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THE HANDLING OF LIVE SUPER SHIPS THROUGH GAILLARD CUT OF THE PANAMA CANAL

by

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[redacted]

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ABSTRACT

The performance of a typical, large, bulk-cargo ship in the confined water of a narrow channel was investigated in a series of model tests, with the objective of determining the best means of handling such vessels in Gaillard Cut of the Panama Canal. It is concluded from the results of the investigation that a deeply laden ship of the type considered does not have sufficient directional stability or rudder control to safely transit the narrow reaches of Gaillard Cut without tugboat assistance. It is also concluded that a tugboat astern of the ship is more effective than a tugboat ahead of the ship for providing the requisite assistance.

INTRODUCTION

The David Taylor Model Basin was requested by the Panama Canal Company to conduct a series of model tests on the handling of deeply laden large vessels through Gaillard Cut of the Panama Canal.[1] The tests have been completed but the data obtained have not yet been fully analyzed. However, the general conclusions reached from a preliminary analysis can be presented.

During the past few years there has been a steady increase in the traffic of large bulk-cargo ships through the Panama Canal. The prognostication is that this trend will continue.[2] Hence, the problem of rendering safe and expeditious transits through the canal for more and larger ships must be faced in the immediate future.

There are, in fact, existing ships of great bulk and draft that can pass through the locks of the Panama Canal, but which have not yet attempted to negotiate the Gaillard Cut channel when deeply ladened. There are, also, somewhat smaller ships of the same type that have experienced difficulty and occasionally come to grief in Gaillard Cut.

Large warships, which generally have relatively larger rudders and are more maneuverable than merchant ships, have successfully transited the Canal on numerous occasions. However, the chief navigational hazard for large ships of all types in the canal is the Gaillard Cut channel, which has conterminous banks and is 300 feet wide by 42 feet deep for approximately 6 of its somewhat more than 7 nautical miles of length.

The principal objective of the investigation, therefore, is to determine the best means of assisting live super-ships through narrow channels. For this purpose tug design, tug position, and speed are factors of immediate

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[1] References are listed on page 20

concern; although ship design and restricted channel characteristics are equally pertinent and perhaps even more important considerations. Basically the investigation is concerned with the effect of the confined water on the performance of the ship. Two series of model tests were conducted to evaluate this effect. In one, the model was attached to the carriage to measure forces, moment, and change in level - or "sinkage" - at various distances from the centerline. In the other, the model was run free under its own power and rudder control, with and without simulated tugboat assistance, to observe its maneuverability and to confirm some of the conclusions derived from the force-measurement tests.

The results of the investigation are discussed in terms of the predicted behavior of the ship maneuvering through the channel, with and without tug assistance. Selected test results and other source material which bear on the problem are introduced. A complete analysis of the detailed data from the model experiments carried out on this program will form the subject of a separate report.

A recent compilation of source material on ship handling in restricted waters is given in Reference 3.

MODELS AND PROTOTYPES

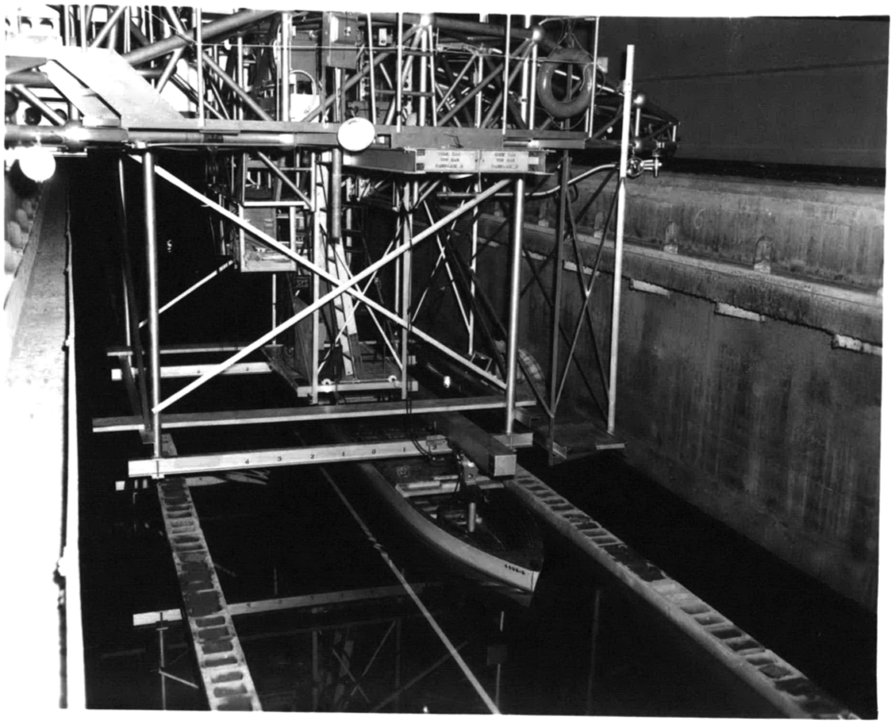
The 712.5-foot tanker WORLD GLORY was chosen as the type ship for the investigation. This ship has a displacement of 57,280 tons at a draft of 37 feet, and is representative of the modern type of large, single-screw, bulk-cargo carrier. A 25.7-foot model of the vessel was made available for the tests through the courtesy of the Bethlehem Steel Company, Shipbuilding Division, Quincy, Massachusetts. The linear ratio of ship to model was 27.74.

The model-test channel, Figure 1, was formed by erecting masonry walls on the concrete bottom of the high-speed basin. It represented a straight wall-sided cut 300 feet wide, 5548 feet long, and 42 feet deep. in some instances a water depth of 47 feet was also represented. The model channel was constructed to the same linear ratio as the model ship.

MODEL-TEST PROCEDURES

The investigation was based primarily on ship speeds of 4,5, and 6 knots through Gaillard Cut.

The model was attached to the dynamometer girder under the carriage, in the desired athwartship position, Figure 1, while the interaction and other hydrodynamic effects were measured. The dynamometer arrangement was of the three-component type, so that the resultant longitudinal and lateral forces and moment could be determined. The rise and fall, or "sinkage," of the model was recorded continuously during significant runs. Figure 2 shows the model entering the channel, and Figure 3 shows it leaving the channel.



PSD-91395

Figure 1 – Force-Measurement Test of the Model Ship in the Model Channel

In the free-running tests, the model was maneuvered under its own power and rudder action, by remote control, from a conning station on the basin towing carriage. The effect of a tug pulling back on the ship was represented by a force exerted on a line attached to the stern of the model.

MODEL-TEST OBSERVATIONS

FORCE MEASUREMENT

The force and moment measurements are not presented in this report, except insofar as necessary to give an example of their magnitude. For instance, when the ship is proceeding through the channel at a speed of 4 knots at a distance from the centerline of 75 feet, and at zero angle of yaw, the interaction force and moment are of the order of 77 tons and 13,000 foot-tons, respectively. The moment is practically doubled at a yaw angle of 2 degrees away from the wall, under otherwise identical conditions.

PSD-91399

Figure 2 – The Model Entering the Channel

PSD-91396

Figure 3 – The Model Leaving the Channel

In general, the force measurements show that the wall, or "bank suction," effect is strong except near the middle of the channel. Away from the middle, the effect of the walls on the flow around the hull produces lateral hydrodynamic forces. When the ship is headed parallel to the banks in a straight channel of uniform width and depth, the resultant force acts toward the adjacent bank whereas the moment tends to turn the ship away from the bank toward the middle of the channel. The yawing moment is thus in some respects advantageous. Nevertheless, the inability to control this yawing moment is the principal cause of the difficulty in handling the ship.

The force-measurement tests show that:

1. When the ship is in the middle of the channel, the yawing moment is zero.
2. When the ship is 25 feet from the middle, the yawing moment can be counteracted by the rudder.
3. When the ship is 30 to 90 feet from the middle, the yawing moment is greater than the rudder action can sustain.

CHANNEL DEPTH

The force measurements show that the depth of the water has an appreciable effect on the controllability of the ship. At a distance of 75 feet from the centerline and at zero angle of yaw, the ship is controllable under the action of the rudder in water that is 47 feet deep, whereas it is not controllable in water that is 42 feet deep.

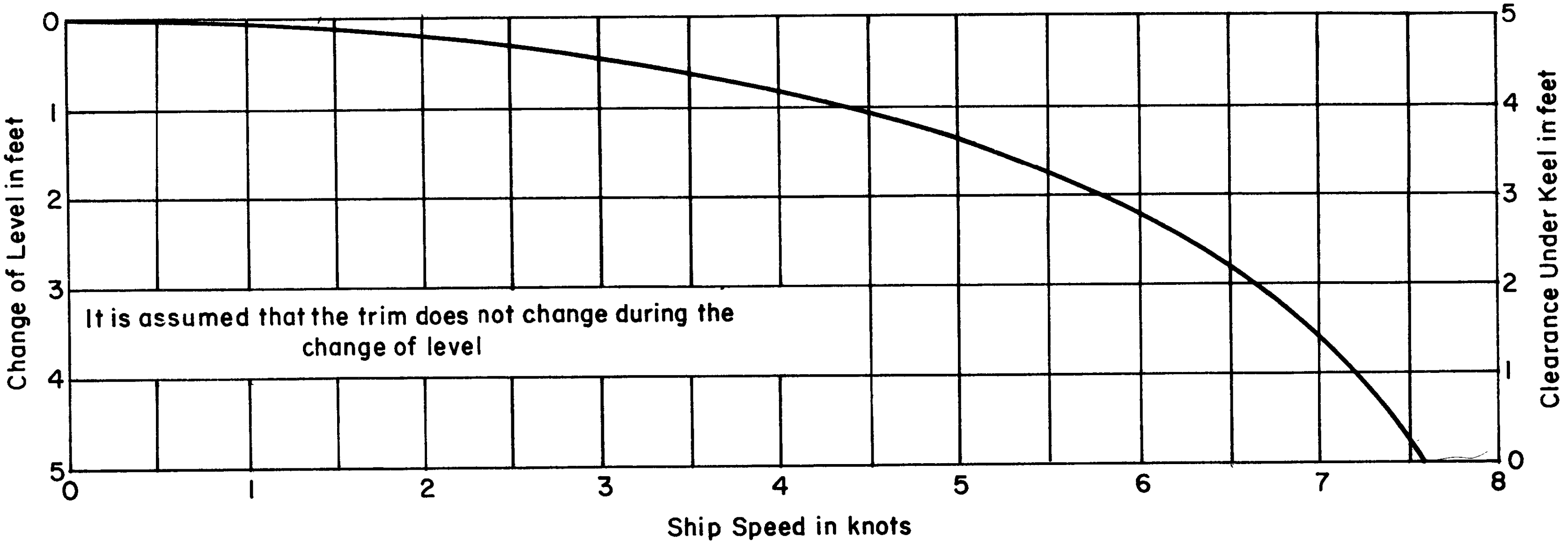
CHANNEL WIDTH

The tests were based specifically on a channel width of 300 feet, but some observations were made during the short run in the full width of the basin at the entrance to the channel, which represented a width of 586 feet. The tests showed that the interaction forces over this portion of the run were of an order that could be controlled by the rudder, distances up to 90 feet from the centerline of the basin being represented. No tests were made with the model close to the wall; however, it is believed that the effect of the opposite side should be smaller than in the narrower channel and consequently the resultant interaction should be even larger.

CHANGE OF LEVEL

The change of level, or "sinkage," observed in the tests was generally in good agreement with although greater than that given by the formula:[4]

$$\frac{22.6\,\Delta H}{V_s^2} = \left(\frac{A_o}{A}\right)^2 - 1$$



Ship Data	
Length	712.5 feet
Beam	102 feet
Draft	37
Trim (assumed)	Even Keel
Midship section area (assumed to be rectangular)	3774 square feet

Channel Data	
Width	300 feet
Depth	42 feet
Side Slope	Vertical

Figure 4 - Theoretical Change of Level Curve

where

ΔH is the mean change of level of the ship in feet,

V_s is the ship speed over the bottom in knots,

A_o is the normal cross-section area of the channel in square feet, and

A is the net water area at midship section in square feet.

This formula is implicit in ΔH, since A is determined by assuming that the change in level of the ship and of the water at the midship section is ΔH. The formula is explicit in V_s, however, which can be determined for assumed values of ΔH and plotted, as shown in Figure 4, whence ΔH can be obtained for any given ship speed. Figure 4, with minor modifications, was taken from Reference 5.

For the ship at 6 knots in water 42 feet deep the maximum change of level according to the tests was nearly 3 feet at the bow, where the greatest change of level of merchant ship forms at slow speeds in shallow water generally occurs. Hence, the remaining clearance under the hull was only about 2 feet, which is extremely small for such a large ship.

RUDDER AREA

The tests show that approximately twice the present rudder force is required to counteract the wall effect and yet retain sufficient reserve to provide normal steering control. Nevertheless, an increase in rudder area of 20 to 50 percent might be effective in curbing the tendency to sheer in an uncontrolled fashion from one side to the other. This aspect of the investigations should be studied further with a view toward establishing criteria for the minimum size of rudder suitable for use on ships passing through the Panama Canal.

WAKE

Wakes of 29.0 and 60.0 percent have been observed on models in shallow water; as compared with 19.5 and 40.0 percent, respectively, for deep water.[6,7] The general conclusion that the wake behind a bulky ship in shallow water is extremely high was borne out in the present investigation; as the effect of the rudder on the model without the propeller was almost negligible. With the propeller in action the rudder had a strong turning effect but was still inadequate to cope with the wall-interaction forces.

The propeller thrust and slipstream velocity were increased for a given ship speed, and the effectiveness of the rudder in the propeller race was markedly improved when a force was exerted to simulate the effect of a tug pulling back on the ship.

WAVE AND FLOW PHENOMENA

The wave and flow observations, in general, are not presented since they are not considered to form an essential part of the report. Attention is called, however, to the strong reverse flow, which is created by the movement of the ship through the confined water of the channel. At slow speeds where the change in level of the ship and the water surface is negligible, the velocity of the return flow is 43 percent of the velocity of the ship, and is negative in direction with respect to the ship velocity. At a speed of about 6 knots where the change in level is 2.5 feet, the velocity of the return flow is estimated to be 56 percent of the velocity of the ship, and is negative in direction with respect to the ship velocity. Thus, a speed of about 9.36 knots through the water is required for the ship to attain a speed of 6 knots over the ground through Gaillard Cut in the Panama Canal.

FREE MANEUVERING

A free-running, remotely controlled model of the ship was repeatedly run through the test channel, but prompt and frequent rudder action was required and the operation was obviously hazardous. The model could be steered over to one side of the channel and brought on a course parallel to the wall. However, this course could not be maintained because the yawing moment near the wall would cause the model to turn against the opposing action of the rudder toward the middle of the channel.

The model could not be kept on a straight course even near the centerline of the channel, where the effect of the walls was largely balanced. Observations on the cause of this uneasy steering showed that the level, or "sinkage," and trim of the model varied almost continually, and that the bottom of the channel was by no means level. The proximity of the vessel to the bottom made the irregularities in depth particularly noticeable.

When a collision occurred with one of the channel walls during these maneuvers, the sequence of events leading up to the collision generally followed a consistent pattern. A momentary loss of control would result in a sheer toward one side of the channel. Control would usually be regained sufficiently to prevent a collision with the wall. Then a rank sheer toward the opposite wall would develop that was difficult to counteract.

The reasons why the control of the model became progressively more difficult were brought out in the tests. The initial sheer started from a position near the middle of the channel, so that only about one-half the width of the channel was available in which to build up a yaw angle. The following sheer started from a position near one side of the channel, where the wall effect created a strong yawing moment, and practically the full width of the channel was available in which to turn toward the opposite side.

When the yaw angle became appreciable, the reverse flow in the channel tended to cause a further increase in the yaw angle by impinging on the bow. Moreover, when the model approached the side at an appreciable angle, the flow between the hull and the wall became faster at the bow than at the stern, with a consequent reduction in the pressure forward on the side adjacent to the wall. The model, in accordance with the Bernoulli principle, therefore tended to turn toward the wall when the angle of approach was large whereas it tended to turn away from the wall when the angle of approach was small.

As the model turned away from the wall during the tests, the rudder was put hard over to stop the swing of the stern and bring the model on a course parallel to the wall. This application of full rudder toward the wall occasioned no difficulty, since the bow could always be brought out from the wall by reducing the rudder angle. The main difficulty was in fully counteracting the yawing moment, and it was generally impossible to do so except near the middle of the channel. Nevertheless, it was helpful to anticipate the need for strong rudder action and to apply it promptly. The model could then be brought away from the wall more slowly, with a better chance of bringing it under control as it approached the middle of the channel.

TUGBOAT ASSISTANCE

The preceding tests show that tugboat assistance is required to handle the ship in Gaillard Cut because the vessel is out of control near either side of the channel and is difficult to steer steadily in the middle. They also show that the principal hazard is the danger of yawing sharply away from one bank and then going aground on the opposite shore.

The tendency to yaw away from the adjacent bank can be controlled by a lateral force acting on the bow toward the bank, or on the stern away from the bank. Some adjustment in the drift angle, or heading, of the ship is required to bring the forces into equilibrium and form the necessary couples, but this is habitual in canal navigation and need not be considered here. It is pertinent to note, though, that a force on the bow toward the bank obviously cannot be provided by a tugboat through a cable connection when the ship is near the bank; but a force on the stern away from the bank can be provided by a tugboat, or by the rudder of the ship.

The maneuvering and the force-measurement tests show that the lateral force of the rudder is inadequate to control the ship except near the middle of the channel. A tug pulling back on the ship, as shown in Figure 5, improves the effectiveness of the rudder by increasing the resistance and propulsion effort, as noted in the section on wake. The rudder force is still inadequate, though, to control the ship near either bank. A supplementary lateral force consequently must be provided by the tug.

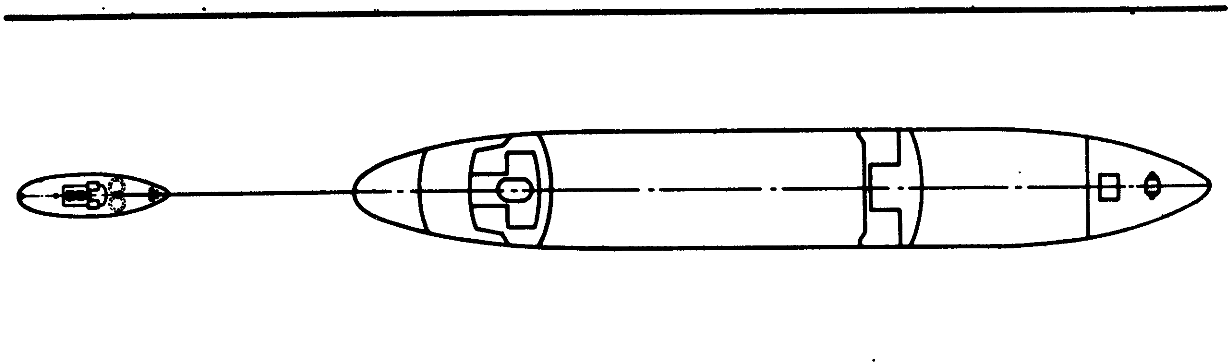


Figure 5 – The Ship Proceeding through the Canal with a Tugboat Holding Back on the Stern

A pull of approximately 19 tons on the stern of the ship from a point in the middle of the channel 300 feet behind the vessel was represented, on model scale, in the tests. With this force on the stern, the model could be kept on a course down one side of the channel without any difficulty.

A tugboat astern of the ship not only improves the directional stability of the vessel by occasioning an increase in flow over the control surface aft, but helps to prevent the ship from yawing off the course by pulling on the stern, as shown in Figure 6. When the ship is in this position, the cable force can be resolved into a force through the center of gravity and a couple opposing the yaw.

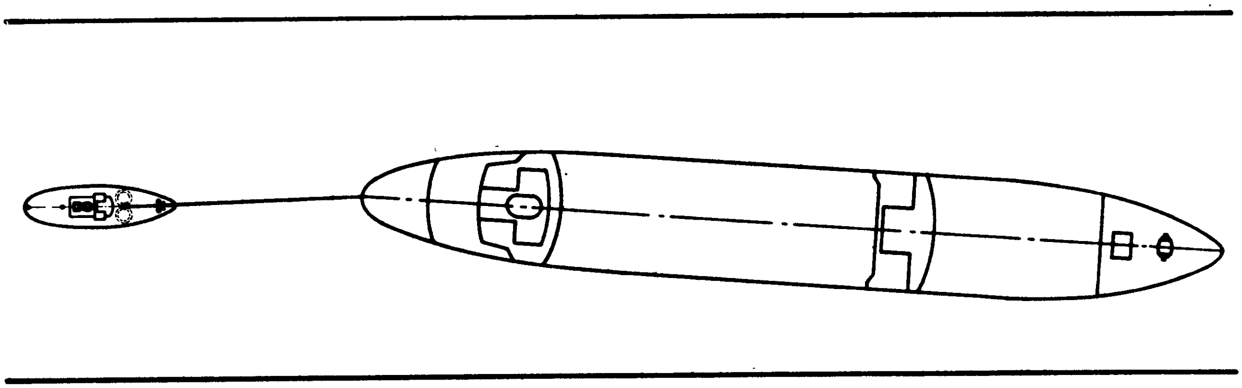


Figure 6 – A Tugboat Astern of the Ship Improves Directional Stability and Opposes Yawing Tendencies

The cable pull helps to prevent yaw until the ship arrives in the position shown in Figure 7. Then its effect is neutral and the ship is free to turn in either direction. If desired, the tug can begin to slack the cable when the ship arrives in this position, so that the stern will be unencumbered as it swings in toward the bank. Yet, on the basis of the tests, it does not appear that any such action is necessary.

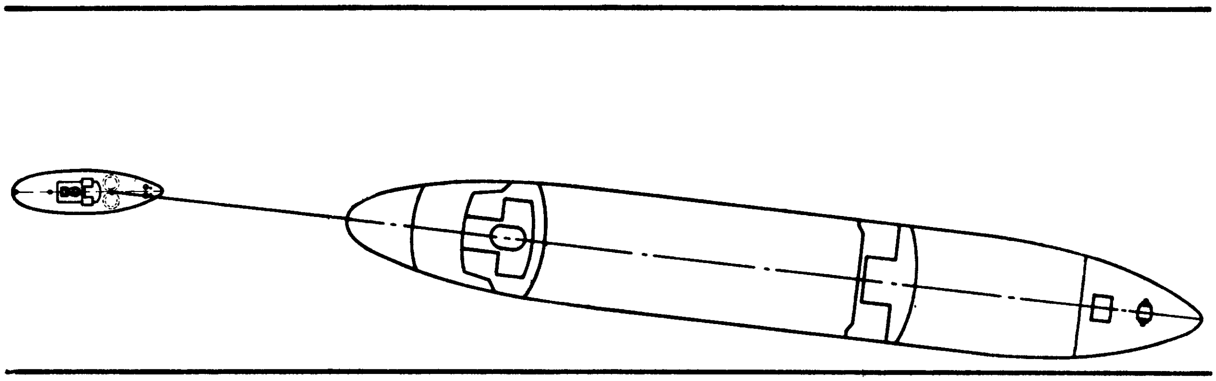


Figure 7 – The Ship Is Free to Steer in Either Direction When the Cable Pull is Directly Astern

Figure 8 shows the ship on one side of the channel with the tug pulling on the stern from a mid-channel position. The forces acting on the vessel are in equilibrium with the hull at a small angle of yaw to the course along the bank, and with the cable and rudder forces acting on the stern away from the bank. The tug maintains a constant pull, and the margin of control is provided by the rudder. The ship, therefore, can be steered in any direction as desired.

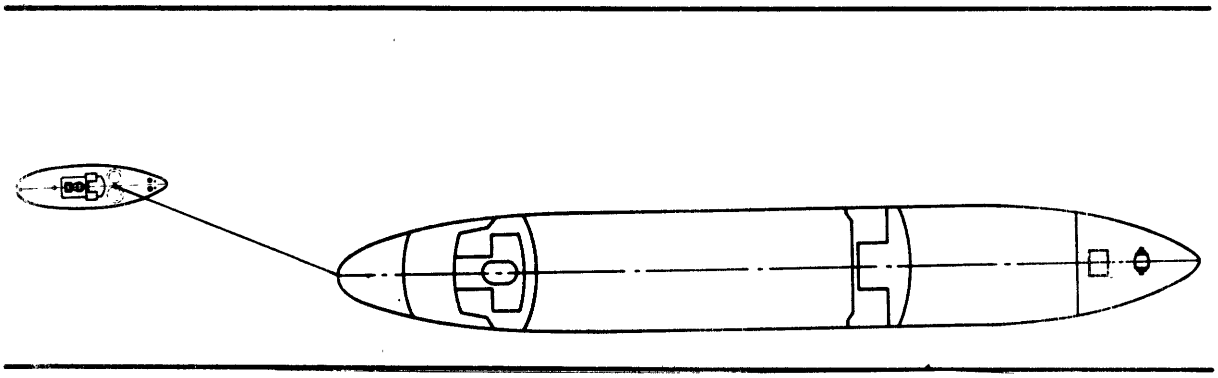


Figure 8 – The Ship Proceeding Along One Side of the Canal with the Tugboat Exerting a Lateral Pull from Mid-Channel

The tests show that a tugboat behind the ship can control the vessel without departing from a position near the middle of the channel. Yet, in the event of any emergency, the tugboat can exert a powerful pull on the ship from the positions shown in Figures 9 and 10.

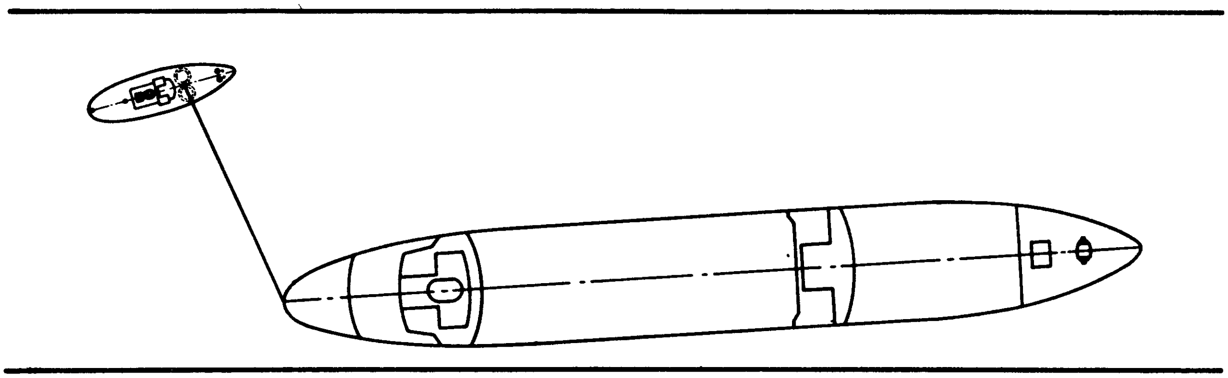


Figure 9 – The Ship Proceeding Along One Side of the Canal with the Tugboat Exerting a Lateral Pull from the Other Side

The arrangement shown in the sketches (Figures 5-10) with the vessels connected by a 200-foot cable will be even more effective in applying a lateral pull on the ship than the arrangement with the 300-foot cable, which was represented in the tests. With the tug behind the ship and pulling astern,there is practically no possibility of one vessel overrunning the other.

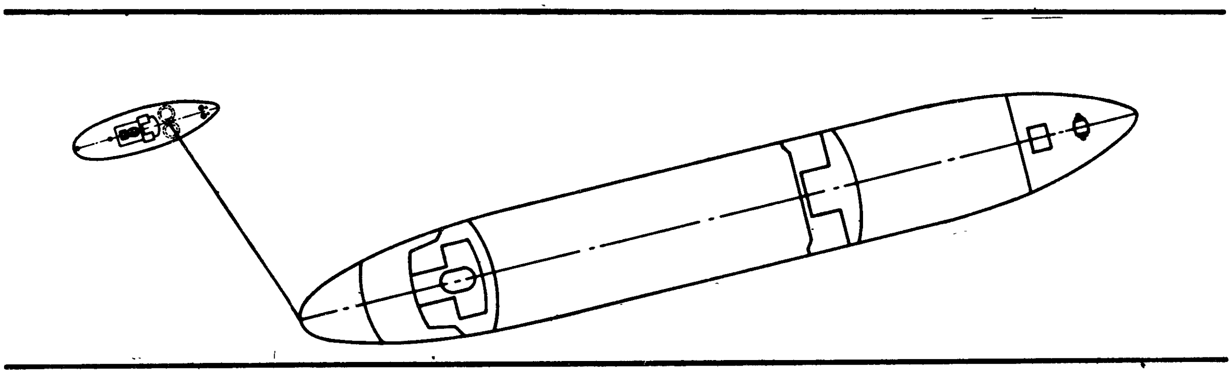


Figure 10 – In an Emergency, A Strong Lateral Pull Can Be Exerted by a Tugboat Having Vertical Axis Cycloidal Propellers

Figure 11 – A View of Gaillard Cut Showing a Tugboat on a Hawser Ahead of a Ship

The tests also show that the present practice of employing a single tug ahead of the ship - as shown in Figures 11 and 12 - is inadequate, particularly for large ships. A tug ahead of a live ship usually runs with the cable slack, except in wind and around bends. It cannot put a strain on the cable without reducing the ship's propeller thrust which - as previously noted - decreases the slipstream velocity and thus diminishes the effectiveness of the rudder.

The principal function of a tug in this position, though, is to aid in emergencies. Hence, when the ship sheers toward one side of the channel the tug pulls toward the other side in an effort to break the sheer and bring the ship back on a parallel course.[8] This action is effective in diverting the ship from a collision with the bank, but unfortunately leaves the tug in the wrong position to be of any further assistance.

When the vessel turns away from the bank, the only proper course of action for the tug is to slack the cable and take up a position where it may subsequently be of assistance. In narrow waters it is axiomatic that a tug should not pull the bow of a ship away from the bank unless the vessel is on a collision course with the bank.

Figure 12 – Another View of Gaillard Cut Showing a Tugboat on a Hawser Ahead of a Ship

EVALUATION OF TUGBOAT REQUIREMENTS

A constant tugboat pull of 19 tons on the stern of the ship was represented in the tests. Hence, on the assumption that a tugboat can develop a pull of 20 pounds per horsepower, a vessel of approximately 2100 horsepower is required. Actually, according to References 9, 10, and 11, a pull of 30 pounds per horsepower can be developed under favorable conditions; but, considering the necessity of providing a lateral pull to counteract the interaction force and the advisability of running usually at reduced power, it does not appear that anything less than 2,000 horsepower should be considered. A tug of even greater power would be desirable, although one of 2,000 horsepower that can apply its pull in the right direction is preferable to a tug of 2,500 horsepower that can only pull harder ahead.

A tugboat intended for use astern of a live ship should be able to steer while pulling back on the ship and to maintain a strong pull at an angle to the ship. Recent data on screw tugs are given in References 11, 12, and 13.

A tugboat with vertical-axis, cycloidal propellers located directly under the forward cable bollard, as shown on the small sketch in Figure 9, has two outstanding advantages for the proposed purpose. One is its maneuverability. The other is that it can apply a pull in the desired direction from any position. Data on tugs with vertical-axis, cycloidal propellers are given in References 14 through 20.

The latest tugs constructed for the British Admiralty are diesel-electric paddle tugs; with paddles that can be operated independently and controlled directly from the bridge, these tugs are particularly maneuverable. Moreover in the experience of the British Admiralty, screw tugs have never been as effective as paddle tugs for maneuvering large vessels into and out of docks and basins. Such tugs are also suitable for use astern of ships in canals. One advantage for this purpose is that they can back both paddle wheels and still steer with the rudder in the normal fashion while going ahead. Since the rudder is not in the slipstream of the paddles, it is not greatly affected by the direction of rotation of the paddle wheels. Data on these tugboats are given in Reference 21.

An ample lateral plane, or broadside area, is generally desirable in a Panama Canal tugboat to enable it to develop the necessary resistance to lateral forces. In fact, if a suitable keel of sufficient area could be provided, very little power in the tugboat would be required to counteract the interaction forces.

Other developments, such as the use of either an athwartship paddle wheel or of a large rudder under the keel are feasible but may not be desirable in a tugboat intended for general use.

DISCUSSION

The results of the investigation show that a typical, deeply-laden, large, bulk-cargo carrier with only 5 ft of water under the keel cannot safely negotiate the 300-ft-wide Gaillard Cut channel without assistance. A free-running, remotely controlled model was repeatedly run through the test channel, but prompt and frequent rudder action was required and the operation was obviously hazardous. No one ever succeeded in steering the model through the channel without having the bow weave back and forth across the centerline, and even this degree of control was attained only by keeping the model always near the middle of the channel. Any appreciable departure from the middle usually resulted in a sheer toward one side or the other, with subsequent loss of control.

The large mass and momentum of the model made it difficult to analyze its behavior from visual observations. However, the force measurements showed that the principal difficulty was due to the wall interaction, or "bank suction," effect that was created by the movement of the bulky hull through the confined water of the channel. This effect was strong except near the middle of the channel, where the hydrodynamic forces acting laterally on the model were largely balanced.

The force measurements also showed that the rudder was inadequate to cope with the interaction forces except when the model was near the middle of the channel.

Yet, no difficulty was experienced in controlling the model when the effect of a tugboat astern of the vessel was represented in the tests. The model could then be kept on a straight course on one side of the channel. Moreover, the pull of the line on the stern did not appear to have any adverse effect on the maneuverability of the model. In fact, with this arrangement, the control of the model was definite and positive at all times.

The tests show that an increase of 5 feet in the depth of the Gaillard Cut channel would be beneficial, although it is not expected that an increase in water depth of this amount would be a panacea, or make tugboats unnecessary. The principal advantages would be in reducing the amount of the change in level, or "sinkage", and in improving the shiphandling conditions near the banks.

The tests also show that the rudder of a typical, large, bulk-cargo ship is rather inadequate for transiting canals. In a table on page 2.6 of Reference 4, the rudder areas of the naval ships, with respect to the product of their length and draft, are roughly from 60 to 100 percent more than those of the large merchant ships. In this connection, attention is called to the possibly beneficial effect in canal operation of a fixed fin between the rudder and the propeller of a ship. A fin in the propeller race should augment the steering force and also have a stabilizing effect.[22] A fin in this position should be particularly effective in canal operation where an even stronger steering force may be required on a straight course than is normally obtained in turning.

In a broad sense, perhaps the best means of providing safe and expeditious transits for super ships through the Panama Canal is through the combined effect of tugboat assistance, wider and deeper channels, and a general improvement in the handling qualities of the ships. Yet, for the time being, tugboat assistance should suffice, provided that the speed of the ships is kept at about 4 knots through Gaillard Cut.

CONCLUSIONS

From the investigation conducted, on model scale, to evaluate the performance of a typical, large, bulk-cargo ship in a 300-foot wide by 42-foot deep canal, it is concluded that:

1. A large, deeply-laden ship of the type considered does not have sufficient directional stability or steering control to safely negotiate the Gaillard Cut channel of the Panama Canal without tugboat assistance.

2. For controlling live (self-propelled) super ships in narrow waters, a tugboat astern of the ship is more effective than a tugboat ahead of the ship.

3. In Gaillard Cut, the effect of the banks on the flow around the hull of a large vessel creates a strong steering bias, except when the ship is near the middle of the channel.

RECOMMENDATIONS

For the purpose of assisting live super ships through Gaillard Cut of the Panama Canal, a tugboat of about 2,500 horsepower with vertical-axis, cycloidal propellers is recommended. This tugboat should be designed especially for operating astern of the ship, and should be capable of exerting a strong lateral pull.

For the present, it is recommended that the speed of super ships over the ground in Gaillard Cut be limited to about 4 knots.

The advisability of eventually increasing the depth of the Gaillard Cut channel by 5 or 10 feet should also be considered.

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