, the width and water depth will change periodically under the effect of tidal waves of sea or ocean. Similarly, the access channels to various docks and/or ports are quite complex due to the large number of ships and diversified loading, unloading, and passing through activities. Given the newly increases in ship sizes and rapid expansion of waterway network, throughput analysis and navigation scheme for restricted tidal waters is an urgent topic that needs attention, not only from academic research but also practical applications.

The authors has developed a calculation model based on Ship Domain Theory (SDT) to help optimize the navigation scheme that maximizes throughput for a given segment of restricted waterways. This manuscript provides a brief literature review and the void in navigation scheme research in tidal water and related applications. Using Funan Waterway as a case study, the authors have demonstrated how to apply the theoretical model in real world waterway navigations and management processes.

2. LITERATURE REVIEW

It is commonly accepted that throughput is an important criteria to measure the efficiency of the waterway infrastructure *(1)*. Similar to roadway traffic throughput analysis, the conventional measure for waterway capacity is largely composed of the number of vessels that can pass a particular point within a given time unit, such as an hour, a day or a month. Different from the roadway infrastructure, the capacity of a particular waterway, especially inland navigation channels formed by nature water bodies, is much more complex due to varied channel width, water depth, and diverse ship sizes. The water level and channel size changes along the time in tidal waters further compounds the complication.

The concept of Ship Domain Theory (SDT) defines that effective area around a ship that a navigator would like to keep clear to other ships or stationary objects in order to ensure the safe operations of the vessel. As the minimum criterion to maintain the safe movement of vessels, the ship domain principal has been generally applied to analyze ship collision avoidance and vessel traffic flow. The ship domain can be measured statistically, analytically or experimentally *(2)*. Many scholars *(3-5)* have applied ship domain theory in port, narrow waterways, ship lock, and crossing waters in China and international locations *(6-8)*.

Queue theory is another important tool used by many scholars to evaluate T-channel and cross-channel vessel traffic flow *(9.10)*, ship arrival patterns *(11)* and port management *(12)*. Queueing theory is a mathematical theory and method which study the random discrete phenomenon of the system and the working process of a random service system. It consists of three parts: input, queuing discipline and service institution. So it can be used in the design of port and berth and the vessel traffic flow of T-channel and cross-channel, which have these three elements. However, in our paper, the object of is a waterway not the port, having no queueing discipline, so the queueing theory is not applicable.

However, the existing literature has not shown research that utilizes the composite ship and time domain in optimizing inland waterway and/or port operations. Moreover, many simulation studies have proposed vessel trip generation and route distribution models based on Monte Carlo method *(13.14)*. Quite a few researchers have focused their attention in software applications that can be used to establish ideal capacity of inland water ways, berths and ports*(15.16)*. The advantages of this study lying in the areas of not only developing theoretical models based on the composite concept of ship and time domain but also applying real world operations and validating the optimization processes, which is lacking in the existing literature throughput analysis.

3. CONCEPTUAL FRAME WORK

As documented in the last section, existing literature on waterway capacity analysis has largely focused on ideal capacity along the navigation channels, which are usually hypothesized ideal conditions. The key concept of this research is to estimate capacity of an irregular channel affected by tidal waves, therefore dynamic traveling conditions, which should be governed by the combination of ship and time domain.

3.1 Vessel Capacity Analysis

According to Ship Domain Theory, an effective area surrounding the boat should be cleared any objects. The size of the buffer area is usually related to the size of the ship, sailing speed, and environmental conditions in the field. As shown in Figure 1, the buffer area is usually delineated by an oval with a long axis of 3 to 6 times and 2 to 3 times of the vessel’s length for big vessels and small vessels, respectively. The short axis is 1.6 times of the vessel’s length in inland channels.

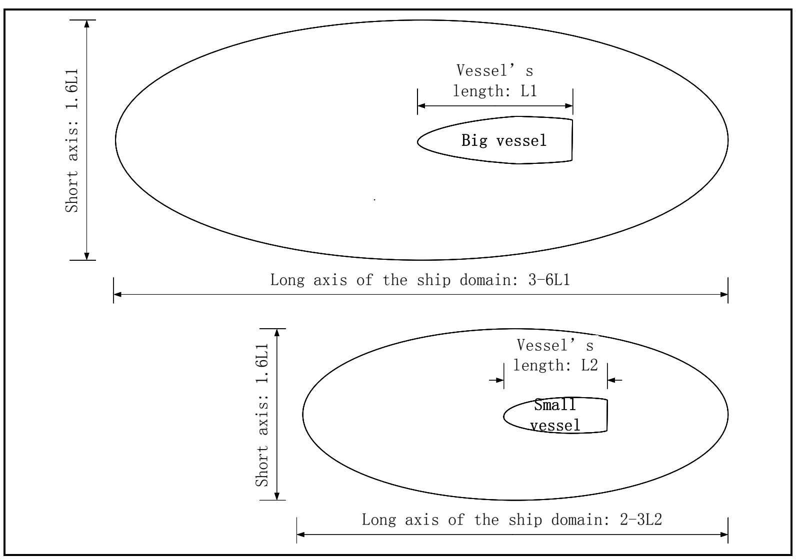


FIGURE 1. Ship Domain Dimensions

When the navigation regulation of the channel, traveling speed of the boat, and environmental conditions are taken into consideration, the capacity of an inland waterway segment can be estimated by the following general equations:

$$C_s = \eta\gamma m \sum_{i=1}^{n} \frac{r_i v_i}{l_i} \qquad [1]$$

Where:

C_s: Capacity for a particular segment of inland waterway;

r_i : The distribution of i type vessels, I = 1, 2, 3 …n;

V_i: The average speed of i type vessels, unit: m/s;

l_i : The long axis of ship domain for i type vessels, unit: meter;

η: modification factor;

γ: The coefficient for time;

m: The number of the lanes.

Most of those parameters are observed and collected for a particular waterway segment by local Maritime Safety Administration and some typical or average values are used to derive the estimated capacity. The data was collected and classified by vessels' length, such as fewer than 30m, between 30m and 50m and more than 180m, etc. The typical vessel refers to the 《Design Code of General Layout for Sea Ports》 published by Ministry of Transport of China to represent corresponding type of the vessels. The average value was simple according to the Code and experience.

For each type of vessels, the distribution is derived from the statistics of the vessels for a specific channel; the average speed of the vessels should take the feature of each type of the vessels , the regulation and the safety standards into consideration. For example, the for the type of vessels whose length is between 90m and 180m, the distribution, average speed, the long axis of the ship domain of the typical vessel are 12%, 8kn, according to the regulation, and 4 times of the typical vessel's length in Funan waterway which is an example in case study. In addition to that, the wind, flow, weather, river regime, interference between the vessels, maldistribution of the arriving influence the throughput of the channel, because of which the capacity need to take 20% to 30% off, indicated by the modification factor η*(17).* If the navigation environment becomes much worse, such as many docks with berthing and departing operations, the narrow navigable width, and so on, the modification factor η would be even lower. γ is a coefficient for time to adjust the capacity for year, month, day, or even second.

3.2 Cargo Load Throughput Analysis

As the true objectives of waterway transportation is to move people or freight not number of vessels, it is only logic to maximize the cargo load, which may or may not be directly proportional to the number of vessels due to the wide range in ship size, cargo load, and other operating characteristics. Similar to the number of vessels sailing through the channel is an important indicator to express the navigational efficiency of the channel, cargo throughput conveyed by vessels to the ports is an essential index to evaluate the economic efficiency of the channel. A more economical way to measure throughput for a particular segment of waterway is to incorporate the density of the ships, cargo loading capacity of various ships. The following equation are used to calculate the cargo throughput carried by vessels:

$$Q_{CL} = \eta\gamma m \sum_{i=1}^{n} \frac{CLi * r_i v_i}{l_i} \quad [2]$$

Where:

Q_{CL}: Cargo throughput carried by vessels

CLi: Cargo load for type i vessels

CLi is the dead weight of the typical vessels referring to the 《Design Code of General Layout for Sea Ports》. Other parameter are the same with equation 1.

The two equations presented above are suitable to general conditions and specific parameters may be developed for a particular location, channel, or post based on the individual applications.

4. CASE STUDY

Funan waterway is the main navigation channel for Zhangjiagang, one of the three main ports of the Suzhou port located in the lower range of Yangtze River. Zhangjiagang carried more than half of all cargo loads for Suzhou Port, which is one of the economic power houses in the Yangtze River Delta. As shown in Figure 2, its close proximity to Shanghai, transition between Yangtze River and the ocean, and its direct access to many fast growing regions in east China signals that the demand for Zhangjiagang, therefore Funan waterways, will only increase in the near future.

FIGURE 2. Location of Zhangjiagang, China

4.1 Funan Waterway

The naturally curvy, narrow Funan waterway, pressured with numerous vessels, became one of the famous Yangtze River bottlenecks and is prone to accidents*(18)*. As shown in Figure 3, Yangtze River in Zhangjiagang segment is divided into two main sections by Fujiangsha, a small island. Funan waterway(red in figure 3), the narrow segment on the south of the island, has deeper water depth of more than 10.5 meters, allowing larger vessels to travel in. Fuzhong waterway(green in figure 3) and Fubei waterway(blue in figure 3), the broad segment on the north of the island, has much shallower water at 4.5 meters and can only allow 1,000 ton or below ships passing. Funan waterway is in the process of constructing the 12.5 meter water level project which will be completed within 3 years, the depth of the lower reach from the Wushan Port in Funan waterway will be maintained in 12.5 meter, and that of the upper reach from the Wushan Port in Funan waterway is maintained in 10.5 meter. As the figure 3 showed, the deeper section in Funan waterway is bending with two swerve, and the slightly shallow section is straight.

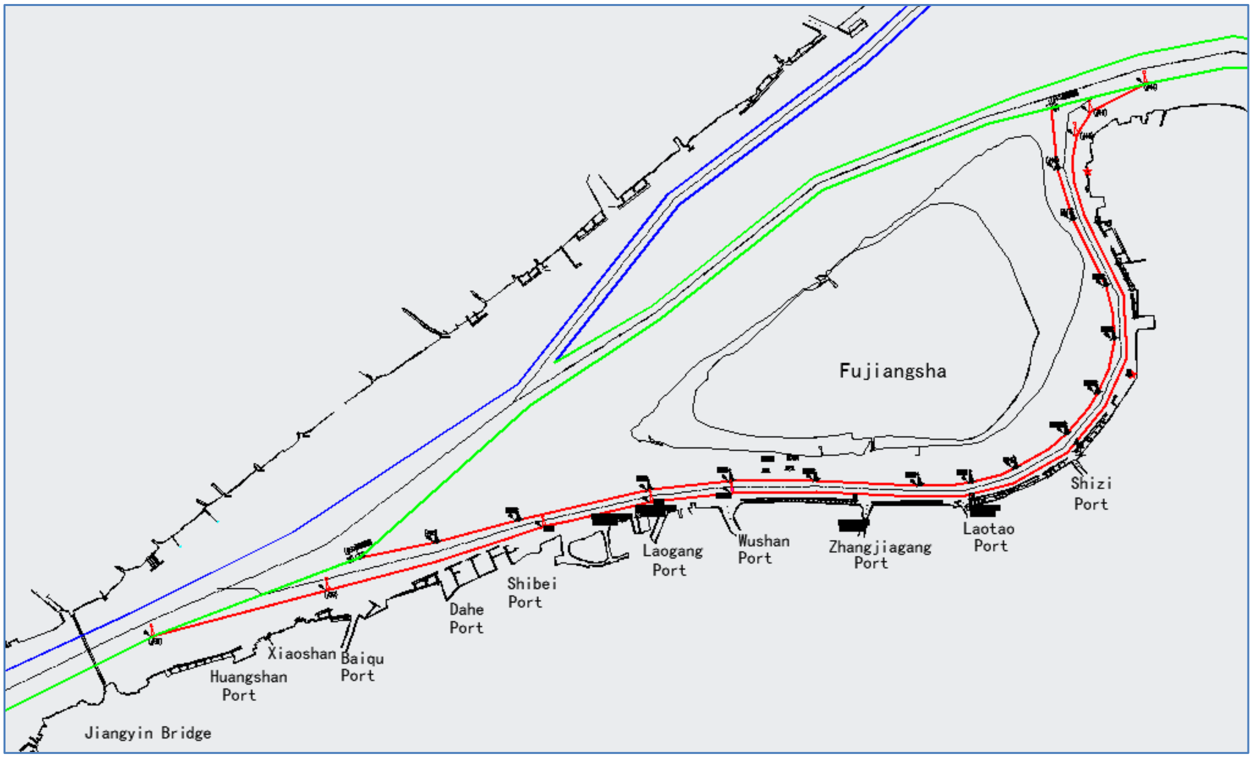


FIGURE 3. Funan Waterway Layout

As introduced earlier, Funan Waterway is a tidal affected channel. Corresponding to the high and low tides in a 15 day cycle, the water levels in Funan channel will heaving and dipping, which affects the width but will not increase the number of the lanes.

In order to analyze the influence on the depth of Funan waterway, figure 4 shows the relationship among the datum planes. The design bottom elevation of the Funan waterway is 12.5 meters under the theoretical lowest tide surface, but the datum plane of the tidal data is 1.5 meters under the mean sea level, which indicates that when the height of the tide is more than 0.712 meters, it will increase the depth of the Funan waterway, otherwise the depth in Funan waterway will keep in 12.5 and 10.5 meters. Figure 5 provides tidal data collected in a nearby field station located in Tianshenggang to represent the height condition of tide in Funan waterway, searched from the Service Network of Chinese Marine (http://en.cnss.com.cn/). There is little difference in change rule of tide between Funan waterway and Tianshenggang with a time lag. The horizontal line in the Figure 5 is represent 0.712 meters.

FIGURE 4 Relationship among Datum Planes

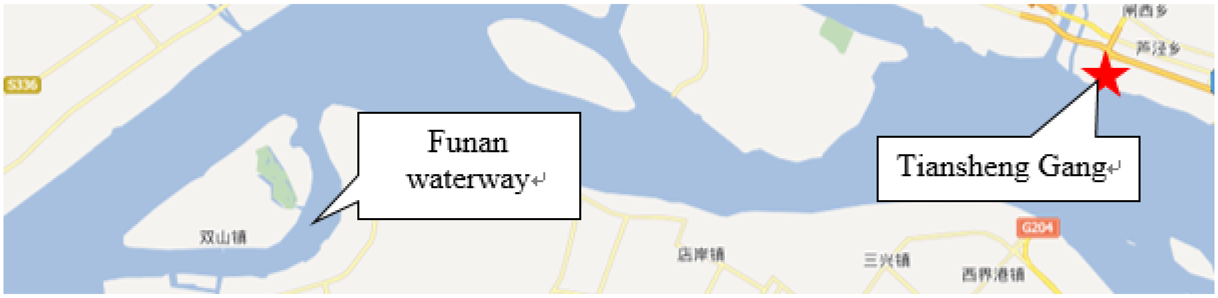


FIGURE 5. Sampling Tidal Data

4.2 Throughput in Funan Waterway

According to a recent tally (The Service Network of Chinese Marine2015), Suzhou port is the third largest port in China carried 479 million tons of freight in 2015. As one of the three main ports in Suzhou region, Zhangjiagang shared more than 50 percent of total cargo load, 279 million tons, for Suzhou Port.

As shown Figure 6, the total throughput for Funan waterway from 2012 to 2014 is fairly stable, around 180000 vessels per year. When zooming into the monthly distributions of passing vessels, it is clear that the peak season is around the early summer months, from April to June.

FIGURE 6. Throughput along Funan Channel, 2012 -2014

The directional traffic split along Funan waterway is roughly 38 and 62 percent for upstream and downstream respectively, according to the statistical data collected by the local Maritime Administration. The ship traveling speed ranges from 0 to more than 20kn but majority of the ships travelled around 8 to 12kn, which is the regulated speed along the arch segment.

Another notable characteristic along Funan waterway is the diverse type and sizes of the ships. As demonstrated in Figure 7, there many different types of ships, barge, passenger, oil, container, fishing, and other special models. The length of those ships ranges from smaller than 30 meters to larger than 180 meters. More than a third of all ships are between 50 and 90 meters, which is on the smaller side of all ships. When many smaller ships with very short spacing/headways travel along Funan waterway, where the channel conditions are complex, accidents are almost set to happen.

FIGURE 7. Diverse Types and Sizes of Ships Traveling in Funan Waterway

4.3 Capacity Utilization

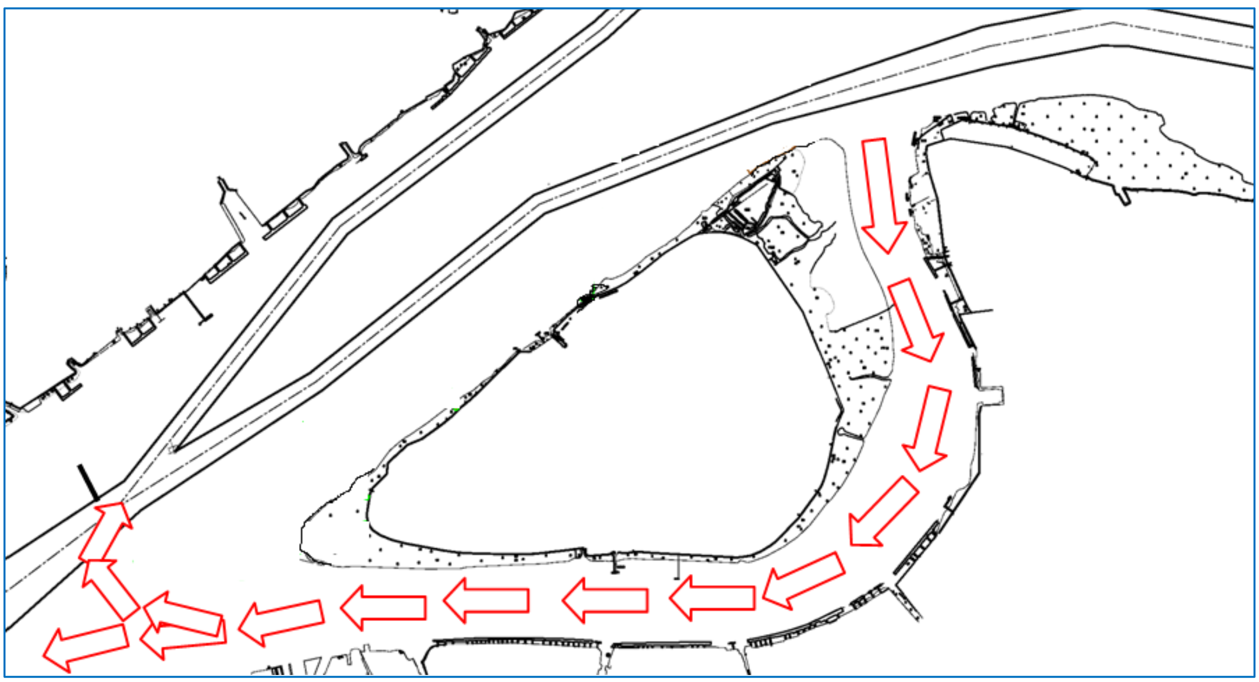
The current operation along Funan waterway is largely inherited from status quo without any systematic analysis or prioritization. Recent accidents have forced the local authority impose control period, maximum speed, and many other regulations.

As analyzed in Section 3, the general capacity and cargo load throughput can be calculated by equation 1 and 2. But for Funan waterway, because numerous docks along the bank, the narrow navigable width, the berthing and departing operation in each dock will affect the navigation, the vessel capacity and cargo load throughput need to take another 40% off, which means the modification factor of the Funan waterway will be 0.42 if taking 30% off and 40% off.

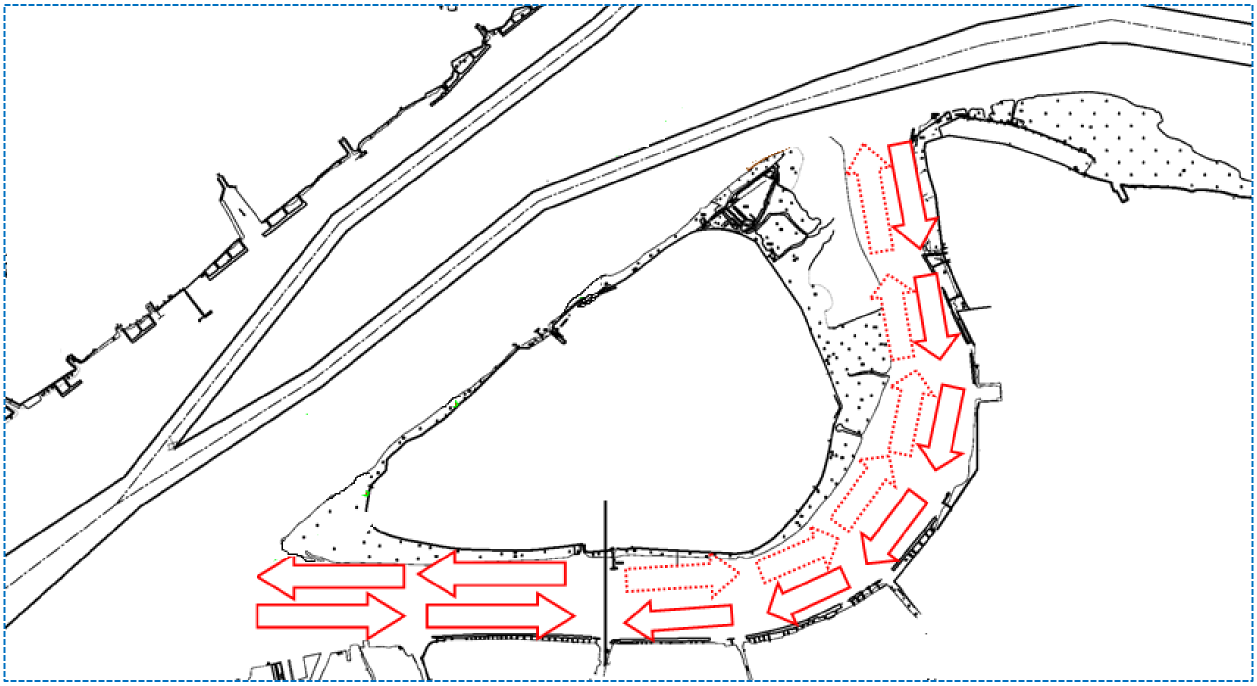
4.4 Navigation Control Method

With the equation presented in section 3, the existing vessel capacity and cargo throughput with no navigation control can be computed. In order to improve the safety condition along the Funan Waterway and maximize cargo throughput, the research team has proposed and evaluated two different possible navigation controlling method in arranging the navigation mode for big vessels:

1. Lower reach in and upper reach out;
2. Lower reach in and out.



(A)



(B)

FIGURE 8. Navigation Control Method

In the first control method, as shown in Figure 8A, vessels entering the harbor with the cargo then departing after discharging, or in contrast; and passing the channel with no operation. Vessels sail from lower reach in to upper reach out in control time. When a big vessel enter the channel from lower reach, other vessels cannot enter the channel from upper reach until the big vessel left. There is rarely any vessel that enters the channel with cargo and departs with another payload. So cargo load throughput in this mode only consider one-way loading.The vessel capacity and cargo throughput brought by vessels can be measured by applying the equations presented in Section 3 with follow equations:

(1) In control time T

In the control time, vessels are not allowed to sail from upper reach to lower reach. Downstream vessels to leave the channel in clear time(t_{cl}) before big vessels sail into and leave the port. Big vessels to sail to the port with other upstream vessels in the sailing time(t_s), there is only big vessels sailing in the time(t), the departing time(t_d) is for big vessels to depart the port with other upstream vessels. With the time sailing in and sailing out have already included, the parameter t is considered to describe the big vessels sailing in the channel except the time of the first big vessel sailing to the port(t_s) and the time for the first big vessel departing the port in the channel(t_d). Vessel capacity and cargo load throughput can be calculated by following equations:

$$Q_{VC} = t_{cl} \times \frac{Q_{VD}}{\gamma} + (t_S + t_d) \times \frac{Q_{VU}}{\gamma} + t \times \frac{Q_{VBG}}{\gamma}$$

[3]

$$Q_{CLC} = t_{cl} \times \frac{Q_{CLD}}{\gamma} + (t_S + t_d) \times \frac{Q_{CLU}}{\gamma} + t \times \frac{Q_{CLBG}}{\gamma}$$

[4]

$$T = t_{cl} + t_s + t_d + t \quad [5]$$

Q_{VC}——the vessel capacity in the control time

Q_{VU}——the upstream vessel capacity

Q_{VD}——the downstream vessel capacity

Q_{VBG}——the big vessel capacity

Q_{CLC}——the cargo throughput in the control time

Q_{CLU}——upstream cargo load throughput

Q_{CLD}——downstream cargo load throughput

Q_{CLBG}——big vessel cargo load throughput

T—— control time

(2) In the uncontrolled time

$$Q_{VN} = (\gamma - T) \times \frac{Q_{V0}}{\gamma} \quad [6]$$

$$Q_{CLN} = (\gamma - T) \times \frac{Q_{CL0}}{\gamma} \quad [7]$$

Q_{VN}——the vessel capacity in the uncontrol time

Q_{V0}—— vessel capacity with no control

Q_{CLN}——the cargo load throughput in the uncontrol time

Q_{CL0}—— cargo load throughput with no control

In total, QV1 and QCL1 are the vessel capacity and cargo load throughput under the first control method.

$$Q_{V1} = Q_{VC} + Q_{VN} \quad [8]$$

$$Q_{CL1} = Q_{CLC} + Q_{CLN} \quad [9]$$

In the second control method, as shown in figure 8B, big vessels use lower reach of the channel and small vessels use upper reach of the channel, vessels need to make a U-turn when they want to sail out of the waterway. As documented in study*(3)*, it takes time for ships to make U-turns. When larger vessels traveling in the channel, other vessels turning and traveling in reverse direction are forbidden. Vessels sailing in this mode generally need to do loading or unloading operations at the port, they will enter the channel with the cargo and depart after discharging, or in contrast. Almost no vessel will enter and depart with the cargo or with no cargo. So one-way loading is taken into consideration. The vessel capacity and cargo throughput brought by vessels can be measured by applying the equations presented in Section 3 with follow equations:

(1) In the control time T

$$Q_{VB} = t_{cl} \times \frac{Q_{VD}}{\gamma} + t \times \frac{Q_{VBG}}{\gamma} \qquad [10]$$

$$Q_{VS} = T \times \frac{Q_{VSM}}{\gamma} \qquad [11]$$

$$Q_{CLB} = t_{cl} \times \frac{Q_{CLD}}{\gamma} + t \times \frac{Q_{CLBG}}{\gamma} \qquad [12]$$

$$Q_{CLS} = T \times \frac{Q_{CLSM}}{\gamma} \qquad [13]$$

$$T = 2t_{cl} + 2t + t_u \qquad [14]$$

Q_{VB}—— vessel capacity of the lower segment in control time

Q_{VS}—— vessel capacity of the upper segment in control time

Q_{VD}——downstream vessel capacity

Q_{VBG}——big vessel capacity

Q_{VSM}——small vessel capacity

Q_{CLB}——cargo load throughput of the lower segment

Q_{CLS}——cargo load throughput of the upper segment

Q_{CLD}——downstream cargo load throughput

Q_{CLBG}——big vessel cargo load throughput

Q_{CLSM}——small vessel cargo load throughput

t_u——the time to make U-turn

(2) In the uncontrol time

$$Q_{VN} = (\gamma - T) \times \frac{Q_{V0}}{\gamma} \qquad [15]$$

$$Q_{CLN} = (\gamma - T) \times \frac{Q_{CL0}}{\gamma} \quad [16]$$

In total, Q_{V2} and Q_{CL2} are the vessel capacity and cargo load throughput under the second control method.

$$Q_{V2} = Q_{VB} + Q_{VS} + Q_{VN} \quad [17]$$

$$Q_{CL2} = Q_{CLB} + Q_{CLS} + Q_{CLN} \quad [18]$$

In this navigation mode, the whole waterway is divided into two part from Wushan port: lower reach with deeper water depth and upper reach with shallow water depth. Vessels bigger than 3000tons use lower reach which only allow one direction in the waterway at a time, smaller than 3000tons use upper reach allowing two direction in waterway. In the lower reach, big vessels cannot sail in ceaselessly with limited number of berths. After considering the number and the size of the berths as well as the speed and the length of the vessels, the time(t) only for big vessels sailing should less than 2 hours once.

As analyzed in section 4.1, the water depth will change with the tide. According to the figure 5, this change help to increase the water depth in more than 19.2 hours in one day, which means the control time(T) in the control method can be up to more than 69120 seconds. In some particular days, control time can even reach 86400 seconds (whole day). The vessel capacity and cargo load throughput are change with control time in navigation control method while the vessel capacity and cargo load throughput stay constant in existing condition with no control.

Figure 9 shows vessel capacity and the cargo load throughput in existing condition and control method with the increase of control time. Along with the increase of control time, the vessel capacity in control method 2 increases dramatically while the vessel capacity in control method 1 drops steadily after fluctuating around the level of existing condition with no control.. The cargo load throughput in control method 2 rises when control time is less than 44069 second, after peaking at 2800000, it decreases slowly. However, in control method 1, the cargo load throughput increases stably.

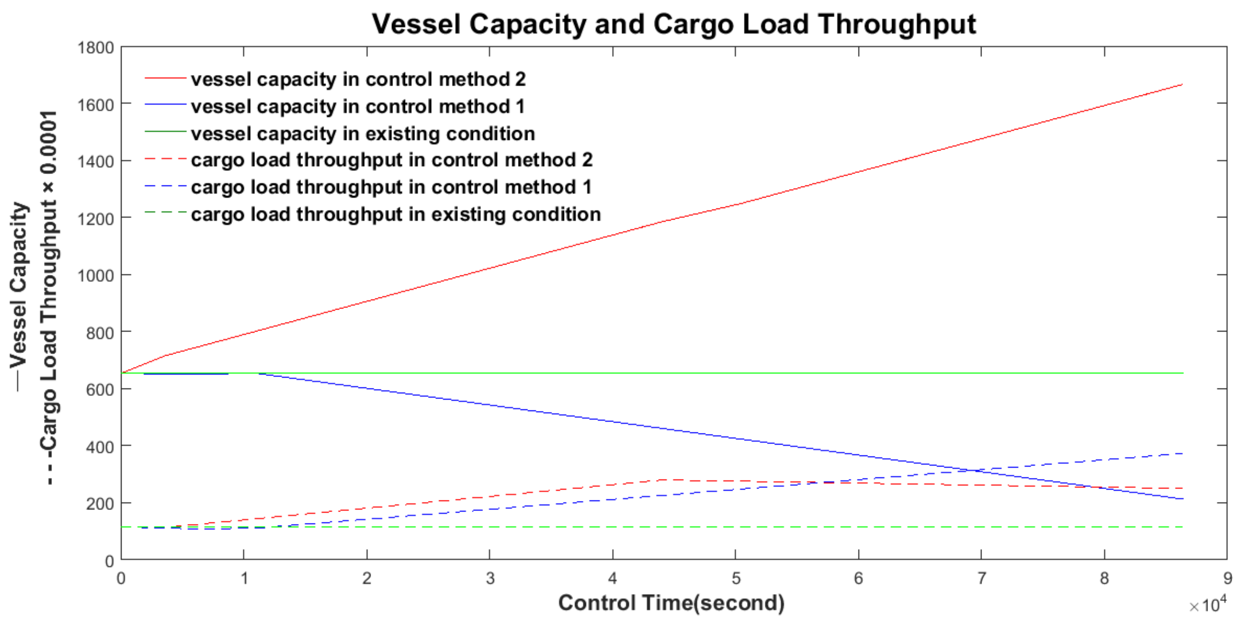


FIGURE 9 Vessel Capacity and Cargo Load Throughput

As showed in figure 9, there is more cargo load throughput in navigation control mode, with it being a little less than the level in no control mode in initial stage of control. The cargo load throughput in control method 2 increase quickly but not stable when compared with that in control method 2. As said in section 2, the throughput is an important criteria to measure the efficiency of the waterway infrastructure. It is apparent that taking control measures on navigation scheme is much more conform to the demand of development of economy. However, beside the factor of the development of economy, the safety of the navigation, the difficulty of the management and feasibility of ship maneuvering also need to be taken into consideration. Firstly, in order to guarantee the safety on water, supervision department hopes to decrease the density of vessels in their precinct which can help to reduce the probability of accident. When compared the three modes, the vessel capacity in control method 1 is less than that in existing condition, then less than that in control method 2, which means fewer vessels transiting huge amount of cargos can be realized by implementing control methods. Fewer vessels represent smaller vessel density leading to smaller probability of accident which can help to improve safety at the waterway. Secondly, managers always tend to implement convenient and simple management measures when the results of measures are the same or the difference between them is smaller. With operations in control method 2 need to pay more attention on the subsection management and vessels making U-turns, the difficulty as well as inputs of labor and property in implementing control method 2 are bigger than that of control method 1. Lastly, the captains, especially captains with limited experiences, dislike to sail in a complicated navigation environment where the encounter situation among vessels is much more difficult to handle. Control method 1 is simple and orderly because it has only one navigation direction while encounter situation in control method 2 is much more complicated, especial in the upper reach. In addition to that, because of the artificial segmentation, the retardance of response to rudder and the influence of wind and water flow, the accidents are easily to occur among vessels sailing near the parting which is bad for the safety at water.

With the consideration of the development of economy, the safety, the difficulty of management and maneuvering complexity, taking navigation control is superior to no navigation control and control method 1 is better than control method 2 for Funan waterway in the long term. However, control method 2 has an irreplaceable advantage of small vessel capacity. If there is a need to let more small vessels sail in, or to transit a huge amount of cargo in a limited time, control method 2 is a better choice for local maritime department.

Table 1 documents all the parameters in the calculation in existing condition, control method 1 and control method 2 by assuming the same ship size distribution observed in the past three years from 2012 to 2014. after considering safety, all long axis of ship domain value for six times of typical vessel’s length and all speeds are set to 8kn(4.1m/s) in the calculation.

TABLE 1. Parameters

ID	0	1	2
Navigation Mode	Existing	Lower reach in and upper reach out for big vessels	Lower reach in and out for big vessels
Navigation Directions	2	1	2 during different stage
γ(s)	86400	86400	86400
η	0.42	0.42	0.42
m	1	1	1
vi(m/s)	4.1	4.1	4.1
li	6 times of typical vessel’s length	6 times of typical vessel’s length	6 times of typical vessel’s length
Q_{Vi}	653	Indefinite value	Indefinite value
Q_{CLi}	1155912	Indefinite value	Indefinite value
T(second)	/	Vary from 1 to 86400	Vary from 1 to 86400
t_{cl}(second)	/	4878 and 1278	3600
t_s(second)	/	3600	/
t_d(second)	/	1278	/
t(second)	/	T-9756	Vary with T
t_u(second)	/	/	2700
Q_{VD}	/	631	631
Q_{VU}	/	688	/
Q_{VBG}	/	147	147
Q_{VSM}	/	/	755
Q_{CLD}	/	148781	148781
Q_{CLU}	/	1648788	/
Q_{CLBG}	/	4156390	4156390
Q_{CLSM}	/	/	551036

5. SUMMARY AND THE FUTURE DIRECTION

This manuscript documents the throughput analyses using the composite ship and time domain. Measured in both number of vessels and cargo load throughput for a particular inland channel is often affected by the vessel, cargo and channel characteristics simultaneously. Using

Funan Waterway as a case study, authors demonstrated that various navigation plans may developed to improve throughput, safety, and efficiency.

As more and more ship in China are equipped with AIS instrument and provide AIS data, it is possible to expand the framework proposed in this manuscript to optimize navigation along inland waterways, port accesses, and other marine transportation systems. Along with the trend of enlargement and normalization of vessels, further optimization can be achieved via continuous tracking of ship movement and detailed loading status/amount. Optimization of the existing navigation plan may have the potential to improve operation efficiency, sometime, avoid costly improvement to the inland water channels. The end result will increase return on investment, ease the pressure on inland waterway systems, and decrease the pressure on environment and management, and regulatory authorities.

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