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SIMULATION OF SHIP TO SHORE INTERACTION IN SHALLOW AND NARROW WATERS

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Abstract: *In recent years research efforts in ship hydro mechanics are devoted to the practical navigation problems in getting larger ships safely into existing harbors, which are usually characterized by narrow and shallow waters. This paper presents a case study of ship to shore interaction when a bulk carrier passes at different speeds through a narrow waterway in Suez Canal. The trials were conducted using NTPRO 5000 navigational simulator and it was studied the ship to shore interaction and also ship squat phenomenon, which, in general, appears in shallow waters, but with a more pronounced effect on canals passage. The results analysis showed that the greater the speed the more pronounced the bank effect is, which translate into an earlier swing of the ship towards opposite bank, an increased final ship-bank distance and a significant yawing moment causing a visible sway. Also it was observed that the ship motion isn't related to the under keel clearance and if the speed is too big, an uncontrolled maneuver could lead into a collision with the opposite wall of the canal. The paper can be useful for maritime officers, masters and pilots, who must take into account ship to shore interaction effects when maneuvering in restricted navigation conditions, in order to prevent any accidents.*
Keywords*: interaction, squat, shore, canal, simulation.*

INTRODUCTION

In the last decade it was observed a continuous increase of the main dimensions of certain ship, especially for container carriers, RO-RO vessels and LNG carriers. In opposition, the dimensions of access channels, rivers, canals, and harbors where these vessels operate do not increase at the same rate. Therefore, the behavior of ships flow in harbors will be influenced by waterways restrictions.

A phenomenon that occurs on vessels in these areas is **ship squat**, which may be defined as the sinkage and/or trimming of the ship due to pressure changes along the ship length in shallow waters. The trim change can be explained by hydrodynamic interactions between the ship and the bottom due to speed and pressure distribution change. Large and fuller ships such as tankers and bulk carriers should pay extra attention when navigating in restricted waters. The squat effect is directly related to ship dimensions, its speed and water depth. Ship to ship interaction or ship to shore is also related to this phenomenon [1].

Restricted waters impose significant effects on ship navigation. In these situations the ship has to navigate close to the shore and other manmade structures because of limited navigable width. The shallow water and proximity of the sides of the channel affects the ship navigating through the restricted waters. With the presence of a side bank in the vicinity of the hull, the flow is greatly complicated. Additional hydrodynamic forces and moments act on the hull, thus changing the ship's maneuverability. These effects cause errors in maneuvering which can lead to grounding or collision [2].

Ship to shore interaction is a phenomenon associated with ship squat and has been the subject of studies in many ways for a long time. In general, most researches still rely on experimental tools or numerical (Computational Fluid Dynamics) techniques, such as model tests and empirical or semi-empirical formulae, which normally treat the bank effect as a function involving hull-bank distance, water depth, ship speed, hull form, bank geometry, propeller performance [3].

Researches on bank effects were started by *Norrbin* in 1970s, when he carried out experiments and proposed empirical formulae to estimate the hydrodynamic forces for flooded, vertical and sloping banks. *Li* et al. (2001) continued *Norrbin*'s investigations and tested bank effects in extreme conditions for three different hull forms, while *Ch'ng* et al. (1993) conducted a series of model tests and developed an empirical formula to estimate the bank-induced sway force and yaw moment for a ship handling simulator. *Vantorre* et al. (2003) discussed the influence of water depth, lateral distance, forward speed and propulsion on the hydrodynamic forces and moments based on a systematic captive model test program for three ship models moving along a vertical surface-piercing bank and *Lataire* et al. (2009) developed a mathematical model for the estimation of the hydrodynamic forces, moments and motions taking into consideration ship speed, propulsion and ship/bank geometry [4].

Although experimental tools and empirical formulae are widely used for bank-effects prediction, they have their shortcomings. For example, empirical formulae are suitable only for cases with similar hull forms and conditions. Otherwise, the prediction is barely reliable. To establish a mathematical model, many systematic and expensive model tests are always required. However, the most important weakness of these tools is their inability to provide detailed information on the flow field, which can help explain the flow mechanism behind the bank effects [3].

SHIP TO SHORE INTERACTION

When a ship is traveling in a canal or a narrow channel, the flow becomes highly complex. Interactions occur between the ship and the side banks, as additional hydrodynamic forces and moments generated by the vicinity of the banks act on the hull and influence ship motion. This phenomenon is named **bank effect**. When the distance between the hull and the canal boundary is reduced, the flow is accelerated and the pressure is accordingly decreased, which has an effect on the hydrodynamic characteristics. The produced hydrodynamic forces, especially in extremely shallow canals, may considerably affect the maneuvering performance of the ship, making it difficult to steer. The ship may collide with the side bank and/or run aground due to the squat phenomenon.

In Figure 1 the ship is close to the stern on the starboard side, while the port side is wide open. When the ship plies with considerable speed parallel to the bank, water flow rushing below from the vicinity of the starboard bow towards the stern gets bottled at the constricted space at the stern. But to satisfy the continuity equation, its speed increases below the starboard quarter. This increase of the passing water speed decreases the pressure at the Z_s zone than the Z_p zone on the port quarter. Consequently water pressure at the port quarter will push the stern more towards the bank making the bow swing towards the center of the channel [5].

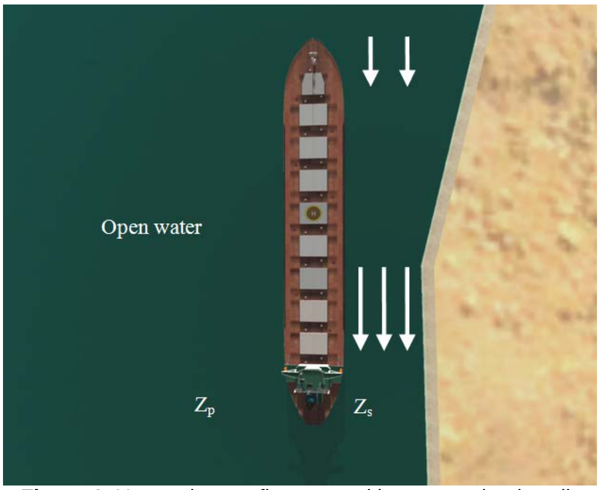

Figure 1. Unequal water flow caused by uneven bank wall

The result of pressure differences between port and starboard sides is a lateral force which acts on the ship, mostly directed towards the closest bank, as well as a yawing moment pushing her bow towards the center of the waterway. The bank effect depends on many parameters, such as bank shape, water depth, ship-bank distance, ship properties, ship speed and propeller action. A reliable estimation of bank effects is important for determining the limiting conditions in which a ship can safely navigate a waterway [6].

A pilot while maneuvering near a bank must slow down to minimize this effect and take the help of rudder to counter it as best as he can. Else he may be forced to move out of the channel. Two ships passing close to each other will experience similar effects in close proximity. Slowing down is the only solution, as usual for both the vessels.

When the ship is approaching a steep bank as in Figure 2, the water pressure at the starboard bow is less than the port bow due the asymmetric flow and the bow is pushed towards the port. This is called bow **cushioning effect**.

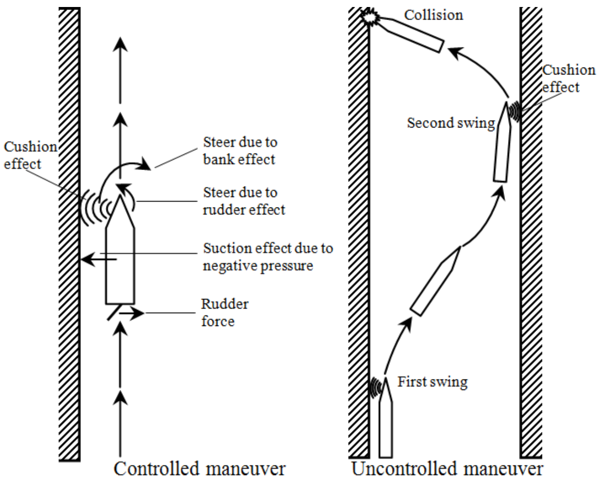

Figure 2. Bank and cushion effects in narrow canals

This effect can be used as a pivot point to bring the ship alongside a bank in berthing maneuver or when a ship has to navigate alongside a riverbank or a jetty. The lack of knowledge about this effect and an uncontrolled maneuver in this case could result in a collision with the side bank, as seen in Figure 2.

Typically a channel bottom and walls have various irregularities, such as way boundaries, under water shoals, jetties, channel walls and traffic ships. The pressure field induced by these irregularities shapes the effects of these factors. For a running vessel the field parameters are governed by the underwater hull geometry, depth under the keel, propulsion and bow thruster performance and the current.

In NTPRO 5000 navigational simulator the mathematical model of the ship motion calculates changes in the pressure field and resulting hydrodynamic forces induced by factors listed above. Interaction forces and moments are determined as integral characteristics of the resulting pressure distribution along the hull surface.

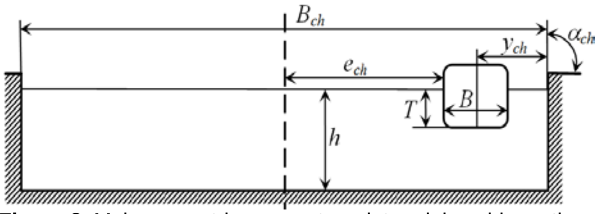

Figure 3. Main geometric parameters determining ship motion in a canal

The effect of the channel or piers is estimated by additional forces and moments calculated as hydrodynamic components of a vector of forces and moments affecting the vessel. The effect of the wall or channel on the inertia forces is also modeled. The principal parameters in ship to shore interaction are beam/draft and length/beam ratios, distance between the vessel center plate sides and channel boundaries, defined as y_{ch} and e_{ch} distances in Figure 3, an angle between the vessel's centerline plane and the line of the wall, vessel's speed V and rate of turn r, as well as the channel's width B_{ch} and depth h, channel wall slope α_{ch}. The effect of these parameters on the vessel hydrodynamic forces is calculated on the basis of analysis of various model testing results in a wide range of bank and ship types [7].

SIMULATED TRIAL

In this paper it is presented a study case of a ship to shore interaction using the navigational simulator NTPRO 5000. Because ship to shore interaction has a greater effect in shallow and narrow waters, the location chosen for this simulation was a waterway of approximately 476 m breadth from the Suez Canal.

The test case for bank-effects was set up for a 76800 tons bulk carrier. In the waterway, straight-line tests at different speeds of the bulk carrier were conducted at three under keel clearances, namely 10, 35 and 50% of the draft, at a lateral position y_{ch} = 58 m for a length of the bank of one nautical mile. The general plan was to investigate the influence of the water depth, ship–bank distance and ship speed on hydrodynamic quantities. The canal configuration is shown in Figure 4, where the hull is moving close to the vertical bank at its port side.

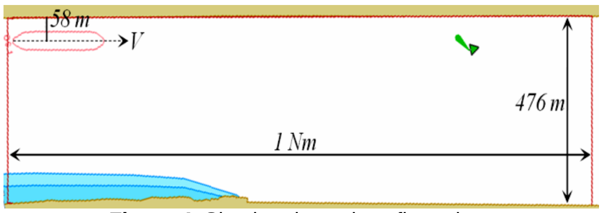

Figure 4. Simulated canal configuration

The ship used as own ship was a bulk carrier with the characteristics described in Table 1.

Table 1. Ship's characteristics

Characteristics	Own ship
Vessel type	Bulk carrier
Displacement [t]	76800
Length [m]	290
Breadth [m]	46
Bow draft [m]	5.67
Mid draft [m]	7.48
Stern draft [m]	9.29

Max speed [knot]	16
Type of engine	Slow speed diesel
Type of propeller	Fixed pitch propeller

The combinations of ship speed *V* and water depth *h/T* in the canal are presented in Table 2. As can be seen, there are seven conditions, some of which are rather extreme. Tests have been carried out with speeds at full scale of 6.2, 7.4, 10.3, 11.8 and 16 knots.

Table 2. Matrix of test conditions

h/T \ *V*	6.2 knots	7.4 knots	10.3 knots	11.8 knots	16.0 knots
1.10 (UKC = 10%*T*)	○	○	○	○	
1.35 (UKC = 35%*T*)		○			
1.50 (UKC = 50%*T*)		○			○

The environment condition of the trial can be considered ideal as the wind and current speed were 0 m/s, air temperature 22°C and pressure 1013 mbar, so that the ship motion in water wouldn't be affected by any environmental factors.

Table 3. Draft increase caused by squat effect for bulk carrier

Under keel clearance	Ship's speed	Bow squat	Stern squat
3 m	14.42 knots	0.3 m	0.52 m
	11.62 knots	0.17 m	0.31 m
	10.14 knots	0.12 m	0.24 m
2 m	14.17 knots	0.33 m	0.6 m
	11.64 knots	0.2 m	0.35 m

The water depth of the area was constant for the three under keel clearances and considering the ship's draft, there were shallow water conditions. Therefore, when ship sails through water it will be affected by squat. For the bulk carrier the increase of draft caused by shallow waters accordingly to wheelhouse poster is presented in Table 3.

RESULTS AND DISCUSSIONS

The trials run in the simulator had the purpose to observe the increase of draft due to ship-bank interaction and also the bank effect on ship's motion. The following results were obtained.

The first trial included a run at 6.2 knots and 1.1*T* water depth. In Figure 5, it can be observed that the ship's drafts at bow and stern are constant due to a constant depth, but their maximum values of 5.748 m, respectively 9.462 m are bigger than the static drafts. The difference between values is ship squat caused by the speed, small under keel clearance and ship-bank interaction. In these conditions, the minimum under keel clearance is 4.452 m at forward and 0.738 m at aft, meaning that the ship should proceed in the canal with extreme care. For all the other tested speeds, similar graphs of draft and under keel clearance are obtained.

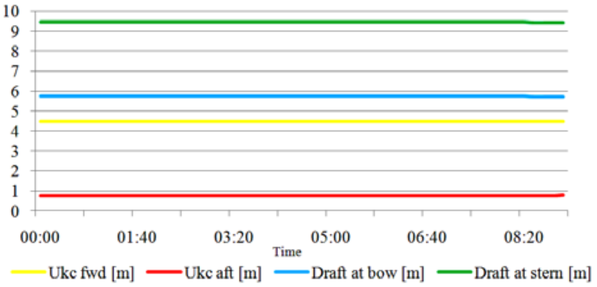

Figure 5. Draft and under keel clearance at 6.2 knots

Regarding the hydrodynamics parameters of the ship when moving along the bank, there were considered the lateral and longitudinal force acting on the hull, yawning moment and sway.

The lateral force acting on transversal axis of the hull has an ascending trend from the beginning of the trial, reaching a maximum value of 12.559 tones and the longitudinal force starts increasing from -20.735 to -18.858 tones when ship reaches the end of the one nautical mile canal. On the other hand, the yawing moment (Figure 6) has a different evolution; immediately after the start, it begins a dramatic decrease at a minimum value of -189.22 t*m causing the ship to be "pushed" towards starboard, then it attenuates until the end of the trial.

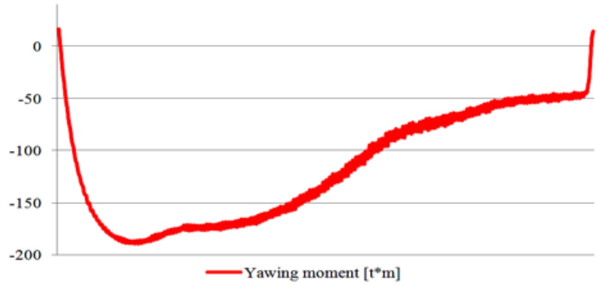

Figure 6. Yawing moment at 6.2 knots

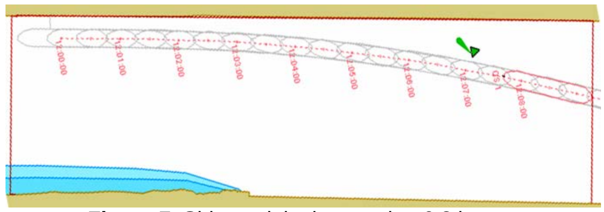

Figure 7. Ship track in the canal at 6.2 knots

The values of these parameters change due to the increase of ship-bank distance as the bank effect is decreasing. The sway measured on ship was quite insignificant, from 0.001 to 0.042 meters to starboard. The ship's track in this trial and final position can be observed in Figure 7.

For the second considered speed of 7.4 knots there were executed trials at all three under keel clearances. Therefore at 1.1*T*, drafts increase at 5.79 m at bow and 9.523 m at stern, causing a dangerous under keel clearance of 0.677 m at aft. The lateral force has an accentuated increase to a maximum value of 29.06 tons followed by a decrease to 7.43 tons at the end of the trial. The longitudinal force increases slightly from -29.89 to -27.78 tons, while the yawing moment has a minimum value of -478.83 t*m. As can be seen, all the measured parameters are greater than the first case due to the increase in speed, even if the under keel clearance is the same. This time the sway increases at a maximum value of 0.063 m to starboard.

At 1.35*T*, the increased under keel clearance of 3.115 m forward and 6.85 m aft causes a decrease of draft, 5.75 m at bow and 9.485 m at stern, in comparison to previous case, meaning that squat phenomenon has a smaller impact on ship motion. Except sway which increases to 0.088 m to starboard, the other hydrodynamic parameters, like lateral force, longitudinal force and yawing moment have small differences on minimum and maximum values than 1.1*T* case and follow the same trend.

For the third water depth (1.5*T*), the hydrodynamic parameters have slightly bigger values, but follow the same trend than the previous cases. The drafts, both bow and stern decrease at 5.735 m, respectively 9.467 m due to a greater under keel clearance. That means squat has a smaller effect on the ship even if the presence of the adjacent bank restricts the flow around the hull. In Figure 8 it can be seen that lateral force acting on the ship's hull moving close to the bank is similar to all the under keel clearance. Graphs with similar characteristics are obtained for other hydrodynamic parameters comparison at any considered depths.

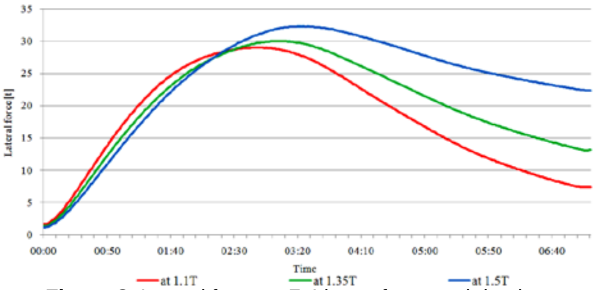

Figure 8. Lateral force at 7.4 knots for tested depths

Studying the ship's track at this speed for all under keel clearances, it was observed that there aren't significant differences between them. Figure 9 shows the same track for all cases and it can be said that under keel clearance has a small impact on ship-bank distance than ship's speed, but due to squat phenomenon it affects more the draft. In comparison with 6.2 knots case (Figure 7), the ship bank-distance is bigger at the end of the trial, meaning that at greater speed the bank effect is felt more pronounced, causing the ship move towards the opposite bank.

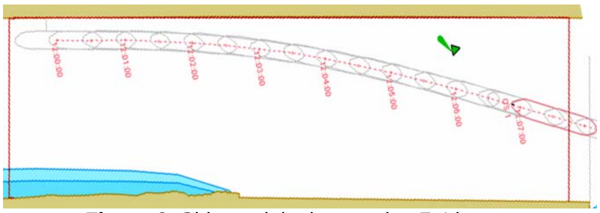
Figure 9. Ship track in the canal at 7.4 knots

For the third considered speed (10.3 knots) maximum ship drafts are 5.927 m at bow and 9.701 m at stern due to small under keel clearance when static and the presence of the adjacent bank. As the ship-bank distance increases the drafts begin to decrease slightly. At this speed the ship should pay extra attention because of 0.5 m aft under keel clearance; in a real situation, such speed wouldn't be allowed. In addition, at 11.8 knots the draft at bow is 6.046 m and 9.86 m at stern, while the under keel clearance is 4.154 m forward and 0.34 m aft. For both speeds the ship-bank distance is bigger than previous cases making the ship to collide with the opposite bank but only after the limit of the considered one nautical mile canal and it wasn't taken into account. In comparison with 7.4 knots trial, lateral force increases proportionally to speed at a maximum value of 85.34 tons for 10.3 knots, respectively 133.69 tons for 11.8 knots. The yawing moment has the same trend but the decrease is more dramatic, from -478.83 t*m at 7.4 knots to -1557.92 t*m for 10.3 knots and -2570.52 t*m for 11.8 knots. These variations are bigger due to the greater bank effect caused by the ship speed at the start of the trial. The sway evolution for these cases is represented in Figure 10, where the maximum value, 0.197 m, is obtained earlier than the others for a ship's speed of 11.8 knots.

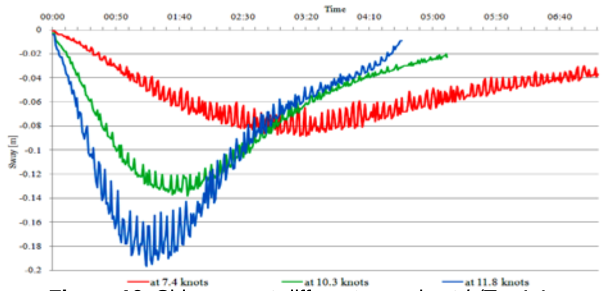

Figure 10. Ship sway at different speeds at h/T = 1.1

It can be concluded that the greater the speed the earlier the ship begins to swing towards the opposite bank of the canal, making difficult to maneuver.
For the 16 knots trial the draft increases at a maximum value of 5.987 m at bow and 9.995 m at stern, but due to 1.5T water depth, under keel clearance over 3.9 m is safe to proceed even if the ship is close to the bank wall in the initial position. Drafts tend to decrease slightly as the ship begins to drift to starboard and the bank effect decreases.
Lateral and longitudinal forces have the same trend as in previous cases but with bigger values, 320.66 tones, respectively -123.74 tones. It was observed that lateral force continues to decrease to negative values until -197.43 tones. This phenomenon is caused by the ship's swing due to bank effect and the approach to the opposite bank, but because of too great speed, the cushion effect from starboard side doesn't have enough "power" to reject the ship's bow, which will end into a collision. The sway ranges first from a maximum value of 0.442 m at starboard then to 0.298 at port side, caused by the opposite bank effect and after the moment of collision it decreases to 0.

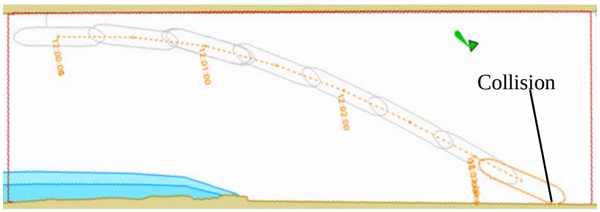

Figure 11. Ship track in the canal at 16 knots

The yawing moment has the same evolution as before; at the beginning it decreases to -8483.46 t*m then attenuates around 0 and after the ship is closer to the opposite bank it dramatically increase, reaching a maximum value of 24050.56 t*m right before the collision.
The ship's track and the position where the ship collided with the opposite bank can be observed in Figure 11. Also, the ship-bank distance increases with greater rate than other trials, causing the collision inside the one nautical mile canal limit.

Conclusions

Restricted waters impose significant effects on ship navigation. Ship squat is a phenomenon that occurs every time vessels are underway but is visible when navigation conditions are restricted, like shallow and narrow waters. With the presence of a side bank in the vicinity of the hull when ship maneuvers in harbors, channels or canals, bank and cushion effects appear and are related to this phenomenon. Experimental tools and empirical formulae are widely used for bank effect prediction, but they lack in providing detailed information on the flow field around the hull and can't be reliable for general use.
The method used in this research was simulation, where the authors studied the hydrodynamic parameters and ship to shore interaction of a 76800 tons bulk carrier moving along a bank in shallow water with constant depth in a 476 m wide waterway from Suez Canal, using NTPRO 5000 navigational simulator. There were conducted straight-line tests at 6.2, 7.4, 10.3, 11.8 and 16 knots for three under keel clearances, namely 10, 35 and 50% of the draft.
Sample numerical results and graphic interpretations have been presented and it was concluded that for every trial the squat acting on ship is bigger in these conditions, due to the presence of the bank in portside, than the one suffered by ship in open water conditions. Another remark was the similar trend of lateral force acting on the hull when ship run with 7.4 knots in every h/T ratio. Therefore, the greater the speed the more pronounced the bank effect is, meaning an earlier swing of the ship towards opposite bank when speed is bigger, an increased final ship-bank distance and a significant yawing moment causing a visible sway on ship. Also for this speed there weren't seen any differences on ship tracks and final positions when the water depth was modified, concluding that ship trend in the

canal doesn't depend on under keel clearance. At 10.3 and 11.8 knots all the parameters have the same trend as previous. For 16 knots trial, the bank effect is felt more pronounced causing the ship to swing very fast to the opposite wall of the canal and the cushion effect which should be felt in the bow is "overwhelmed" by the speed, trajectory that will end into a collision. If at the start of the trial, ship moved towards starboard, when closer to the opposite wall, yawing moment and sway change their direction, acting towards port.
Understanding such effects acting on ship in shallow and narrow waters can avert possible marine accidents. The best preventive procedure for a master while maneuvering near a bank is to slow down and take the help of rudder to counter them as best as he can.

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