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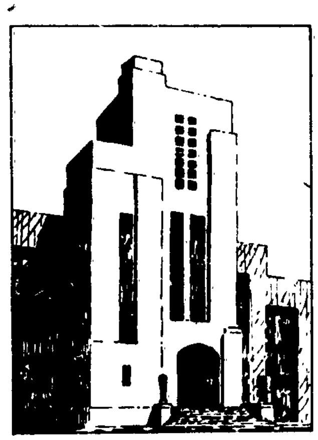
491305

THE DAVID W. TAYLOR MODEL BASIN

UNITED STATES NAVY

THE PERFORMANCE OF MODEL SHIPS IN RESTRICTED CHANNELS IN RELATION TO THE DESIGN OF A SHIP CANAL

BY R.S. GARTHUNE, B. ROSENBERG, D. CAFIERO
AND C.R. OLSON



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THE PERFORMANCE OF MODEL SHIPS IN RESTRICTED CHANNELS IN RELATION TO THE DESIGN OF A SHIP CANAL

ABSTRACT

In this investigation a series of tests were made with selected ship models operating in restricted channels. The tests were made to determine the effect of channel dimensions on the relative controllability and the sinkage of ships in straight channels and to determine the effect of channel-bend design on the controllability of ships.

The hydrodynamic phenomena of major importance in the study are bank suction, interaction between ships, and the change of level of the water surface in the vicinity of a moving vessel.

The major test variables include the width and depth of the channel, bend design, ship speed, position of the ships in the channel, type of ships represented, and the velocity and direction of channel currents.

Most of the tests were conducted in model channels representing full-scale channels ranging from 268 to 770 feet in width and from 45 to 80 feet in depth. The major emphasis was on ship speed between 5 and 10 knots with respect to the water, but the change-of-level tests were made at speeds up to 20 knots in some channels. The channel currents ranged between 5 knots following current and 5 knots ahead current. The ships represented in the tests were selected because of their extreme size, their poor handling characteristics in restricted channels, or because they were representative of a large number of ships now using the Panama Canal. The model ships and the model channels were constructed to the same linear ratio and their ratio ranged from 35 to 86 for the various phases of the test program.

Data were obtained by direct observation of tests, by analysis of photographic records of the test runs, and by direct measurement of physical phenomena.

Accurate methods of estimating sinkage of a vessel underway in a restricted channel are developed. Bank suction is measured in terms of the rudder angle required to counteract it and also in terms of the forces and moments produced on the ship by it. Graphs show the variation in bank suction and in sinkage with changes in the test variables. The significance of interaction between ships is evaluated. A technique for selecting channel width, depth, and bend design is presented.

SECTION 1

INTRODUCTION

The David Taylor Model Basin has conducted a series of model tests to study the performance of ships underway in restricted channels. The immediate purpose of the tests was to obtain information which would be of assistance to the Panama Canal in the selection of the cross-sectional dimensions and the design of bends for a modernized canal across the Isthmus of Panama. The information obtained from this study should be useful in the design of ship canals and it should also be useful to canal pilots and other individuals concerned with the problems of navigation in restricted channels. These tests, which were sponsored by the Panama Canal under the authority of Public Law 280, 79th Congress, are the subject of this report. This study was carried on under Project SRD-630/46. TMB File H1-2/HG contains the correspondence on the project.

Acknowledgment is due to the Panama Canal officials and staff members for their advice, cooperation, and forthright criticism. The Special Engineering Division, Panama Canal, gave invaluable assistance in selecting the broad phases of the test program and in determining general specifications for ship speeds, channel currents, channel dimensions, bend designs, and types of ships to be represented. Special acknowledgment is due to the Panama Canal pilots who aided with the tests and gave unbiased and valuable criticism. Acknowledgment is also due to C.A. Lee for general supervision of the project and to C.E. Bowers, the project manager. Mr. Lee, Mr. Bowers, and Mr. Bradley are the authors of several status reports, the content and wording of which have been used freely in this report.* D. Cafiero, W.F. Brownell, and W.V. Coyle guided the construction and design of the model setup. F.W. Puryear conducted the force-measurement studies. F.D. Bradley and C.R. Olson conducted the maneuvering studies. C.R. Olson is the author of Section 5. B. Rosenberg conducted the change-in-level tests and is the author of Sections 6 and 7. Mr. Cafiero is the author of Section 3. R.S. Garthune assisted by Miss V.R. Gilchrist and C. Larson, compiled and analyzed most of the data. Mr. Garthune, the author of Sections 1, 2, 4, and 8, had general supervision of writing the report.

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* Mr. Lee and Mr. Bowers also contributed a paper (15)† to the ASCE Proceedings which has been used liberally.

† Numbers in parentheses indicate references on page 9.1.

SECTION 2

GENERAL CONSIDERATIONS

PRELIMINARY STUDIES

A preliminary search of the literature with respect to navigation in restricted channels revealed a long and continuing interest and activity on the part of those people immediately concerned with the problems and dangers of restricted-channel navigation. More specifically, it was found that navigation in canals is difficult, not only because of the limited space available but also because of various hydrodynamic phenomena which introduce additional hazards.

After the search of the literature and after preliminary discussion with members of the Special Engineering Division, Panama Canal, it was concluded that the major hazards arising from restricted-channel navigation are:

a. The change of level, or sinkage, of a ship while underway in a restricted channel with respect to its level while stationary in the same channel,

b. "Bank suction,"

c. The interaction between ships meeting in a restricted channel.

Previous to these tests several investigations into change-of-level phenomena had been made. However, earlier studies were usually limited to tests with a single ship model in a single channel and the analysis was not considered sufficient to permit accurate estimates of the change of level of any ship in any restricted channel. It was known that the Bernoulli equation furnished at least a partial explanation for the change-of-level phenomena. It was also realized that at high speeds a large vessel might actually sink enough to strike the channel bottom or possibly cause the pilot to lose control of the ship.

The expression "bank suction" has long been used to describe a phenomenon which occurs when a ship is underway on a course closer to one side of a restricted channel than to the other side. In this situation, an asymmetrical flow distribution develops on opposite sides of the ship which causes the water surface to assume different levels at corresponding points on opposite sides of the ship. As a result, unbalanced lateral forces act on the ship. These lateral forces are of such magnitude and direction that the vessel develops a sheer away from the near bank of the channel. The canal pilot uses a rudder setting which tends to turn the vessel towards the near bank to counteract bank suction; thus, if a vessel were underway on a course near the right bank, it would be necessary to use right rudder to counteract bank suction. The tendency to sheer may in some circumstances be so great that it cannot be overcome by use of the rudder, and as a result the vessel may strike one of the banks. A similar phenomenon occurs when a ship passes projections in the channel or passes through changes in the channel section.

The third major hazard listed as arising in restricted-channel navigation is the interaction between ships meeting in a channel. This phenomenon is of course superimposed on the bank-suction phenomenon just discussed. Little was known as to the effect of channel dimensions, ship speed, ship size, or ship lines on the magnitude or seriousness of this problem.

PROBLEMS TO BE INVESTIGATED

It was decided that the two primary problems to be investigated in this study were the variation in the controllability and in the change of level of selected ships, as affected by variations in channel cross-section, channel-bend designs, channel currents, ship speed, and possibly other related factors.

Another hydrodynamic phenomenon of considerable interest, which might have been investigated, is the change in resistance of a ship underway in a restricted channel compared with the resistance of a ship in open water. The change-in-resistance phenomenon was not considered significant for the purpose of this study; however, interested persons will find references on this topic in the bibliography.

The determination of controllability of full-scale ships in restricted channels based on tests with ship models appeared to be the most difficult of the two primary problems. This conclusion may be justified for the following reasons: First, the variety and the complexity of the factors entering into a rating of controllability; Second, no tests of this nature had ever been attempted; Third, it was necessary to design new types of test apparatus, some of which were rather complex, and to develop new testing techniques; Fourth, no standards or measures of controllability were in use and therefore objective standards or measures had to be developed. Controllability involves the major navigational hazards previously discussed; it also involves the steering characteristics of the vessel, the effect of the restricted channel on the steering characteristics of the vessel, and the human element, i.e., the skill of the pilot.

TEST PROGRAM AND PLAN OF REPORT

With these ideas in mind, the test program was designed to emphasize the investigation of controllability. It was realized that the program would need to be revised from time to time as the test results accumulated and as the analysis progressed.

The test program as actually carried out may be divided into four major phases, each phase involving a variety of tests. The major phases are treated separately in the report. The reader may identify these phases by reference to Sections 4, 5, 6, and 7 in the following outline of the report.*

1. Introduction
2. General Considerations
3. Test Equipment
4. Controllability of Ships in One-Way Traffic in Straight Channels
5. Controllability of Ships in Two-Way Traffic in Straight Channels
6. Controllability of Ships in Channel Bends
7. Change of Level in Restricted Channels
8. Summary
9. Bibliography

Each section from 2 to 7 inclusive is presented in the form of a complete report. Information and data were obtained by direct observation of tests, by analysis of extensive photographic records of the tests, and by means of direct measurement of physical phenomena.

It was believed that Section 3 on test equipment should be quite complete because novel and difficult design and construction problems had to be solved to ensure the quality of the test results. In many cases the test apparatus was developed and improved as the tests progressed. It is believed that the apparatus and techniques discussed in Section 3 may be of value not only in interpreting the test results but also as a source of information if similar tests are attempted in the future.

Two major TMB facilities, the shallow-water basin and the circulating-water channel, were used in the test program. These facilities are fully described in Section 3.

The tests described and discussed in Sections 4, 5, and 6 are essentially an investigation to determine the effect of channel dimensions and bend designs on the relative controllability of specified ships under specified conditions of operation.

The tests described in Section 7 are directed towards finding the effect of channel dimensions on the change of level of specified ships underway in restricted channels under specified conditions of operation.

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* The photographic records of the test runs are addenda to this report. Because of the nature of these records only one complete copy was prepared and this copy is retained by the Panama Canal. The Taylor Model Basin has one copy of Addenda I, III, and VI; see page 2.7 for an index of the Addenda.

Section 8 presents an overall summary of the results of the investigation, together with an example showing how the test results described in the various sections of the report can be combined to give a more rational basis for the selection of channel dimensions and channel bend designs than has hitherto been possible.

MODEL LAWS AND ASSOCIATED NOTATION

Tests with ship models have, for many years, furnished a reliable basis for estimating the horsepower, speed, turning circles, and other characteristics for full-scale ships. In such tests, standard methods of testing and of estimating full-scale performance have long been used. It is seen that the present investigation involves an extension in the use of ship-model tests to more complex phenomena. However, the same physical laws that have proved dependable in earlier ship-model studies are still applicable.

It is necessary to understand the physical laws relating model and full-scale dimensions and data in order to plan and conduct tests with ship models and in order to interpret the results of these tests. In such tests, a condition of dynamic similarity or similitude exists between model and full-scale phenomena when the Froude number for the model is equal to the Froude number for the prototype. This law is applicable when geometrical similarity exists between the model and the prototype. In the tests described in this report it was necessary not only to maintain geometric similiarity between the model ship and its prototype but also between the model channel and the prototype channel. In other words the entire model setup was geometrically similar to the prototype setup. The Froude number, which is a dimensionless parameter that allows for the influence of gravitational forces, is defined as

$$F = \frac{V}{\sqrt{gL}}$$

where V is the velocity in feet per second,

L is a convenient linear dimension in feet defining a fixed boundary condition, and

g is the acceleration due to gravity in feet per second per second.

It follows that the condition of dynamic similarity or similitude exists when

$$\frac{V_m}{\sqrt{gL_m}} = \frac{V_p}{\sqrt{gL_p}}$$

where the subscripts m and p refer to model and prototype respectively.

Froude's law is thus the basis for adjusting velocity, rate of change of rudder angle, and revolutions per minute of the propellers of the model to represent operating conditions of the full-scale ship.

It was obvious, because of the size of the ship models used in the tests, that the effects of surface tension and elasticity were negligible and therefore that the Weber number and Cauchy number for the model need not equal the corresponding prototype numbers in order to assure dynamic similarity. Likewise, it was apparent that the Reynolds number of the model need not equal the Reynolds number of the prototype. This was true because the Reynolds number of the smallest ship model at the slowest speed was approximately 7×10^6, a value which would assure turbulent flow in the boundary layer about the model, except for a small area at the bow which could not materially affect the flow pattern. Consequently, in the present tests only the Froude number was of importance.

On the basis of the Froude number the following relationships for time rates and velocity obtain:

a. Time rates for the model, i.e., rate of rudder movement, revolutions per minute of the propellers, rate of calling orders from the "pilots" to the "quartermaster," and any other time rates should equal the time rates for the corresponding elements on the full-scale ship multiplied by the square root of the linear ratio.

b. Velocity for the model, i.e., speed of the model ship and velocity of the water in the channel during moving-water studies, should equal the respective full-scale speeds divided by the square root of the linear ratio.

SELECTION OF SHIP MODELS

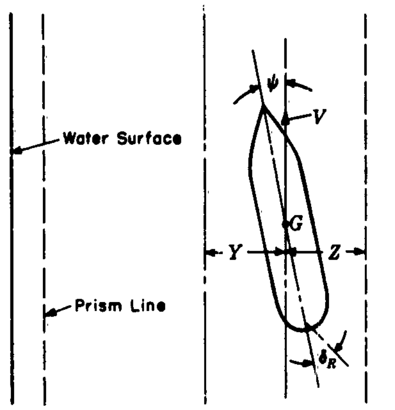
Discussion of the ship types to be represented in the model studies led to the decision that the vessels should be selected for one of the following reasons:

a. Their large size.

b. Their poor handling characteristics in restricted channels.

c. Their being representative of a large percentage of present ships transiting the canal.

It was decided that the investigation should emphasize tests of vessels selected for reasons a and b. This decision appeared to be justified because vessels of these types present the most difficult navigation problems. Also, a canal which is designed for operation of these types of ships should present no serious navigation problems for ordinary canal traffic.



LEGEND

ψ - Angle of yaw
G - Center of gravity
δ_R - Rudder angle
Y - Distance from ℄ of channel to G of ship
Z - Distance between G of ship and prism line
V_S - Ship speed (with respect to water)
V_W - Water speed (+ indicates following current, — indicates ahead current)
LWL - Load waterline length
λ - Linear ratio

Model Number	Type of Ship*	Linear Ratio λ	Dimensions of Model in feet			Dimensions of Full-Scale Ship in feet			Propellers		Rudders	
			L W L	Beam	Draft	L W L	Beam	Draft	Number	Rotation	Number	Projected Area of one in ft²
3769	Large Naval Vessel a	45	20.00	2.51	0.717	900	113	32.25	4	Outward	2	350
3859	Tanker b	35	20.58	2.855	0.914	720.6	100	32.13	2	Outward	1	340
4018	Tanker b	45	16.00	2.221	0.714	720.6	100	32.13	2	Outward	1	340
3748-4†	Liberty c	45	10.01	1.33	0.6326	450.4	59.85	28.47	1	Right Hand	1	158.9
3992	BB-61 a	86	10.00	1.256	0.4025	860	108	34.625	4	Outward	2	445.5
3673-A	BB67-71 a	44.5	20.00	2.585	0.815	890	115	36.27	4	Outward	2	400

* Reasons for selection

a. Large size.
b. Poor handling characteristics in restricted channels.
c. Representative of a large percentage of present ships transiting the canal.

† Model 3748-4 was built to represent a Liberty Ship to the scale of 42.685 to 1. The channels in which this model was tested, however, had been built to a linear ratio of 45 to 1, and in these channels the model represented a ship slightly larger than a Liberty Ship.

Figure 2.1 - General Information on Ship Models used in Restricted-Channel Tests

On the basis just described, six ship models were selected for use in the course of the investigation. Figure 2.1* presents the pertinent data for the ship models and for their prototypes. Figure 2.1 also defines the common symbols used throughout the report. Other more specialized symbols are defined in the sections in which they are used. It will be noted from Figure 2.1 that the linear ratio of the models ranged from 35 to 86. This variation in scale was not intentional but was the result of differences in the linear ratio of available TMB ship models, such as Models 3859 and 3769, or was the result of limitations imposed by the size of the facility in which the tests were to be run, as Model 3992.

Model 3673-A was discarded early in the test program because its construction made it unsuitable for continuous usage.

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* In this system of numeration the digit to the right of the point indicates the figure, that to the left denotes the section. Tables, equations, pages, and appendices are numbered similarly.

APPENDIX 2.1

INDEX TO ADDENDA

As stated previously in Section 2, the photographic records of the test runs are addenda to the report. The addenda contain a complete log of the tests for which photographic records exist in addition to the classified and labeled photographic records. The Panama Canal has the only complete copy of the addenda. The Taylor Model Basin has one copy of Addenda I, III, and VI. A complete list of the addenda is presented.

Addendum I

Vol. I - Streak Photographs of the Ship's Path in the 40-Degree Widened Bend at a Linear Ratio of 86.

Vol. II - Streak Photographs of the Ship's Path in the 26-Degree Parallel-Widened Bend at a Linear Ratio of 86.

Vol. III - Streak Photographs of the Ship's Path in the Double 13-Degree Bend at a Linear Ratio of 86.

Vol. IV A - Streak Photographs of the Ship's Path in the 26-Degree Parallel Bend at a Linear Ratio of 86.

Vol. IV B - Streak Photographs of the Ship's Path in the 26-Degree Parallel Bend at a Linear Ratio of 86. This volume includes streak photographs of the "Planned Breakdown Tests."

Vol. V - Streak Photographs of the Ships' Paths in La Pita Bend at a Linear Ratio of 45.

Vol. VI - Streak Photographs Showing the Path of Model 4018 in the 26-Degree Parallel Bend at a Linear Ratio of 45.

Vol. VII - Streak Photographs Showing the Path of Model 3748-4 in the 26-Degree Parallel Bend at a Linear Ratio of 45.

Vol. VIII - Streak Photographs Showing the Path of Model 3769 in the 26-Degree Parallel Bend at a Linear Ratio of 45.

The streak photographs of Addendum I and the rudder-angle film of Addendum II are complementary.

Addendum II

Film Record of the Rudder Angles Used in the Channel-Bend Studies

This section contains nine rolls of 16-mm film which are packed in a box labeled Addendum II. The rolls are numbered to correspond with the volume numbers of Addendum I.

Addendum III

Test Schedules for the Straight-Channel One-Way and Two-Way Traffic Maneuvering Runs

The test schedules are complementary to the film in Addenda IV and V.

Addendum IV

Film Records of the Ship's Path in the Straight-Channel One-Way Traffic Maneuvering Runs

The numbered rolls are packed in a box labeled Addendum IV.

Addendum V

Film Records of the Ship's Path in the Straight-Channel Two-Way Traffic Maneuvering Runs

The numbered rolls are packed in a box labeled Addendum V.

Addendum VI

Restricted-Channel Investigations, The Panama Canal

This is an official U.S. Navy motion picture film.

SECTION 3

TEST EQUIPMENT

INTRODUCTION

The primary purpose of the model studies in the restricted-channel investigation at the Taylor Model Basin was to obtain information that would assist in the selection of the channel cross-section and the characteristics of the channel bends for a modernized Panama Canal.

The purpose of this section of the report is to describe the equipment used in the restricted-channel investigations to enable this agency or other interests to duplicate or develop equipment to continue the tests and to furnish background information necessary for a proper evaluation of the test results.

The equipment was developed to simulate model channels of varying cross-sectional dimensions; to simulate several types of channel bends; to create stream flows within the channels and bends; to maneuver self-propelled model ships along the length of the channels and bends; to measure side forces, yawing moments and changes of level on a model ship.

This section will describe the equipment for the straight-channel one-way-traffic studies; channel-bend tests; change-of-level studies; and the equipment for the production, control, and measurement of current in the channels and bends of the moving-water studies.

The organization of this section on test equipment follows the organization of the report; the equipment used in the still-water tests described in Sections 4, 5, 6, and 7 is here described in the same order. The equipment for the production of stream flow in the channels and bends is here described as a unit since this equipment was used for the tests in Sections 4, 5, and 6 that required moving water.

The limitations of the equipment are discussed at the end of this section.

Acknowledgement is due to the Industrial Department of the Taylor Model Basin for the design, fabrication, and procurement of the test equipment. Special acknowledgement is due to the shops and labor forces for the spirited cooperation in the assembling and the disassembling of the numerous test installations. Messrs. Bland, Pierce, and Mackert of Code 647, and Mr. J. Breickner of Code 446 of the Bureau of Ships were extremely helpful in obtaining information on the 12,500-gpm pumps and the priming unit used in the moving-water tests; Mr. A.A. Wright of the Hull Piping Section and Mr. J.

Weiss of the Technical Research Group of the U.S. Naval Shipyard, Phila., Pa., assisted generously in securing the 24-inch gate valves used in the moving-water tests.

EQUIPMENT FOR STRAIGHT-CHANNEL ONE-WAY-TRAFFIC STUDIES

The studies pursued under this phase of the restricted-channel investigation consisted of:

A. Observational tests
   a. Equilibrium-rudder-angle tests
   b. Maneuvering tests

B. Force-measurement tests
   a. Equilibrium-rudder-angle tests
   b. Total lateral force and yawing moment at zero angle of yaw
   c. Tests to determine the rudder angle required to produce zero moment at zero angle of yaw for self-propelled and for towed models.

The analysis of A and B is discussed in Section 4.

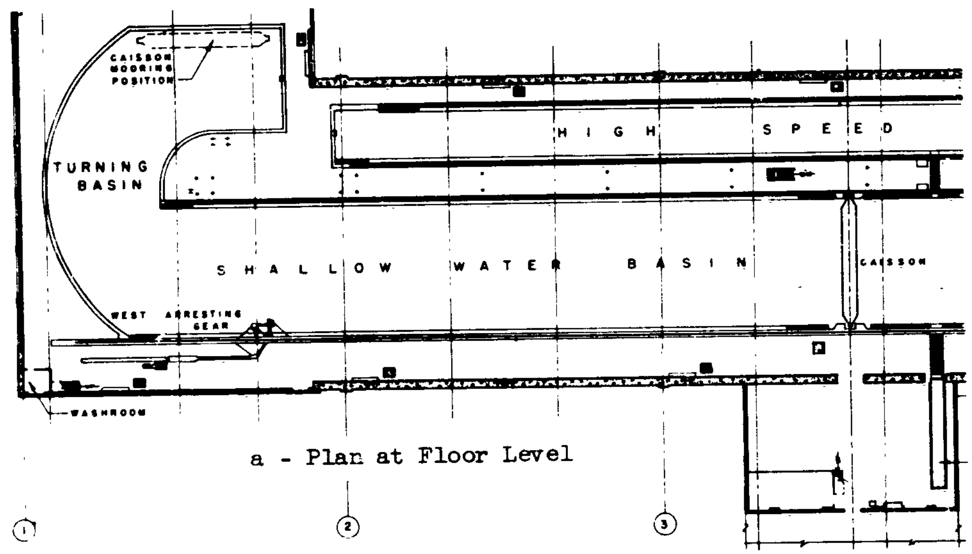
The tests under A above were conducted in the shallow water basin and the tests under B were conducted in the circulating-water channel.

OBSERVATIONAL TESTS

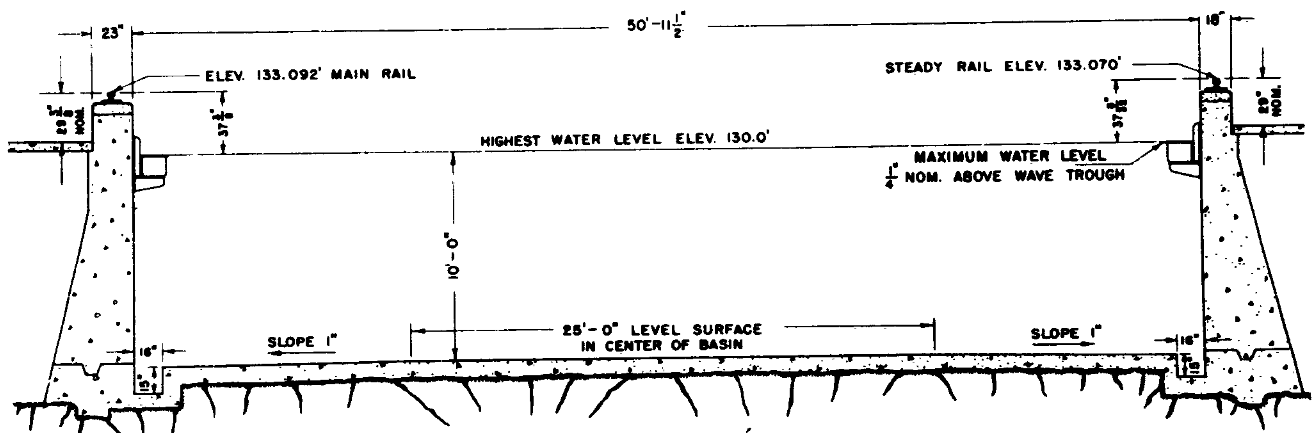
The observational tests were made in the shallow water basin which is a concrete-lined channel 52 feet wide, 10 feet deep, and approximately 300 feet long; see Figure 3.1. The water level in the basin can be set as desired from zero to 10 feet. The straight portion of the basin was used for the observational tests.

A towing carriage, shown in Figure 3.2, spans the basin. It runs on tracks mounted on top of the basin walls and can be operated at speeds up to 8 knots forward and reverse.

The equipment problem had two broad phases; the installation of portions of the canals of various sizes to scale and the maneuvering of a self-propelled model ship through the canal. The first involved utilizing the dimensions of the shallow water basin to obtain the desired canal widths and sections; the second involved the control of the ship's propellers and rudder mechanism, the acceleration of the model to the desired speed before releasing it for a run self-propelled, and the recording of the ship's path during its transit of the canal.



a - Plan at Floor Level



b - Typical Section through Shallow Water Basin

Figure 3.1 - Plan and Section Views of the Shallow Water Basin of the David W. Taylor Model Basin

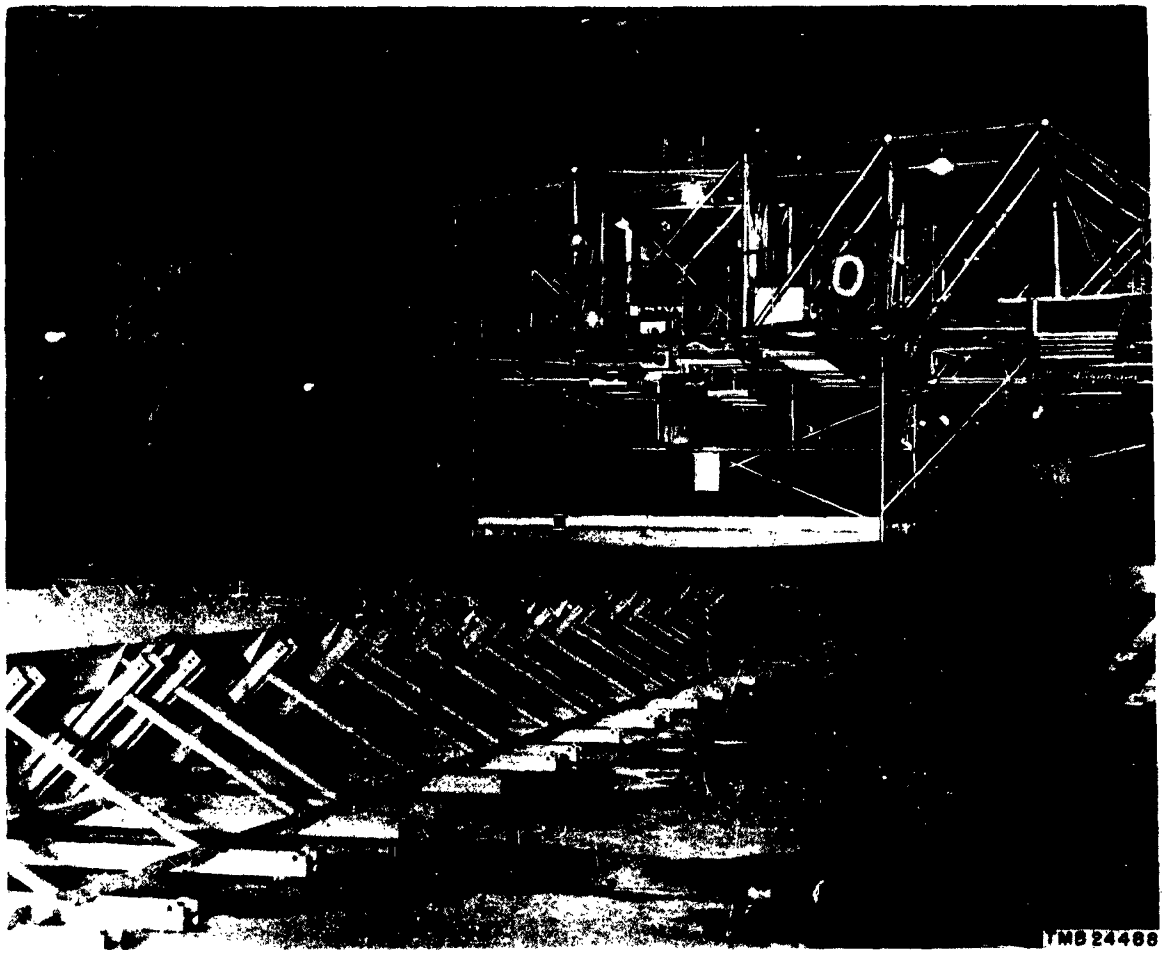


Figure 3.2 - Basic Installation of Test Apparatus for Straight-Channel Studies

In the Basin:

Steel units assembled in length form the scale model of the test channel. One or both walls can be moved to simulate different channel widths; water depth can be varied as desired. Wooden baffles are placed transversely in open water outside the channel to dissipate circulation and waves.

On the Carriage:

The platform frame suspended from the underside of the carriage serves to mount towing devices, sinkage gear, observation platforms, power supply for self propulsion, and a working platform for test personnel.

The upper carriage structure supports the boom and the K-24 aerial camera for recording maneuvering tests, and lights for illuminating the vessel and channel to be photographed by the camera.

The straight sections of the test channels consisted of a number of steel units assembled to the desired length. The unit section is shown in Figure 3.3. Each section was composed of a 4-foot by 10-foot plate mounted as shown. The angle between plate and basin floor could be set at 90 degrees, 45 degrees, 30 degrees, and about 18 1/2 degrees. However only the 45-degree slope was used.

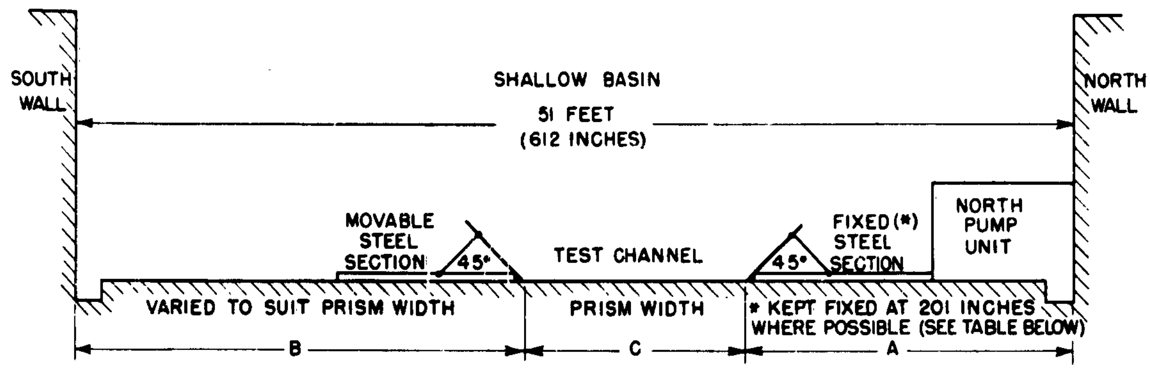
Figure 3.3 - Steel Units Used in the Construction of the Straight Channels

The joint between the basin floor and the length of the canal was sealed by inserting a sponge-rubber strip under the edge of the plates. The weight of the sections acting through the sharp edge of the plate sealed the channel from leakage under the walls and the consequent variance of pressure inside the channel.

The joints from one steel unit to the next were sealed by the use of a heavy-duty hose, fitted in the hollow formed where the plates butted; as shown in Figure 3.2. C-clamps at the joint supplied the necessary pressure to seal the joint as well as to hold the channel walls in a straight line.

In addition to the 4-foot by 10-foot plates, a plate section 5 feet by 10 feet was supplied. The 5-foot plate could be added to the 4-foot plate to extend the canal walls to hold 3 feet of water depth at canal slopes of 30 degrees and 18 1/2 degrees. However, the 30-degree and the 18 1/2-degree slopes were not tested owing to lack of time.

The placement of the steel sections across the shallow water basin had to be planned carefully to keep the handling time to a minimum when changing the prism widths of the channel. Figure 3.4 shows the transverse positioning of the steel sections in relation to the cross-sectional dimension of the basin due to the installation of the north pump. Table b of the same



a - Section through Shallow Basin, Showing Scheme for Positioning Steel Sections.

Linear Ratio	Prism Width Full Scale (feet)	Location of Steel Section (See Sketch Above) B (Inches)	C (Inches)	A (Inches)	Water Depths Full Scale (feet)	Model (Inches)	Notes		
45	300	321	80	201	45	12.0	Straight Channel	Still Water Tests	
					60	16.0			
					80	21.3			
45	500	277	134	201	45	12.0		Still Water Tests	
					60	16.0		Still Water Tests and With 3&5 knots Channel Currents	
					80	21.3		Still Water Tests	
45	700	224	187	201	45	12.0		Still Water Tests	
					60	16.0			
					80	21.3			
45	300	114	80	418	42	11.2	La Pita Bend-Still Water Test, No Channel Current		
	560	114	150	348	60	16.0	26 degree Parallel Bend		Still Water Tests and With 3&5 knot Channel Currents
86	560	114	78	420	60	8.37	Double 13 degree Bend		
	560	114	78	420	60	8.37	26 degree Parallel Bend		
	560	114	78	420	60	8.37	26 degree Parallel Widened Bend		
	600	114	84	414	60	8.37	40 degree Widened Bend		

b - Table of Channel Widths and Water Depths for Tests in Shallow Water Basin.

Figure 3.4 - Arrangement of Steel Sections to Suit Channel Widths

The dimensions A, B, and C were used to position the steel sections.

figure shows the dimensions for setting the *A*, *B*, and *C* distances. The distance *A* was fixed at 16.75 feet from the north wall and the distances *B* from the south wall were varied to suit the required prism line of the canal. The distance *A* was set at 16.75 feet to suit the distance taken by the width of the north pump installation plus the width taken by the steel channel section.

The pumping unit was installed to circulate water in the canal for the moving-water tests; it will be described later.

Wooden baffles as shown in Figure 3.5 were placed at the open ends of the channel as well as in the open water outside the canal. The baffles dissipated the waves created by the travel of the ship model in the canal and discouraged the circulation of the water through the canal.

The model was equipped to run under its own power which was supplied through long flexible cables attached to the electrical source on the towing carriage. The items mounted on the ship, illustrated in Figure 3.6, consisted of

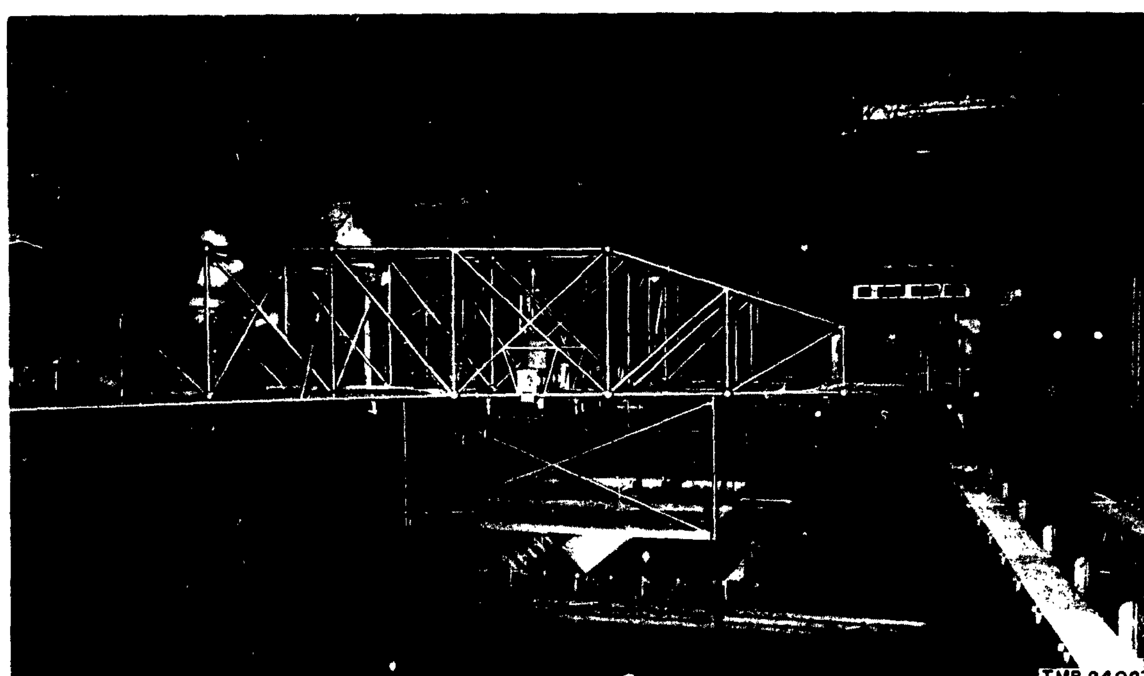


Figure 3.5 - Shallow Basin, Looking West, from Caisson

Note especially the platform frame suspended from the underside of Towing Carriage 1.

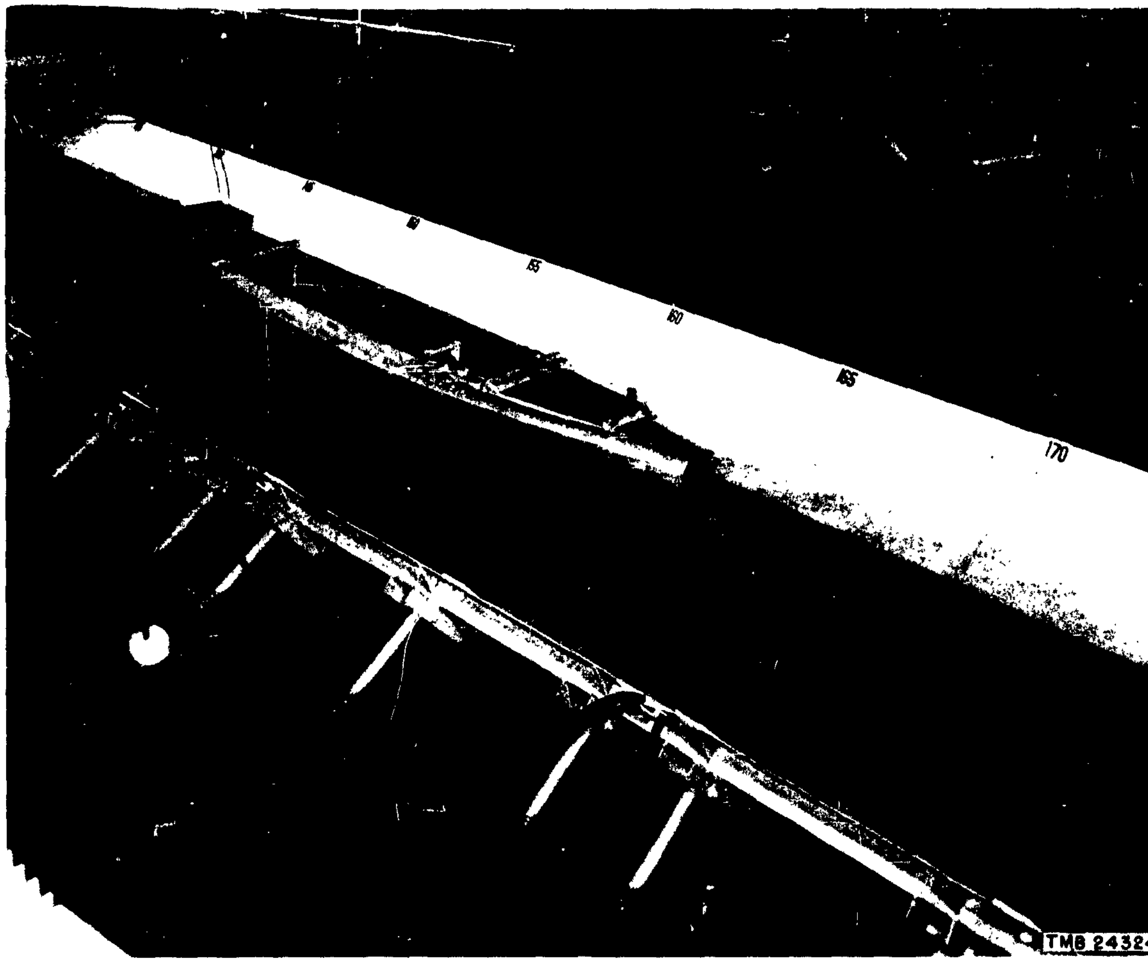


Figure 3.6 - Bamboo Cable-Guide Pole

1. Towing brackets fore and aft on the starboard side,

2. A variable-speed, direct-current electric motor, connected through a gear box to the propellers,

3. The rudder-control mechanism with a rudder-angle indicator mounted on the stern of the vessel,

4. Wooden extensions mounted fore and aft, port and starboard, to serve as crash arms for protecting the ship's propellers and rudders,

5. A parabolic reflector and light source, mounted at the bow, which cast a 4-inch beam of light to a horizontal scale mounted at the far end of the canal. The movement of the light spot on the scale indicated to the pilot the heading and rate of swing of the ship at all times.

6. Small lights which were mounted on the crash arm over the centerline of the ship appeared as dots in the photographic record and were used for measuring the ship's position in the canal.

The problem of control involved accelerating the ship model to the desired speed, releasing the model, and then controlling the ship's propellers and rudder during its self-propelled run through the canal.

In order to utilize the carriage for these various processes it was necessary to suspend a rigid platform from the lower members of the towing carriage. The platform frame, as shown in Figure 3.5, consisted of a 20- by 21-foot rectangle made of structural-steel channel sections. This open frame was suspended from the towing carriage by a pipe structure. The frame was used for mounting the tow pins used for accelerating the model; for mounting the gear used for the change-of-level tests; for supporting platforms to hold operating and test personnel; for mounting instruments to control and record the ship's speed, rudder angle, and position in the test channel.

Before releasing the ship for its self-propelled run it was necessary to accelerate the model to the desired test speed. This was done by accelerating the carriage and towing the model by a set of tow pins attached to the rigid platform frame. The tow-pin assembly is shown in Figure 3.7. It consisted of a cylinder in which a spring-loaded shaft was fitted. This assembly was mounted on a box girder with machined edges.

The two box girders were fastened to the channel sections of the platform frame and could be separated to accommodate length of the vessel. The tow pins, one mounted on each box girder, could be fastened at any point along the box girder to position the ship transversely in the canal.

A latch on each tow-pin unit held the shaft extended when it was engaged in the towing bracket on the vessel. Tripping the latches allowed the shafts to recede into the cylinders and disengage the model for self propulsion.

Power for the ship's rudder and motor control was supplied by the direct-current generators on the carriage which could deliver from 110 to 440 volts. The ship's motor was controlled by switches and relays mounted in the control box as shown in Figure 3.8. The two toggle switches at the lower right-hand corner of the control box regulate the ship's motor, one for driving the motor forward or reverse and one for opening or closing the power circuit. The voltmeter at the upper right corner of the control box has three voltage ranges; the black switch just under the meter was used to select the voltage range desired.

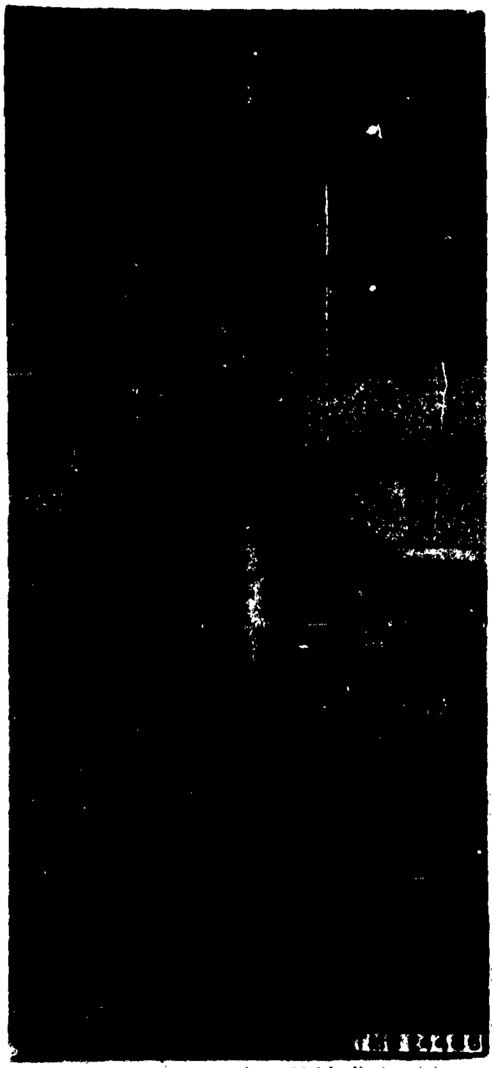


Figure 3.7 - Tow-Pin Assembly

The tow-pin assembly is mounted on a box girder. The pin assembly can be set at any point along the girder thus permitting the lateral positioning of the ship in the channel.

Another tow-pin assembly and box girder parallel to the one shown, is mounted on the platform frame. The distance between the two tow-pin assemblies can be varied to suit the length of the model to be towed.

The speed of the model was determined by the voltage applied to the ship's motor. Three potentiometers, as shown in Figure 3.8, were wired for cascade operation; one for rough, one for close, and one for vernier control of the voltage applied to the ship's motor.

The speed of the model was ascertained by noting the voltmeter reading and consulting a previously determined ship's-speed and voltage-calibration chart. The variables that affected the speed of the vessel were: the prism width of the canal, the water depth of the canal, and the position of the ship in relation to the centerline of the canal. Thus, for any one model ship a speed-voltage calibration had to be made for a change in any of the variables mentioned.

The towing-carriage speed was used as the speed standard since it could be run at accurately predetermined speeds. The model was rigged for towing under the platform frame by means of the tow pins. The carriage was brought up to the calibrating speed and then the potentiometers were adjusted to bring the model ship under self propulsion. While the vessel was being towed, the tow pin would bear against the forward end of the slot in the towing bracket. As the voltage to the motors was increased there would come a point where the contact between tow pin and tow bracket would be broken. From that point, the vernier adjustment of the potentiometer would be used to bring the model ship to such a speed that the tow pin would assume a free, stationary position with respect to the towing slots in the towing bracket. The voltage that maintained such a condition for ten or fifteen feet of run was considered indicative of the particular

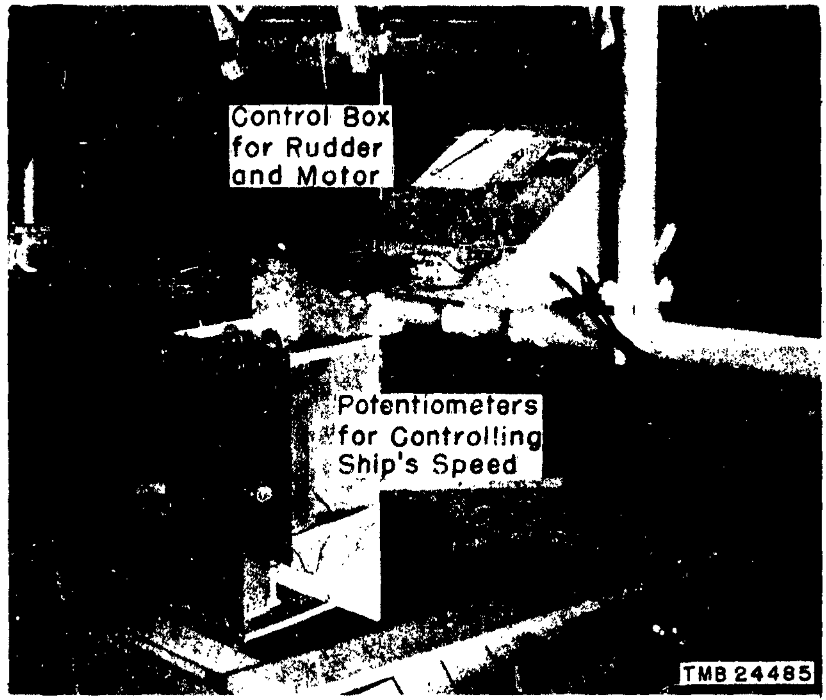


Figure 3.8 - Control Units for Observational Tests

carriage speed. A plot of a progressing series of speeds gave the data for the speed-voltage chart for the particular test arrangement under study.

The rudder-control unit was a servo mechanism; the synchromotor was mounted in the control box shown in Figure 3.8 and the synchro-generator was mounted on the stern of the vessel, as shown in Figure 3.6. A rudder-angle indicator is shown on the stern of the vessel in Figure 3.6, and another on the upper left corner of the control box in Figure 3.8. Throwing the switch shown just under the rudder indicator in Figure 3.8 to the right or left actuated the ship's rudder right or left. The position of the ship's rudder indicator and the indicator on the control box read alike. Thus the operator of the control box could concentrate on the controls at hand and on the orders of the pilot, who by oral command, maneuvered the model from his observation post on the platform frame.

To provide current for the operation of the ship's motor and rudder mechanism, cables were directly connected between the control box and the mechanism aboard ship. A cable-guide pole mounted on a vertical member supporting the platform frame was used to support the power cable. Figure 3.6 shows the bamboo cable-guide with a pulley-and-cord arrangement for paying out the electric cables in accordance with the variation in the ship's position relative to the carriage. By means of the cable-guide pole the electric cables were held in a vertical position over the model in such a manner that practically all of the cable weight was carried by the pole.

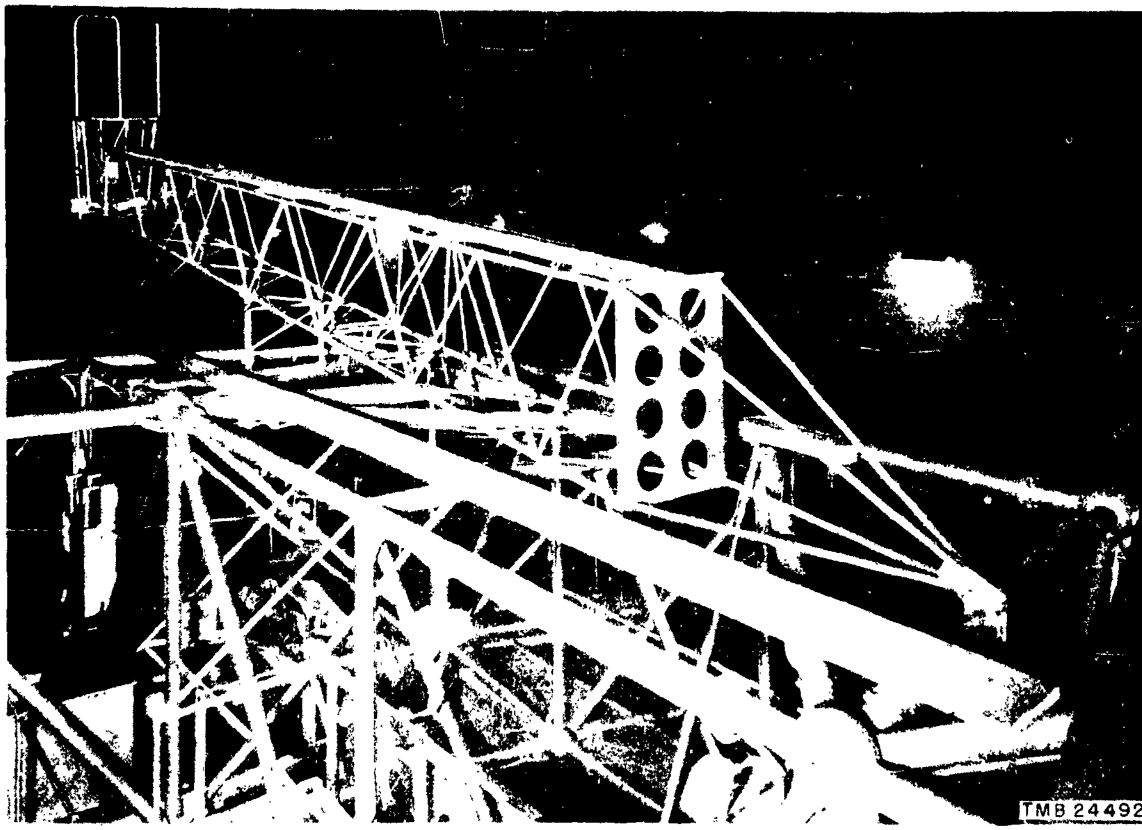
Adjustments of the cables on the cable-guide pole were made to suit the transverse position of the ship in the canal and the variation in the relative position between towing carriage and the model ship as the model transited the length of the channel. The carriage followed the model ship at approximately ship speed after the model was released from the tow pins for its self-propelled run.

A number of observations had to be made frequently during the transit of the ship through the channel. It was decided to use photography to record the pertinent data. In each exposure of the camera the ship's position in the canal, the ship's rudder angle, and the time in minutes and seconds were photographed, as shown in Figure 4.14.

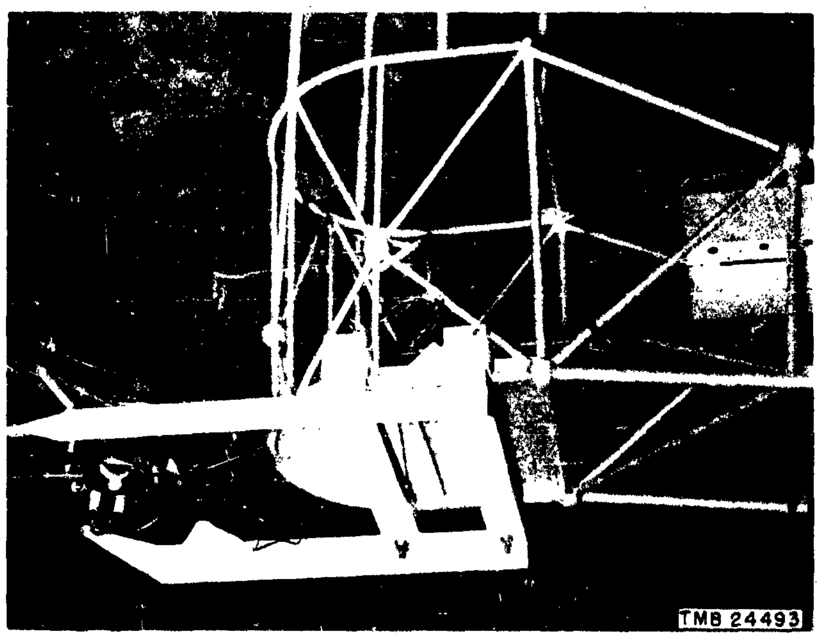
An aerial camera mounted on the end of a boom which was fixed to the carriage was used to record the data. The boom which is normally used for turning trials was removed from its position on the northwest side of the carriage and mounted on the upper members of the carriage along the centerline. The end of the boom hung about 20 feet over the centerline of the carriage, as shown in Figure 3.9a. A K-24 aerial camera was mounted at the end of the boom as illustrated in Figure 3.9b. The camera was fitted with a wide-angle lens for photographing the model and an auxiliary lens for simultaneously recording a sweep-second clock. A Cine-Kodak automatic time-interval control, operated from a 24-volt battery unit, made exposures at rates from 2 per second to 1 every three seconds as desired.

During the photographic recording of the path of the model the carriage kept pace with the ship as it transited the canal and at the same time kept at a distance behind the ship so as to keep the camera as nearly as possible directly over ship. The field about the model was illuminated by 48 Type R-2 reflector flood lights mounted on batons which were secured to the carriage and projected ahead of the carriage. In addition, flood lights were mounted on the carriage and their light was focused to a point ahead of the carriage and just under the camera. Thus it was possible to keep the camera and light source abreast of the ship throughout its travel through the canal.

In order to estimate the position of the ship in the canal from the film record it was necessary to mark the canal along its length. Numbered plaques, 6 inches square, were hung from the top of the channel as shown in Figure 3.2. The plaques were numbered 0, 5, 10, 15, ...etc. The zero plaque



a – Boom Secured on Upper Members of Towing Carriage



b – K-24 Aerial Camera Mounted on End of Boom

Figure 3.9 - Equipment for Photographic Recording of Straight-Channel Maneuvering Tests in Shallow Basin

was mounted at the caisson end of the canal, as shown in Figure 3.2. From there on, the 5 plaque was mounted five feet from the end, the 10 plaque ten feet from the end, etc. Similar plaques were mounted on the other canal wall. These plaques appeared in the photographic record as shown in Figure 4.14.

However, as seen in Figure 4.14, it is difficult to measure the position of the ship either along the length of the canal or in its transverse position in the canal without additional means of indicating finer distances. To this end a series of black lines were painted on the channel walls between plaque 70 and plaque 95 on both sides of the canal. The stripes appearing vertically in the figure are one foot apart; another set of stripes painted horizontally at elevations represent 45-, 60- and 80-foot channel depths. These stripes cannot be seen in the figure. A detailed explanation of the uses of these stripes in relation to determining the transverse position of the ship in the canal is given in Addendum III.*

FORCE-MEASUREMENT TESTS

A series of force-measurement tests, treated in Section 4, were made in the circulating-water channel.** The circulating-water channel shown in Figure 3.10 is a major facility at the David Taylor Model Basin. In this facility the ship model is held stationary by a dynamometer and the water moves. The working space in this facility is 22 feet wide, 9 feet deep, and 60 feet long. The depth can be set from 0 to 9 feet as desired and the water speed can be maintained at values from 0 to 10 knots as desired for the 9-foot depth.

The model channels tested in the circulating-water channel were constructed with steel wall units similar to those described for the shallow water basin with the exception that they did not have the provision for adjusting the slope angle of the channel wall; see Figure 3.11a.

As explained in the description of canal construction in the shallow basin the seal between the steel wall units and the floor was made by insertions of strip rubber and the seal between the 10-foot steel sections was made by rubber hose and clamps.

The model canal had vertical walls and was constructed of four 10-foot steel sections on each side of the canal. The distance between the vertical walls of the canal was varied to suit the test widths desired.

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* See page 2.3 for the location of Addendum III.

** For a full description of the circulating-water channel see: "The Circulating-Water Channel of the David Taylor Model Basin," by Capt. Harold E. Saunders, USN, and Lt. Comdr. Clyde W. Hubbard, USNR., Transactions of the Society of Naval Architects and Marine Engineers, Vol. 52, 1944, pages 325-364.

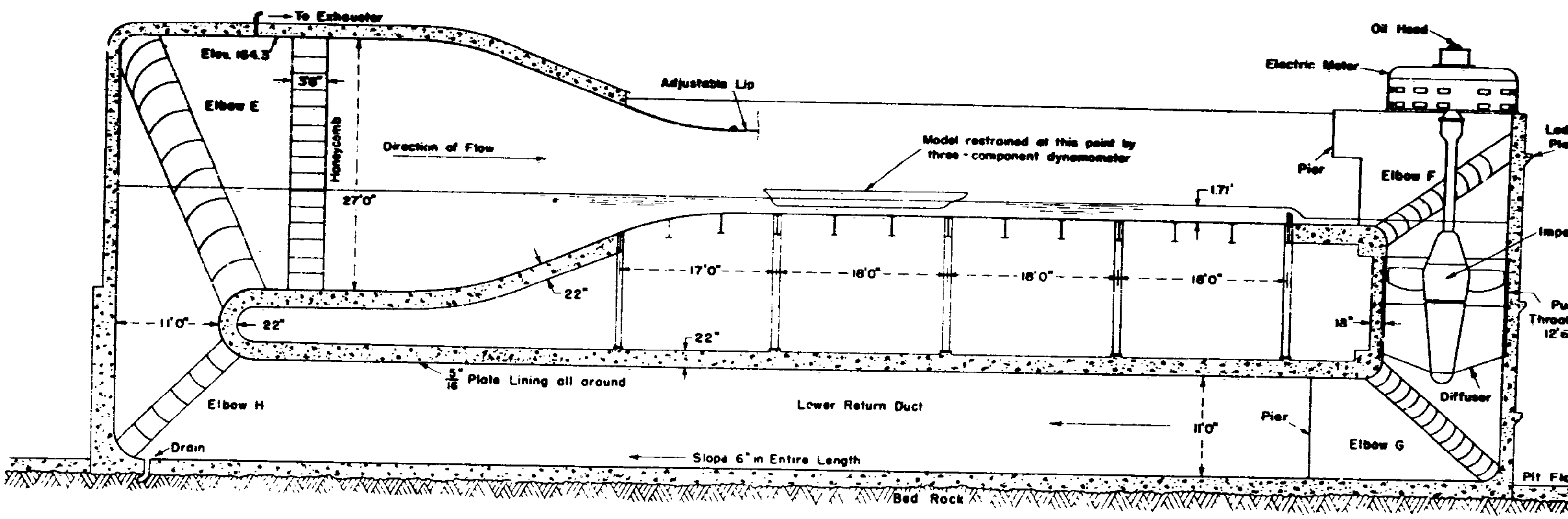
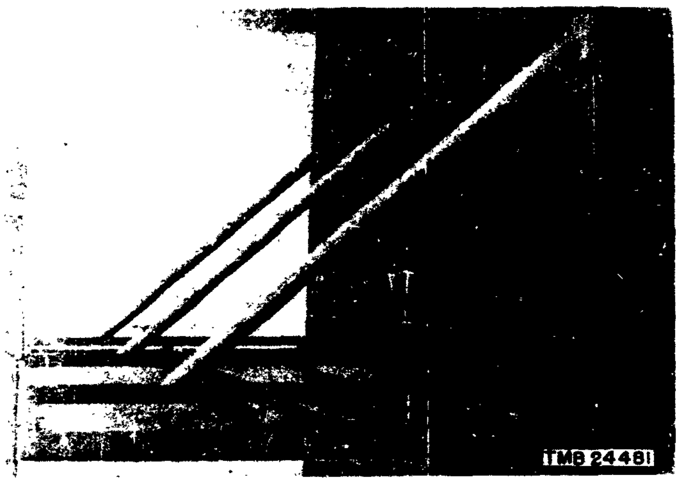


Figure 3.10 - Vertical Longitudinal Section Through TMB Circulating-Water Channel

This is a section offset from the middle line and run through the centerline of one of the pumps. The channel has a constant inside width of 22 feet and a rectangular section everywhere except at the pumps and in the upper and lower transition sections in Elbows F and G. These elbows, and the pump rings, are in pairs, separated by a central pier 18 inches thick. The axis of the enlarged section slopes downward to correspond with the slight slope in the test section and the enlarged section is symmetrical about that axis. The water depth can be varied from zero to 9 feet. The waterline shown in the view represents a full scale of 60 feet for which TMB Model 3859 was tested during some of the restricted-channel studies. The weir, which is shown at the downstream end of the test section, was installed for shallow-water tests, and is used to assist in the control of the water depth and speed. Movable walls were installed in the test section to simulate restricted channels of different widths.



a - Steel Wall Unit

b - Three-Component Dynamometer

c - Three-Component Dynamometer

Figure 3.11 - Equipment for Force-Measurement Tests in the Circulating-Water Channel

The model ship was fitted with self-propulsion dynamometers for driving the ship's propellers. The dynamometers were connected to an electrical circuit which contained a rheostat for adjusting the voltage to the dynamometers and a voltmeter for indicating the value of the voltage applied to the dynamometers. By means of a stop watch and the revolution counters on the dynamometers the revolutions per minute of the propellers could be ascertained.

The model ship contained a manual adjustment for the rudder displacement and a scale for indicating the rudder angle. The ship was fitted with three mounts for connection to the arms of the 3-component force-measurement dynamometer.

The force-measurement tests were tests in which the model was restrained while the forces which tended to move the ship were measured with the 3-component dynamometer. The dynamometer as shown in Figures 3.11b and 3.11c measured forces by the deflections of cantilever beams.

The hydrodynamic force on the ship was transmitted through the dynamometer arms as a moment applied to the cantilever beam. A known weight moved along the dynamometer arm imposed a correcting moment which brought the beam almost to its zero deflection. An Ames dial, registering deflection in thousandths and tenths of thousandths of an inch, indicated the correction necessary to "Zero" the beam. With the position of the weight and the Ames-dial reading, the force in pounds was read from the calibration chart.

Three arms extended downward from the dynamometer. Two of these arms were used for measuring side forces. They were located 2.5 feet forward and aft of the ship's center of gravity. The third arm was located near the bow and measured the drag force on the model.

The dynamometer was designed so that the model could be attached at any desired transverse portion in the channel. When it was desired to give the model an angle of yaw the whole dynamometer was turned. All forces, therefore, were measured parallel or perpendicular to the centerline of the model regardless of the angle of yaw.

The side force-measuring arms of the dynamometer terminated in slotted pieces which fitted over vertical rods fastened to the ship. Each rod consisted of two segments of brass separated by insulating material. A light was connected electrically to each of the four segments.

The lights were wired to the two rods in such a manner that the flashing of a light or lights indicated a displacement of the ship's centerline with respect to a line passing through the mid-points of the ends of the force-measuring arms of the dynamometer. When any of the four lights were lit it indicated the existence of forces and their directions. When none of the lights were lit it indicated that the rudder angle and the angle of yaw were set for the equilibrium condition.

The lights were used in performing the following tests, which are discussed in Section 4.

a. Equilibrium-rudder-angle tests

b. Tests to determine total lateral force and yawing moment at zero angle of yaw

c. Tests to determine the rudder angle required to produce zero moment at zero angle of yaw for self-propelled and for towed models.

EQUIPMENT FOR STRAIGHT-CHANNEL TWO-WAY TRAFFIC

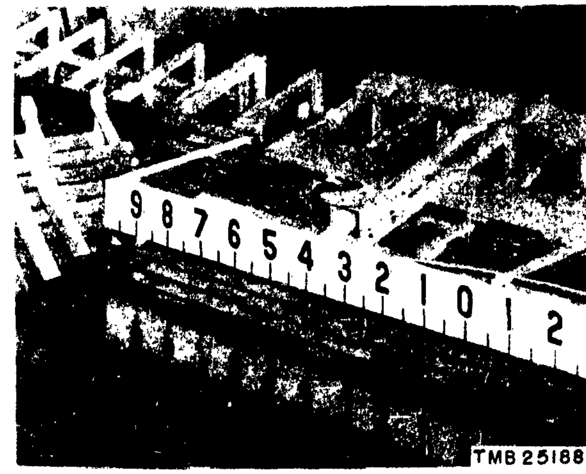
The two-way-traffic studies consisted of maneuvering tests in which one ship was maneuvered from the carriage as in previously described straight-channel tests while the other vessel was towed by a model-towing unit, shown diagrammatically in Figure 5.3.

The restrained model was towed by an 1/8-inch aircraft cable fitted as an endless belt over two pulleys. The pulleys were mounted at the extreme ends of the straight channel. The powered pulley, shown in Figure 3.12c, was driven by a variable-speed electric motor through a V-belt speed-reducing system. The motor was controlled by an operator stationed at the control panel of the cable-towing unit shown in Figure 3.12b. The towline and attached model ship could be accelerated and decelerated from this panel. The pulley at the other end of the canal was an idler pulley, shown in Figure 3.12a.

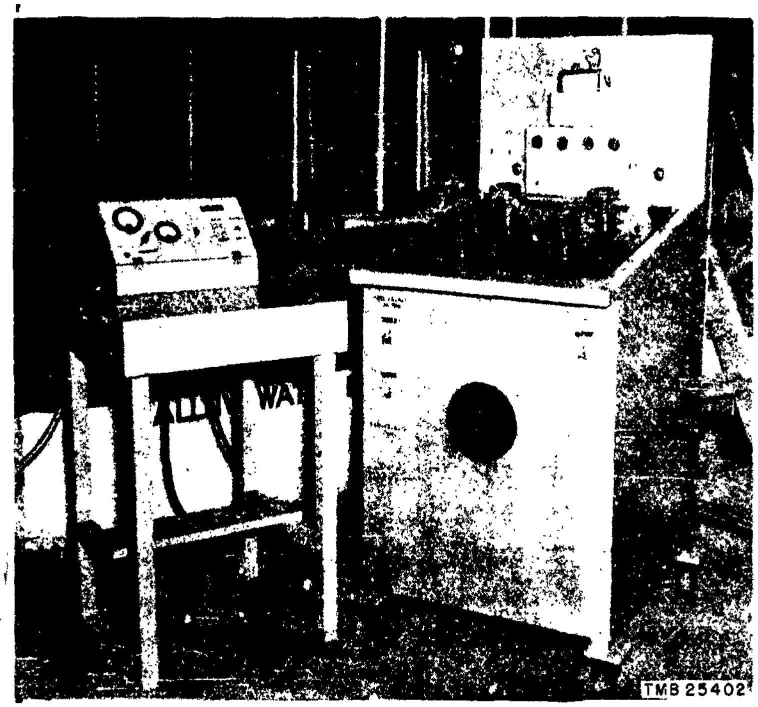
The powered-pulley and idler-pulley assemblies were mounted on the large wooden baffles at the ends of the canal. Each pulley unit was clamped to a track-like foundation which allowed for movement of the pulley up or down on the face of the wood baffle. The adjustment of the pulleys along the track gave the vertical positioning of the cable to suit the various depths of water in the test channels. To position the cable transversely in the canal the pulley unit with the track was moved along the length of the baffle. Figure 3.12a shows clearly the idler pulley mounted on the baffle at the west end of the channel.

A counterweight was attached to the idler pulley in order to maintain a constant tension in the towline. As a result of imposing a high initial tension in the towline the load carried by any one bearing in the pulley assembly did not change appreciably either between runs or during a run.

Conditions in the two-way-traffic maneuvering studies were similar to those in the maneuvering tests in the one-way-traffic studies, excepting for the addition of the model towed by the model-towing unit.



a - Model Towing Unit Showing
the Idler Pulley



b - Two Speed Control Shown at Right. The Microammeters Shown at Left are for Indicating Speed.

c - Model Towing Unit Showing
the Powered Pulley

Figure 3.12 - Model-Towing Unit and Controls for Towed Model Used in the Two-Way-Traffic Tests

The speed of the towed ship, as measured by an electric tachometer mounted on the motor shaft of the model-towing unit, was read from a milliammeter on the control panel, and the readings were calibrated against the speed of the carriage, as follows.

The speed of the towing-unit motor was set to give a particular milliammeter reading.

The towing cable towed the model ship along the canal.

The carriage operator followed the towed ship with the carriage and adjusted the speed of the carriage to a value that would enable the carriage to keep pace with the towed ship.

The carriage speed in knots was read and plotted against the particular milliammeter reading.

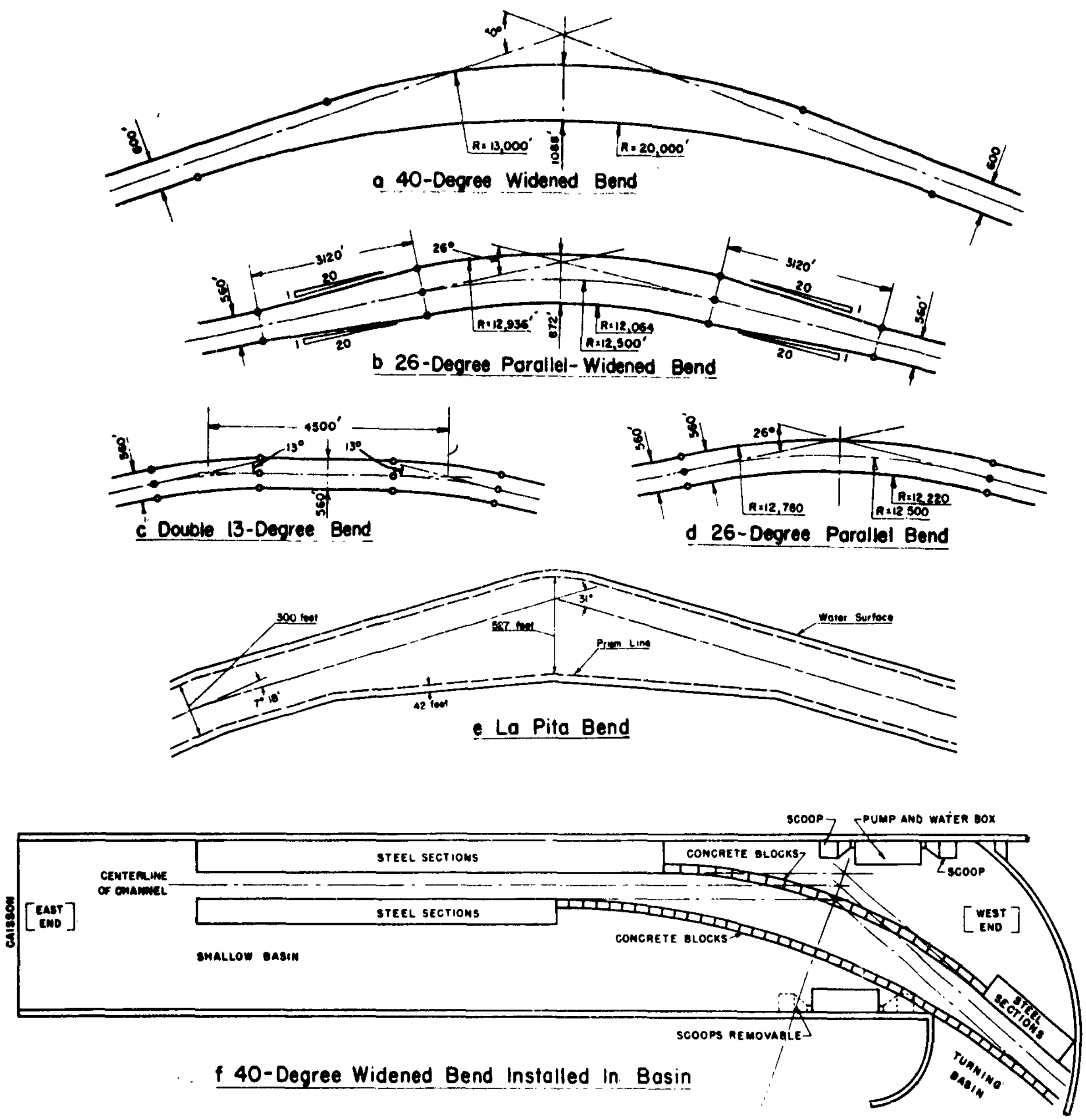
A series of milliammeter readings and the corresponding carriage speeds were plotted to obtain the speed-milliampere calibration.

EQUIPMENT FOR CHANNEL BENDS

The channel-bend studies were made in the shallow water basin and turning basin. Five bends were tested; the dimensions are indicated in the table of bend data in Figure 3.13. The bends were installed at a linear scale ratio of 1/45 or 1/86. The self-propelled model ship was maneuvered through the straight section into the bend and the course of the model ship was photographed as the ship traveled through the channel bend.

A typical installation of a channel bend is illustrated in Figure 3.13 for the 40-degree widened bend. In the eastern portion of the shallow basin the straight section of the canal was installed for a length of about 100 feet. In this section the model ship was brought up to the desired speed and released for self-propulsion through the bend. The carriage traveled as far as the pump units; for the transit through the remainder of the bend the carriage boom and cable-guide pole, each manipulated by an operator, carried the power cables over the model ship.

The walls of the bends were constructed of reinforced concrete blocks approximately 30 inches high, 4 inches thick, and 4 feet long. The bend units rested on two steel supports permanently set in the concrete block unit as shown in Figure 3.14. Each block was cast to give a canal slope of 45 degrees. The concrete units of the bends were first cast for the 40-degree widened bend installation as indicated in Figures 3.13a and 3.13f. The outer radius of the bend was formed with twenty 65-inch concrete-block units, and the inner radius of the bend was made with forty 48-inch concrete units. The units were tapered to suit the radius of the outer and inner curve and to suit the side slope of 45 degrees. Extra concrete units were cast to bring



BEND DATA (DIMENSIONS GIVEN IN FULL-SCALE FEET)											
NAME OF BEND	REFER TO	LINEAR RATIO	STRAIGHT SECTION EAST	STRAIGHT SECTION WEST	OUTER RADIUS	INNER RADIUS	CENTER-LINE RADIUS	PRISM WIDTH	OTHER STRAIGHT SECTION	GREATEST PRISM WIDTH	WATER DEPTH
26° PARALLEL	d	45	5400	45	12780	12220	12500	560	NONE	560	60
LA PITA	e	45	6300	1350				300	NONE	535	42
26° PARALLEL	d	86	12000	2580	12780	12220	12500	560	NONE	560	60
DOUBLE 13°	c	86	12000	3440	CURVED CHANNELS ARE SPIRALS APPROXIMATING 8800 ft. RADIUS			560	2500 MID-SECT	560	60
26° PARALLEL WIDENED	b	86	9480	86	12064	12936	12500	560	NONE	872	60
40° WIDENED	a	86	9480	NONE	13000	20000		600	NONE	1088	60

Figure 3.13 - Channel Bend Layouts

Figure 3.14 - Concrete Units for Installing Channel Bends

the total number of blocks to 100. For the channel bends of other radii, see Figure 3.13, the units were used with additions of short wooden fillers to maintain a tight, smooth-curved canal.

Rubber strips were inserted between the basin floor and the concrete units to preserve a tight canal. In addition, a sealing compound was forced into the joint at the floor of the basin as well as between the abutments of the concrete units.

In addition to the equipment described under the section on straight channel one-way traffic, the ship, as illustrated in Figure 3.15, had a set of blinker lights which can be seen forward and aft, mounted on the raised portion of the ship. These lights were mounted on the centerline of the model ship and over the forward and the after perpendiculars and were used to record the ship's path and speed through the channel bend.

The rudder-control mechanism used in the one-way-traffic tests did not always permit the quartermaster to set the exact rudder angle requested by the pilot; however, the necessary adjustment could be made quickly. The electronic rudder-control system which was used subsequent to the one-way-traffic tests eliminated this difficulty. The rate of rudder movement for the model, based on a linear ratio of 45, is $\sqrt{45}$ times faster than for the full-scale ship. The electronic rudder-control system, as shown diagrammatically in Figure 3.16, turned the rudder-gear mechanism on the model ship through the same angle as set by the control operator on the electronic

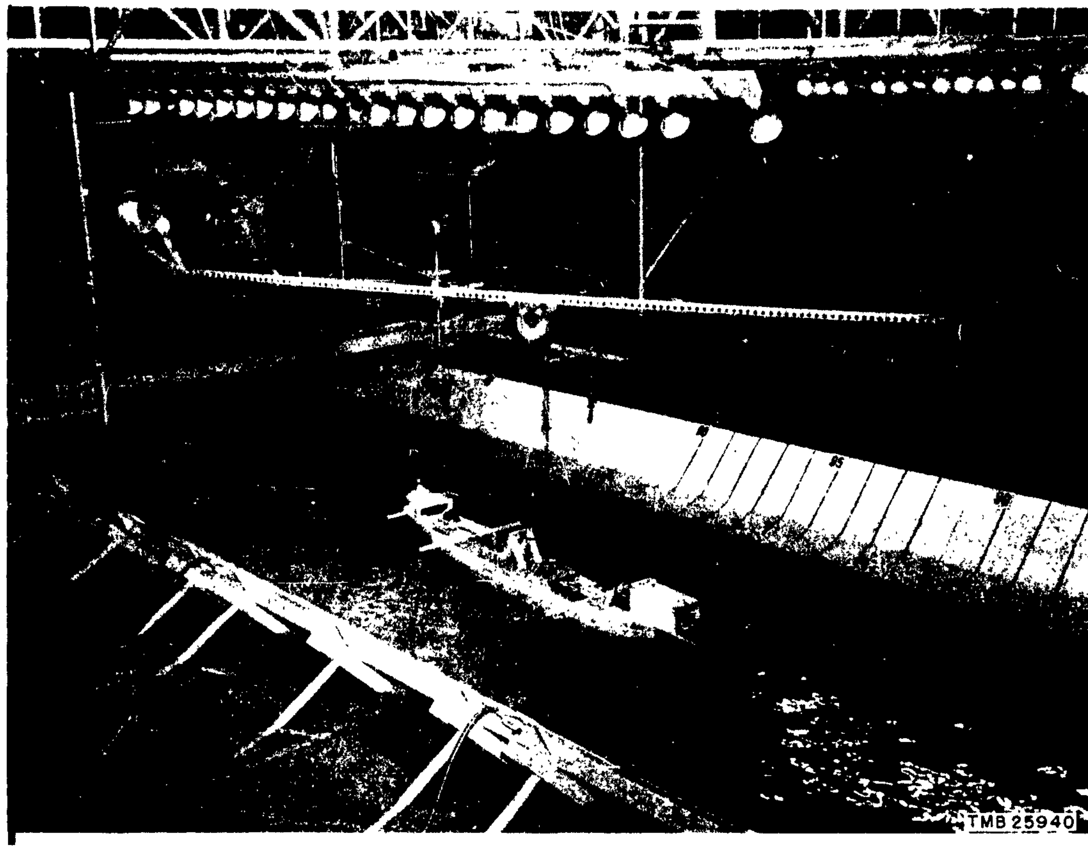


Figure 3.15 - Metal Cable-Guide Pole

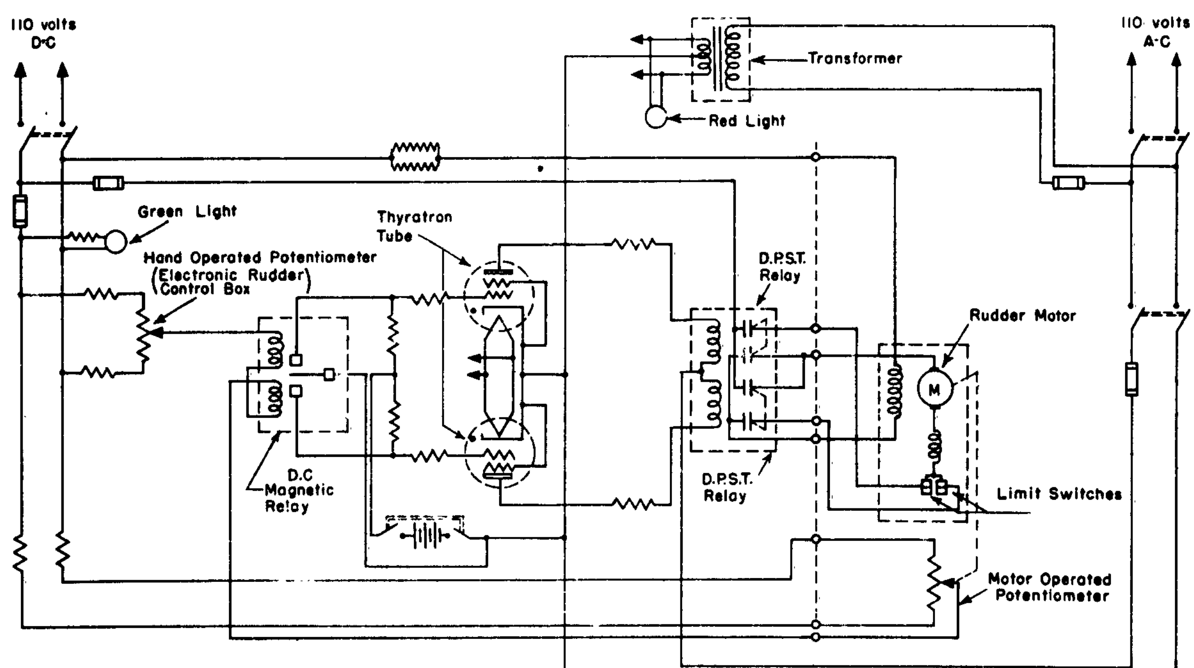


Figure 3.16 - Schematic Wiring Diagram for Electronic Rudder-Control System

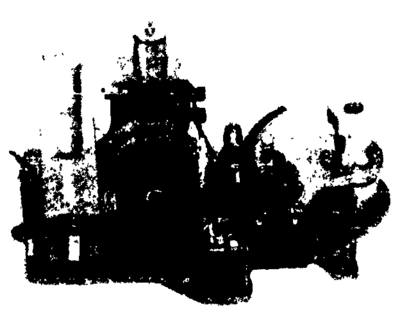
This is the wiring diagram for the rudder-control units shown in Figure 3.17.

rudder-control box on the carriage. The electronic rudder-control box and the rudder-gear mechanism are shown in Figures 3.17b and 3.17a.

Since the carriage, as previously indicated, could not follow the ship model through the entire length of the canal, some means had to be provided by which the power cables to the ship could be extended beyond the point where the carriage stopped. The carriage boom was removed from its position as shown in Figure 3.9 and mounted on the carriage as shown in Figure 3.18. In that position it could be controlled by an operator who by manipulating valves on a compressed-air system could cause the boom to swing through an arc about the boom's hingepoint.

In a basket at the end of the boom another operator controlled a cable-guide pole. The cable-guide pole shown mounted on the end of the boom was the same as shown mounted on the carriage frame in Figure 3.15. This metal guide pole was an improvement over the first-used bamboo pole (Figure 3.6) in that the cable-adjustment pulleys were more closely fitted and easily moved.

The movement of the boom and of the cable-guide pole at the end of the boom was similar to the movement of the human arm. It was possible to pay out the cable lines as necessary and to follow the ship as it transited through the bend.



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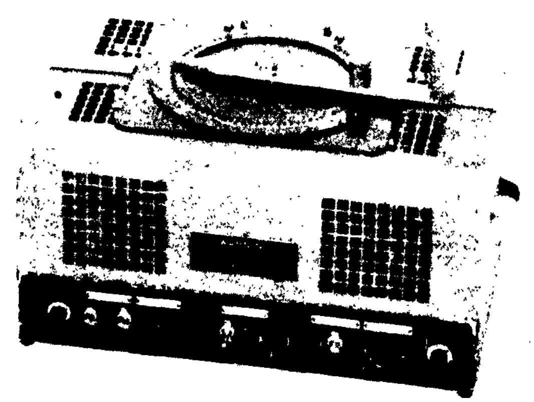
a - Rudder-Gear Mechanism



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b - Electronic Rudder-Control Box

Figure 3.17 - Rudder-Control Units

The unit shown in a is mounted on the stern of the model ship; the unit shown in b is mounted on the platform frame. The control wires are carried from b to a by the cable-guide pole.

Figure 3.18 - Equipment for Bend Studies

The boom is mounted on the carriage as for turning-trial tests. The metal cable-guide pole is mounted on the end of the boom and requires an operator. An operator (not shown) swings the boom by controlling a compressed-air device. A coordinator stationed on the walkway synchronizes the carriage speed, boom swing, and cable hang. He gives oral instructions over an intercommunication system between himself, the boom operator, the cable operator, and the carriage operator.

The broken streaks attached to the model are caused by the flashes of the argon lamps mounted forward and aft on the model ship. The solid streak paralleling the forward broken streak is the pilot light, which is used to identify the path of the forward argon light. These lights produced the streaks on the streak photographs as shown in Figure 3.20.

Three operators, directed by a coordinator, were required to control the carriage, boom, and cable-guide pole. The coordinator watched the movement of the ship from a position on the upper walkway of the carriage. He can be seen in Figure 3.18 leaning over the rail with a telephone head-set. The coordinator issued instructions to the operators over the intercommunication system. He called instructions on carriage speed, boom swing, and cable hang. Through the cooperation of these men the electric powering cables were held in a vertical position over the model ship so that practically all of the cable weight was carried by the cable-guide pole.

The items to be recorded as the ship traveled through the model canal were: The path of the bow, the path of the stern, the speed of the model ship. The path of the model was photographed by a camera mounted on the camera platform 50 feet above the turning basin. An 8- by 10-inch plate camera fitted with two Goertz-Hypar lenses was used. Each lens recorded a little more than half of the bend - one lens the east portion, the other the west portion of the bend. Both portions appear on the 8- by 10-inch photograph as shown in Figures 3.19 and 3.20.

To provide markings for estimating the position of the ship in the canal a centerline was painted on the canal floor. The centerline was divided every five feet by short cross lines and a cross interposed in the centerline at the entrance and exit of the bend as well as at the mid-point of the bend. Numerals were painted on every fourth concrete block of the canal. In addition a board was mounted on the canal wall on which figures and letters could be set to identify the test run.

To obtain a background pattern such as shown on Figure 3.19, on which to record the streak photograph as shown in Figure 3.20, a number of R-2 photo-flood lights were mounted along the channel-bend walls and for part of the distance along the straight channel adjoining the bend. To obtain a pattern such as shown in Figure 3.19 the photographic plate was exposed just long enough to obtain a picture of the canal walls and the centerline markings. Then the photo-floods were extinguished; the bend was then in darkness.

As the model ship travelled through the canal the argon lights mounted on the vessel blinked at set time intervals. These flashes appeared as an interrupted streak on a record such as shown in Figure 3.20. From the broken streak the path and speed of the vessel could be estimated with relation to a centerline painted on the floor of the canal and in relation to the numerals painted on the walls of the canal.

On the carriage an 8-mm camera was mounted above the electronic rudder-control box. The camera recorded the rudder angle as set by the rudder-control box, a clock with a sweep-second hand, and a run-identification

(Text continued on page 3.30)

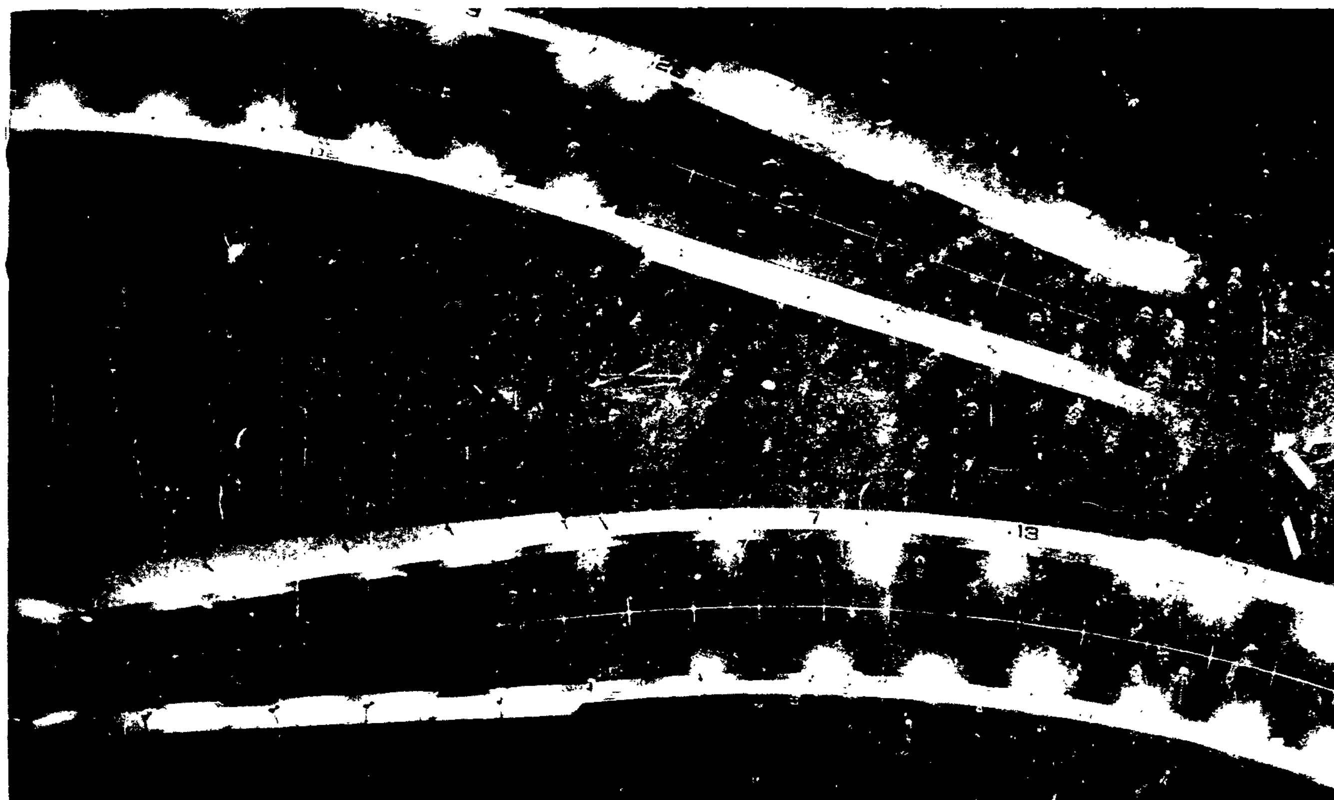


Figure 3.19 - Background for Ship's Path

The bend shown is illuminated by R-2 photo-flood lights mounted along the canal walls. For positioning data, a centerline with cross lines five feet apart was painted on the canal bottom, and numerals were painted on every fourth concrete unit.

A ship's path record as shown in Figure 3.20 will appear as interrupted lines superimposed on a bend background such as the one above.

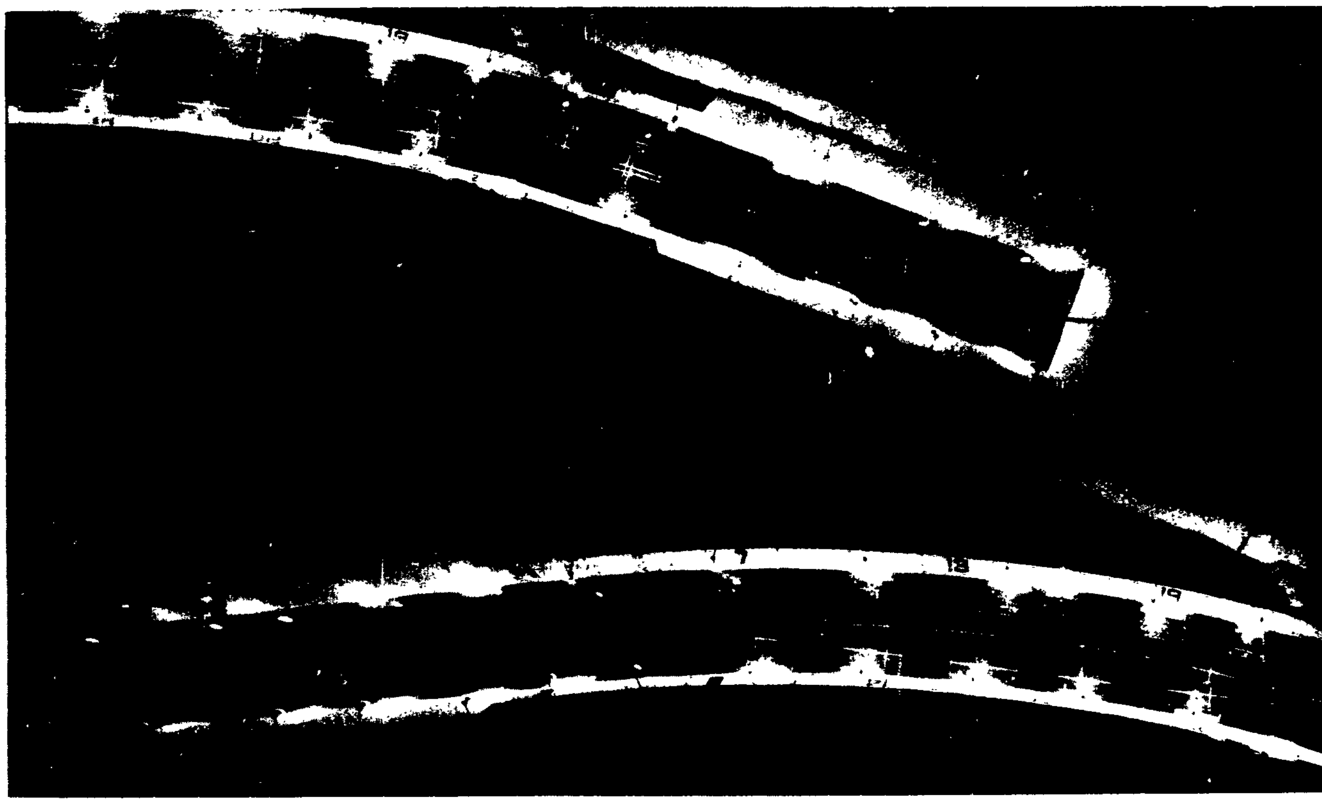


Figure 3.20 - Path of a Ship as It Is Maneuvered through a 26-Degree Parallel Bend

This photograph which is a print of a photographic plate that was taken by an overhead camera during the passage of TMB Model 3992 around the 86-scale, 26-degree parallel bend illustrates the method of obtaining data for use in comparing the maneuverability of a ship model under the various test conditions. The size of the bend made it necessary to use two lenses to cover the desired field. Two intermittent argon lights, one near the forward perpendicular and the other near the after perpendicular of the ship, mark the ship's path and serve to correlate its position with the rudder angles used as recorded by synchronized motion pictures of the remote-control rudder system. A steady light source on the port side of the forward intermittent light makes a third path which is parallel to that produced by the forward intermittent light and thus permits the identification of the bow and stern paths.

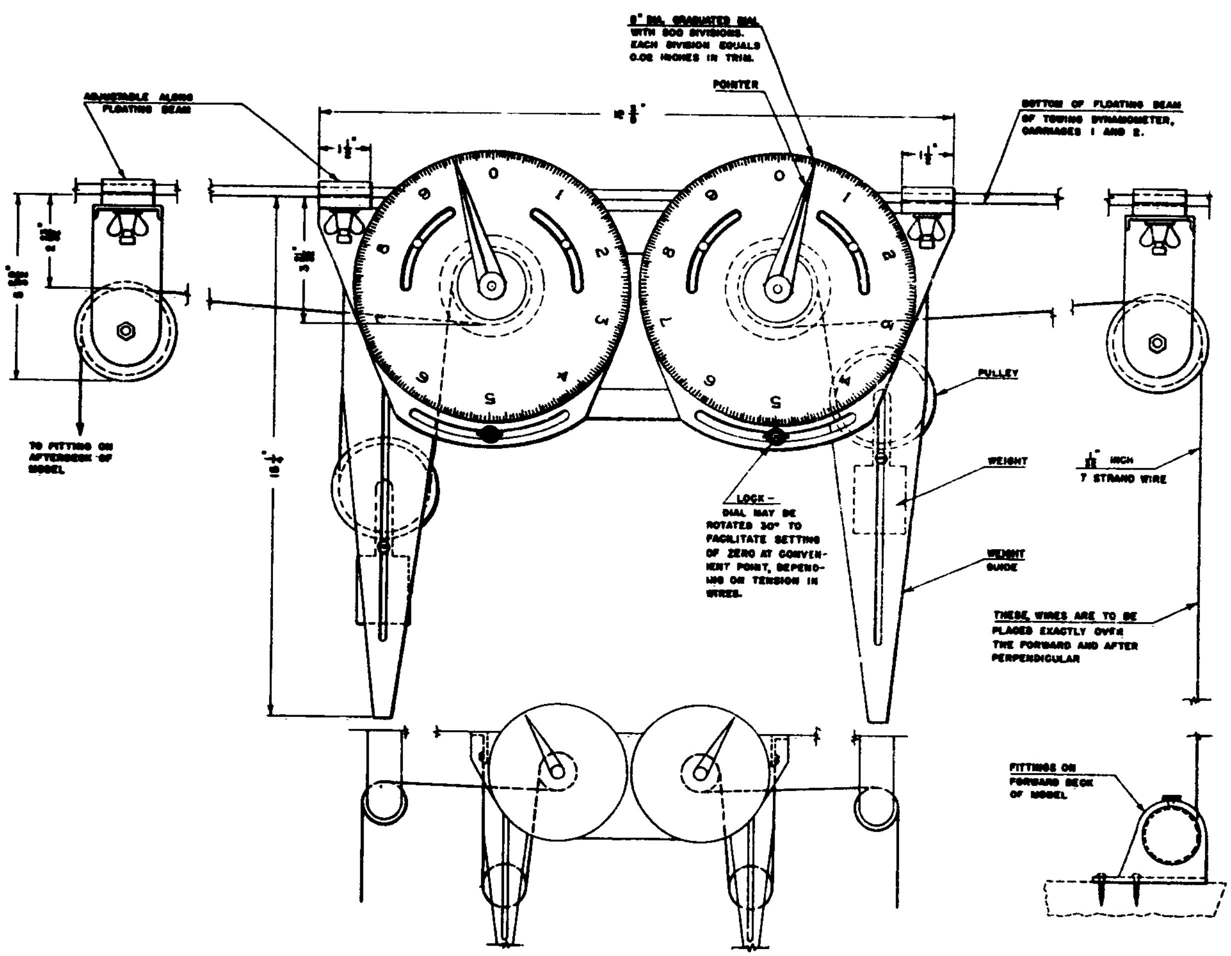


Figure 3.21 - Details of Trim Gage Used in Change-of-Level Studies

number which corresponded to the run-identification number mounted on the canal bend. A spotlight above the electronic rudder-control box illuminated the subject. The 8-mm camera was timed with the flashes of the argon blinkers on the model ship. The camera and argon lights were timed by a Cine-Kodak automatic time-interval control.

EQUIPMENT FOR CHANGE-OF-LEVEL STUDY IN THE SHALLOW WATER BASIN

In addition to the maneuvering tests, "change-of-level" tests were made in the various straight channels. The trim gage as shown in Figures 3.21 and 3.22 was installed parallel to the length of the ship and fastened to the box girders which held the tow-pin assemblies. The dials on the trim gage gave direct readings. The pointers were connected by a wire-and-pulley mechanism to fittings mounted on the model ship.

It was not possible to mount the trim-gage connections directly over the forward and after perpendiculars as desired. However, the connections were made as near as possible to the desired location and corrective calculations were made to obtain change of level over the ship's forward and after perpendiculars.

Change-of-level studies were made with self-propelled models in most cases. The ship was wired to the towing pins in such a manner as to keep the pins free in the slots of the towing brackets. The ship was free to assume vertical motion but not capable of transverse movement. The ship's motors were operated at a voltage to keep the ship model speed identical to the carriage speed required for the test. The value of voltage used for the ship's speed was taken from a previously constructed speed-voltage chart made for the particular test condition.

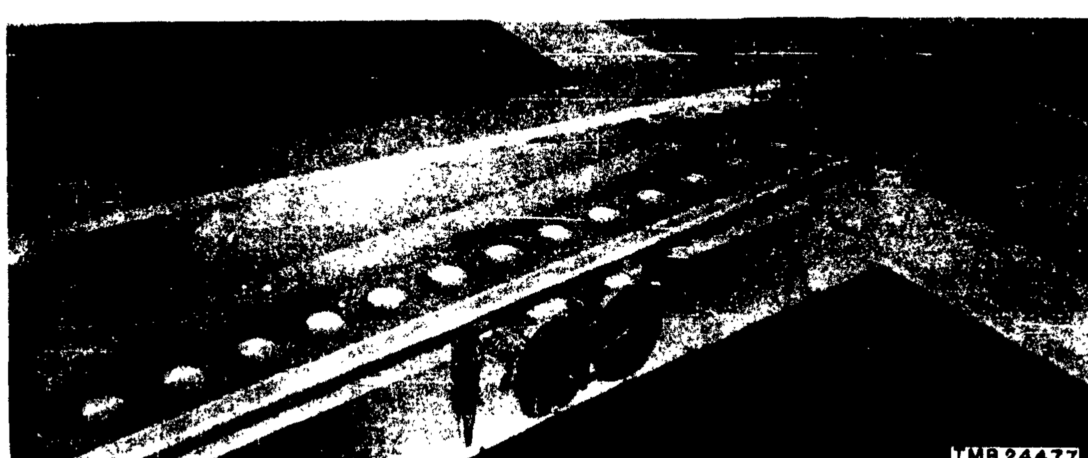


Figure 3.22 - Trim Gage Set up for Change-of-Level Tests

The trim-gage support beam is adjustable along the box girders and the trim gage is adjustable along the trim-gage support beam.

EQUIPMENT FOR MOVING-WATER STUDIES IN THE SHALLOW WATER BASIN

Tests made with a current in the canal paralleled the straight-channel one-way- and two-way-traffic studies and the channel-bend tests in still water. All the equipment necessary for the still-water tests was required for the moving-water studies. In addition extensive pumping equipment had to be added to the shallow water basin to create the moving stream in the canal.

Water speeds equivalent to 3 and 5 knots full-scale current were required in these tests duplicating the studies in still water. Moving-water tests were made with ahead and following currents.

PRODUCTION OF CHANNEL CURRENTS

Almost half of the tests made in the shallow water basin were made in channel currents. Figure 3.23d tabulates the dimensions of the channels in which channel currents were produced.

After considering the use of a paddle wheel and the employment of large eductor units it was decided that a low-head, high-discharge pump such as used on the condenser circulation system aboard ships would be more satisfactory. The basin power available was 250 HP at 230 volts dc. Two pumping units were obtained from the Bureau of Ships. The data on each unit, as shown in Figure 3.23b was:

a. Type -- Allis-Chalmers, vertical, 20- by 20-inch, single stage, marine, centrifugal pump.

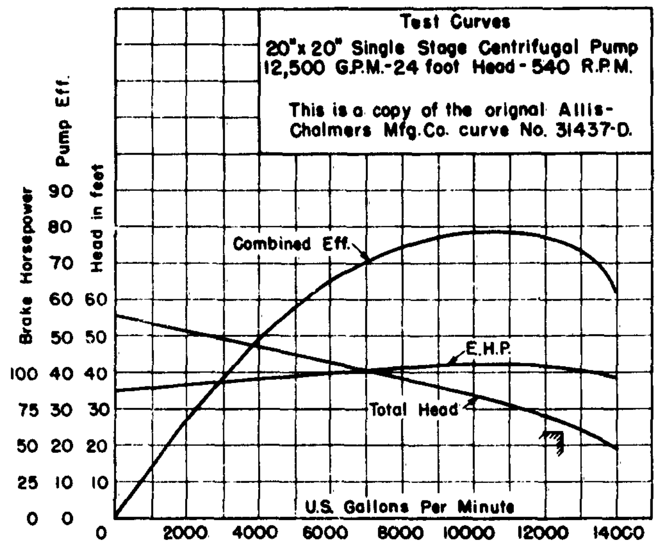
b. Rated Discharge -- 12,500 GPM at 24 feet total head

c. Operating Speeds -- 405 to 540 RPM

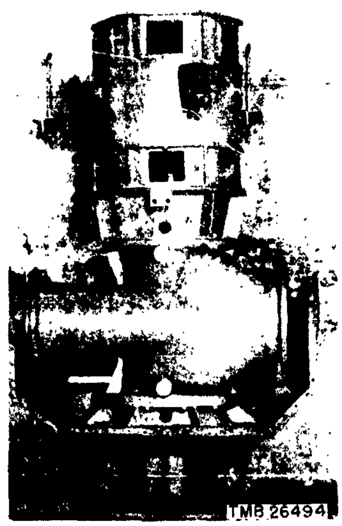
d. Drive -- 100 HP, 230 volt d-c electric motor

Figure 3.23a shows the pump test curves and indicates the performance of the pump unit for flows of 12,500 GPM and less; the pump curves in Figure 3.23c show the estimated capacity that may be obtained. In the extreme case, then, 16,000 GPM could be obtained at a total head of about 8 feet.

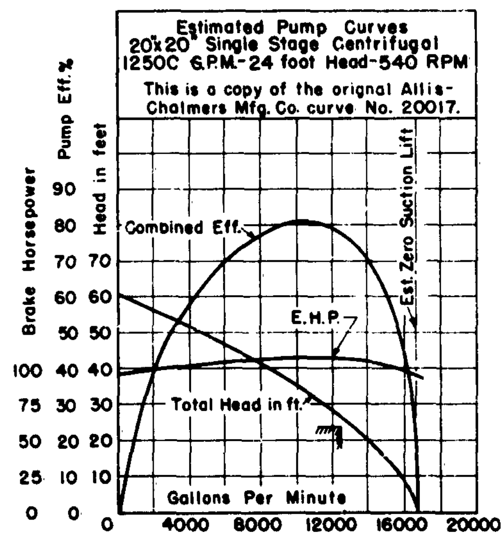
Figure 3.24a shows the general arrangement of the pumping system; Figure 3.24b shows the south-wall pump installation. The basin was divided, hydraulically, into two watertight compartments, interconnected by the model canal which was a waterway between them. For flow from east to west in the model canal, Scoop A and Gate D were open, Scoop C was blanked, and Gate B was closed. Thus the pump took suction through Scoop A from the west compartment and discharged water via the pump-discharge box and Gate D to the east compartment.



a - Pump Curve for 12,500 GPM-Pump



b - Allis-Chalmers 12,500 GPM-Pump

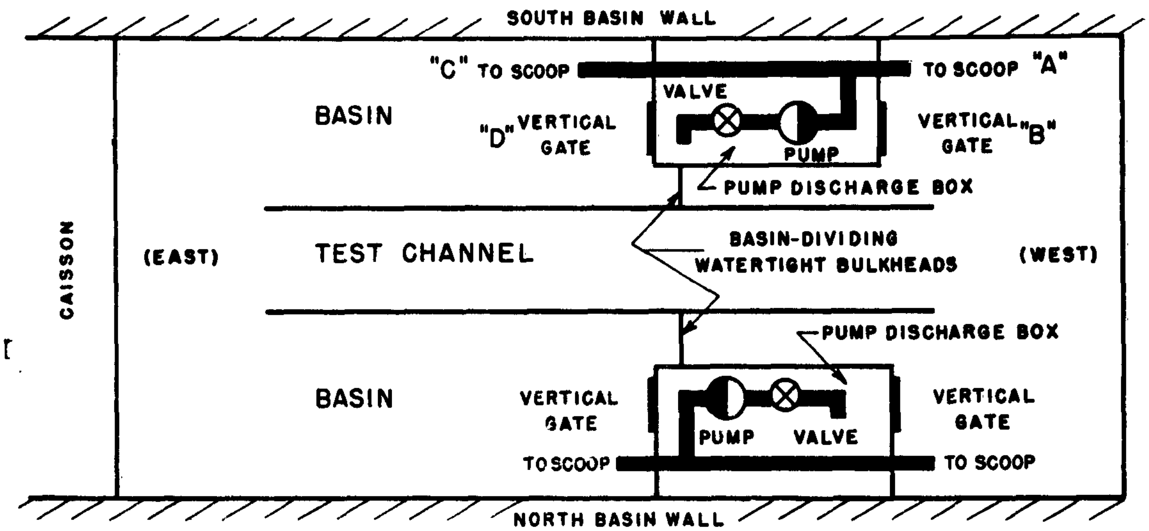


c - Estimated Pump Curve for 12,500 GPM-Pump

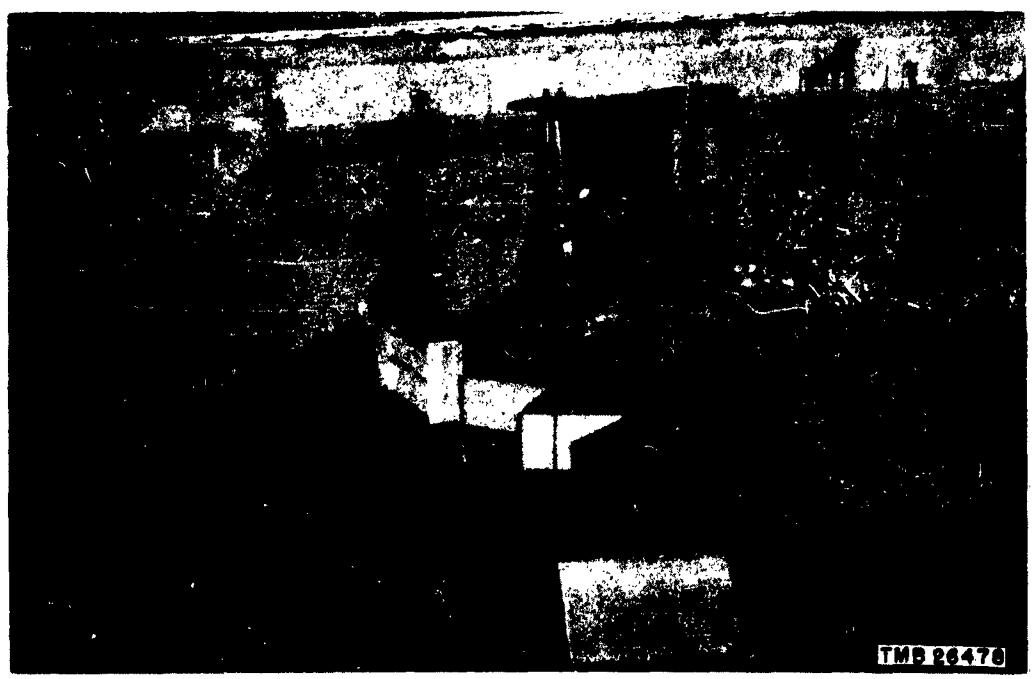
	Linear Ratio	Prism Width (feet)	Water Depth (feet)	Name	Channel Current 3 knots	Channel Current 5 knots	
Slope of Channel Walls is 45 degrees	45	500	60	Straight Channel	5650	9400	Gallons Per Minute Flow in Model Channel
		300	42	La Pita Bend - No Current	—	—	
		560	60	26 degree Parallel Bend	6300	10500	
	86	560	60	Double 13 degree Bend	1250	2070	
		560	60	26 degree Parallel Bend	1250	2070	
		560	60	26 degree Parallel Widened Bend	1250	2070	
		600	60	40 degree Widened Bend	1320	2200	

d - Table of Pump Discharges for Model Channels

Figure 3.23 - Pump, Pump Curves, and Flow Requirements for Model Channels



a - Diagrammatic Arrangement of the Pumping System



b - Pump, Pump Discharge Box, Scoop C, and Basin-Dividing Bulkhead for South-Wall-Pump Installation

Figure 3.24 - Moving-Water Equipment in Shallow Water Basin

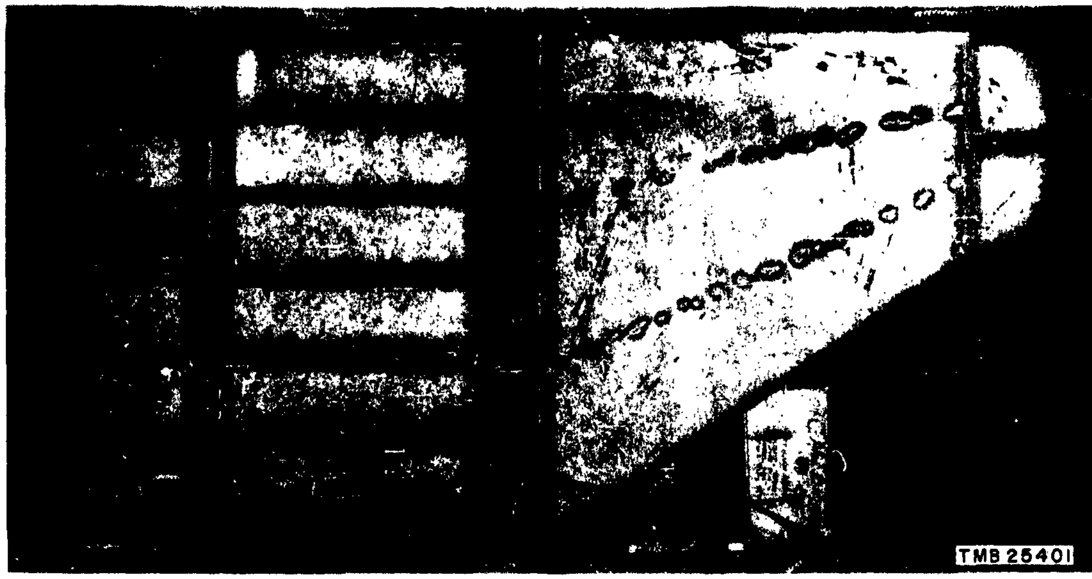
A head of water was developed in the east compartment and a sink was developed in the west compartment, which caused the water to flow through the canal from east to west. The velocity was dependent on the quantity flowing through the model canal and the depth of water in the canal. The quantity of water delivered by the pump was governed by the gate valve at the pump discharge.

For reversal of flow, Scoop C and Gate B were open, Scoop A was blanked and Gate D was closed.

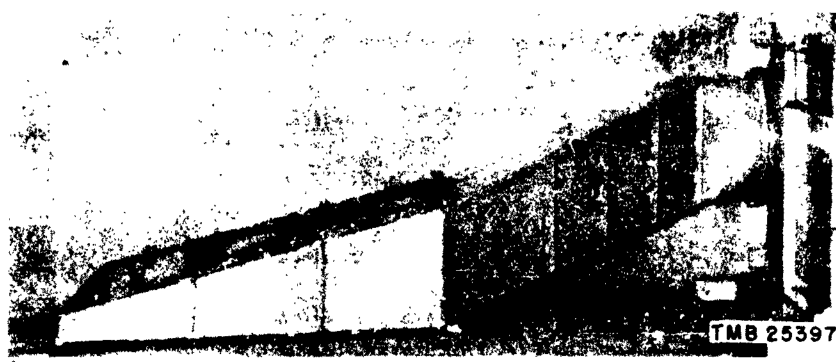
The suction scoop as shown in Figure 3.25 was designed to take water from water depths of 6 to 36 inches. The shape of the scoop resembled a vacuum-cleaner head. The suction end of the scoop contained removable covers. The first cover was 60 inches long by 3 inches wide, the second cover was 60 inches long by 20 inches wide, the third cover was 60 inches long by 39 inches wide. When the covers were removed in that order the suction area increased successively to take water depths from 6 to 12 inches, 12 to 24 inches, and 24 to 36 inches respectively. Although pump manuals state that the suction entrance velocity should be about 2 feet per second, the scoop was designed to take a suction entrance velocity of 10 feet per second because space requirements for the canal installations did not permit increasing the width of the scoop beyond 60 inches.

However, it was not the water entry velocity that caused loss of prime in the pumps but the entry of air through the scoop covers. The bolts holding down the covers and gaskets were not large enough to make an airtight joint. To remedy that situation the covers were welded on the scoop and a hole was cut in the underside of the scoop. The hole, shown in Figure 3.25c was placed to fit over the drainage gutter of the basin. The 9- by 48-inch opening in the bottom of the scoop handled the quantities of water required for the depths of 8 to 16 inches, in the shallow basin that were used in the moving-stream tests. Whirlpools appeared at the corners of the scoop but were not rapid or deep enough to suck an appreciable amount of air to destroy the prime of the pump.

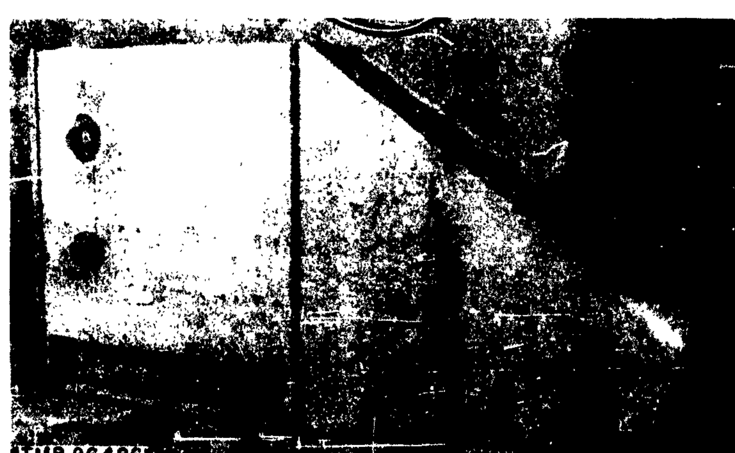
The pumps were primed by a Nash Hi-Tor vacuum pump connected to a central priming system with a barometric separation tank. The priming system is shown diagrammatically in Figure 3.26a. The separation tank was located about 50 feet from the basin floor. A limit switch cut in the pump at vacuums of 10 inches of mercury and cut out the pump at a vacuum of 20 inches of mercury. The priming could be operated manually or automatically; the automatic operation was used to ensure prime.



a - View from Top with Top Covers Off



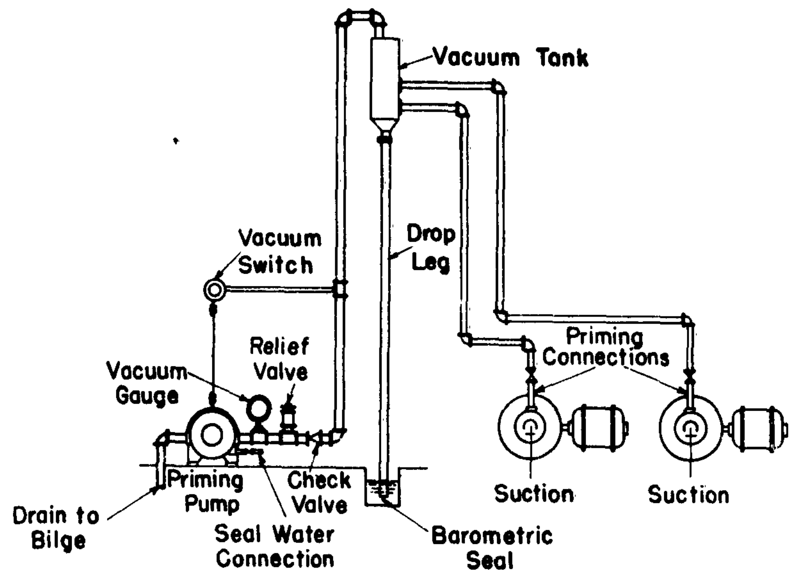
b - Side View with Covers On



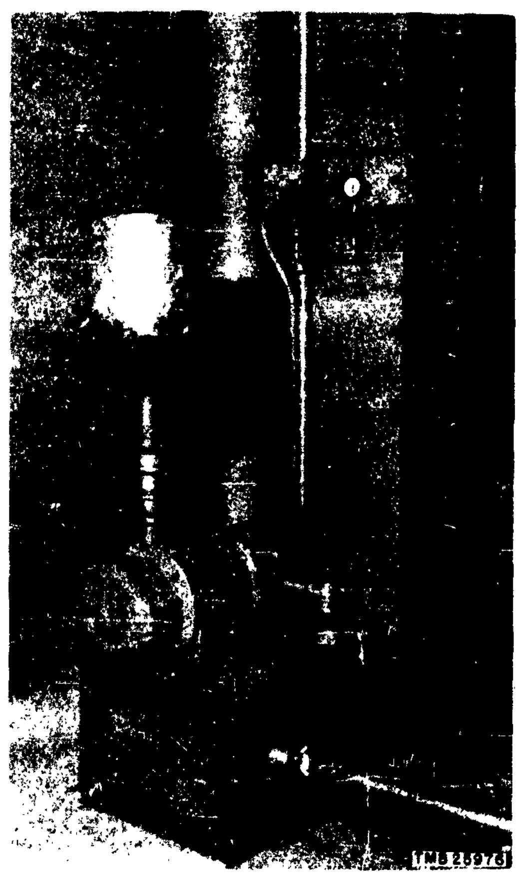
c - Bottom View

Top covers have been welded permanently to scoop and the original suction opening blanked. The hole shown is the new suction entrance, positioned to lay over the basin gutter.

Figure 3.25 - Scoop for Pump Suction



a - Diagrammatic Sketch of the Central Priming System with Barometric Separation Tank (Vacuum Tank)



b - Nash Hi-Tor Vacuum Pump and Vacuum-Limit Switch

Figure 3.26 - Pump-Priming System for the Allis-Chalmers Pumps

To prevent the possibility of air entering the pump through the discharge gate valve the discharge line was extended to a point 6 inches above the basin floor. This created a water seal at the discharge end and no trouble was encountered from air entering the pumping unit and destroying the pump's prime.

FLOW CONTROL

The water in the canal was to flow smoothly at the correct velocity and at the correct depth. A change in velocity affected the depth setting and vice versa. To obtain a representative flow in the canal, screens and slot baffles were introduced in the upstream end of the canal and an adjustable weir fitted in the downstream end. The rough velocity setting was made by controlling the discharge of the pump; the finer setting by adjustment of the weir, slot baffles and, at times, interposing objects in the stream at the entrance to the canal.

A wire screen was fitted at the water-entry end of the canal to lessen the turbulent entry of water into the canal. The unit was made of fine brass-wire screening brazed to a pipe frame which was formed to fit snugly along the sides and bottom of the canal. However, the screens were found to be impractical due to sludge which collected in patches on the screen and gave rise to an uneven flow distribution in the canal.

About two feet downstream of the point where the screen was fitted to the channel an adjustable slot baffle was fitted in the canal. The slot baffle, as shown in Figure 3.27, was made in two parts. Each part consisted

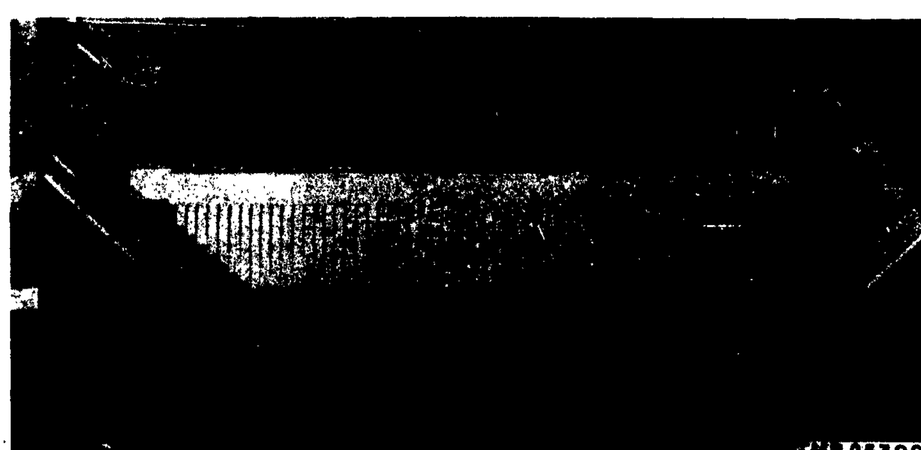


Figure 3.27 - Adjustable Slot Baffle

The short unit (adjustable) is held on the long unit (fixed to channel walls) by steel straps. The adjustable unit may be moved to the right or left causing the openings between the two units to vary.

of a wooden beam with slats 1 inch wide spaced at a distance of 2 inches between the centerline of the slats. One unit was made to fit the cross-section of the canal and was fastened to it. The other unit was shorter by a few inches and was built to be supported by means of steel straps to the fixed unit. The shorter slot section was, therefore, movable along the longer slot-baffle section so that the slats of one unit could be manipulated to cover the openings of the other unit. The transverse movement of the movable baffle varied the size of the openings to the water flow from 0 to 1 inch as desired.

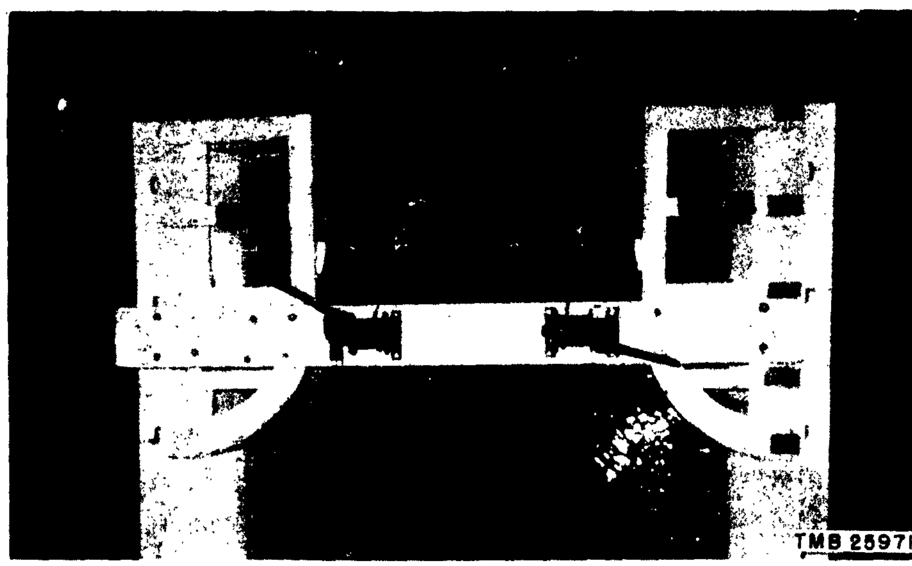
The adjustable slot-baffle unit helped to smooth the water flow into the canal but did not remedy the uneven velocity distribution at the canal entrance. In an attempt to remedy the uneven flow, the movable section of the slot baffle was cut into three pieces of equal length. Each piece was adjustable to vary the openings from 0 to 1 inch over the section of the canal covered by its length. However, it was found that dead spots and eddies appeared in the stream when the flow was varied by different adjustments of the three sections of the slot-baffle unit. As a result the slot-baffle unit was used with the maximum openings at all times.

The installation of the 40-degree widened bend as shown in Figure 3.13f was typical of the other bend installations. The backwater on the north wall of the canal was always much greater than the backwater on the south side of the canal. The south pump had to deliver approximately as much water as the north pump, and considering the areas through which equal quantities of water must flow, the south delivery channel required a much greater stream velocity. As a consequence the entrance swirl on the north side of the canal was neatly formed and the entrance whirl about the south side of the canal was rapid and shifted toward the opposite bank.

The resultant tendency was to create a rapid flow along the north side of the channel and a slow flow along the south side. The water at the south entrance to the channel had to be diverted from its trend toward the north bank. A concrete channel-wall unit was set in the canal entrance at an angle to divert the water issuing from the south pump to the south wall of the canal. The position and angle of this block was changed until a fair flow pattern was obtained at a distance of 20 feet from the canal entrance.

The discharge end of the canal contained a weir placed between two curved transition pieces which formed the discharge outlet as shown in Figures 3.28a and 3.28b. The curved outlets were made of wood and bolted to the canal sides. The weir consisted of a flat rectangular piece hinged to the canal floor. The weir swung outward with the flow and was raised and lowered by hand winches.

a - Weir Shown in Closed Position



b - Weir with Winches Shown in Open Position

Figure 3.28 - Weir Installation for Flow Control

To obtain an approximate flow setting in the canal, the basin was filled with water to a depth one quarter inch above the desired test depth. This measurement was made at the mid-point of the canal along its length. The weir was resting on the bottom of the canal; the slot baffle was in full-open position. The discharge of the pumps was controlled by the gate valves with the pump operating at its maximum rated speed, 540 RPM. When the smaller discharges could not be controlled by the gate valve alone, the rheostats at the electric control panel shown in Figure 3.29 could vary the speed of the pumps from 540 to 405 RPM as desired. A chip floating with the stream was timed over a set distance to obtain an approximate velocity setting. When

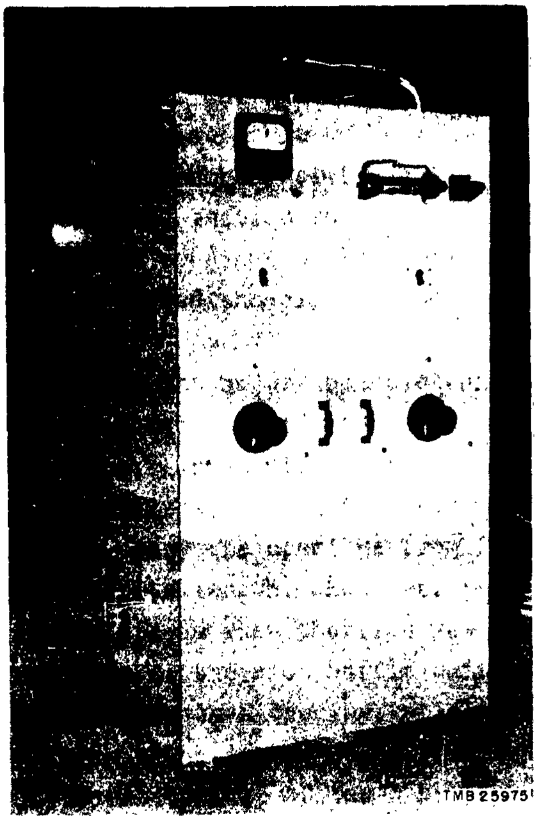


Figure 3.29 - Electrical Control for the Allis-Chalmers Pumps

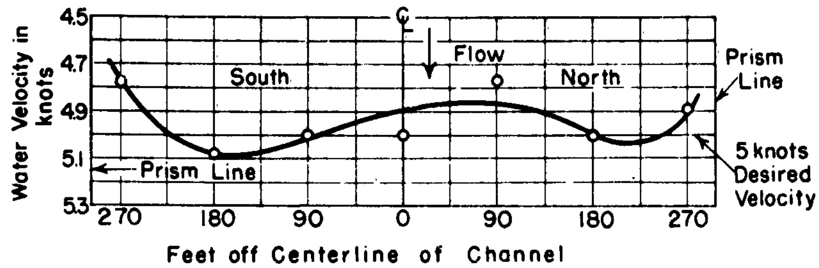
the surface velocity was about 20 per cent higher than the desired velocity, the water level in the channel dropped almost to the correct depth. If the water dropped a little lower the weir was raised to bring the level to the required depth. The surface velocity was tested by the chip method and adjustments were made to the discharge of the pumps to bring the velocity to the required value. The surface velocity as measured by the chip method was then taken at the center and the quarter points in the section of the canal. When they indicated almost equal velocities at the required value the stream was ready for a finer adjustment as explained under the heading "Flow Measurement."

FLOW MEASUREMENT

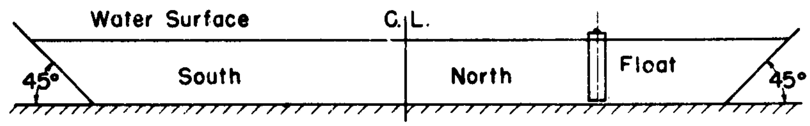
The resistance of the solid boundaries of the open channel caused the velocity to diminish near the sides and bottom of the channel. The filament of the maximum velocity is below the surface and may be found at two points across a horizontal in the stream, these being one on each side of the center, as indicated in Figure 3.30a. It is indicated from texts on flow in open channels that, usually, the velocity of the stream at 0.6 the depth will give the mean velocity of the vertical within 5 per cent. The ratio of the mean velocity in any vertical to the surface velocity is between 0.8 and 0.9. The ratio diminishes with the velocity of flow, roughness of the channel and the ratio of the channel width to channel depth.

The ratio of the mean velocity over the whole section to the maximum surface velocity usually lies between 0.60 and 0.85 and increases with the depth of the stream. The velocity at mid-depth to mean velocity in any vertical ranges from 1.02 to 1.06. Therefore a value of 1.04 may be taken for the mean velocity within 3 per cent for all normal sections and velocities of flow.

Two methods of measuring flow in the channel were used; the pitot-tube and the depth-float method. When the pitot tube was used the velocities



Graph of Velocity Distribution Across Channel

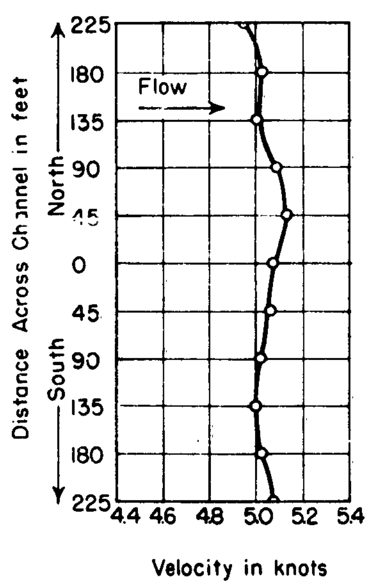


Section Through Channel

Channel Prism Width 560 ft.
Channel Water Depth 60 ft. } Full Scale
Desired Velocity 5 knots

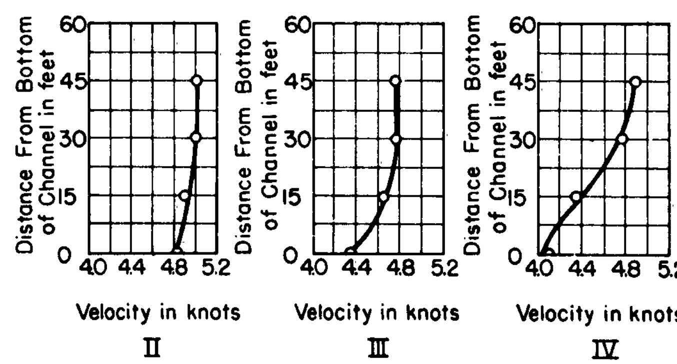
Installed with Linear Ratio of 86

a - Velocity Distribution by Float Method



Horizontal Traverse

I - In a plane parallel to bottom and at half depth



Vertical Traverses

II - In a plane through centerline of channel

III - In a plane through south quarter of channel

IV - In a plane through north quarter of channel

Full Scale Channel Data

Prism Width = 500 feet

Water Depth = 60 feet

Side Slope = 45 degrees

Desired Velocity = 5 knots

Installed to Linear Ratio of 45

b - Velocity Distribution by Pitot Tube

Figure 3.30 - Graphs of Velocity Distribution

recorded were the velocities at the mid-depths across the channel; when the float method was used the velocities recorded were the velocities obtained by timing the float over a specified distance. Figures 3.30a and 3.30b show the graphical results of traverses taken by float and pitot-tube methods.

For consistency in establishing the desired flow conditions the following standards were set:

a. The velocity measurements were taken at about 20 feet from the adjustable-slot baffle.

b. A horizontal velocity distribution in which the variation was within plus or minus 10 per cent was considered acceptable.

The flow conditions were established near the upstream end of the channel because it was felt that the variation of the velocities occurring in the channel bends from that point on would approximate the variations normally occurring in the prototype.

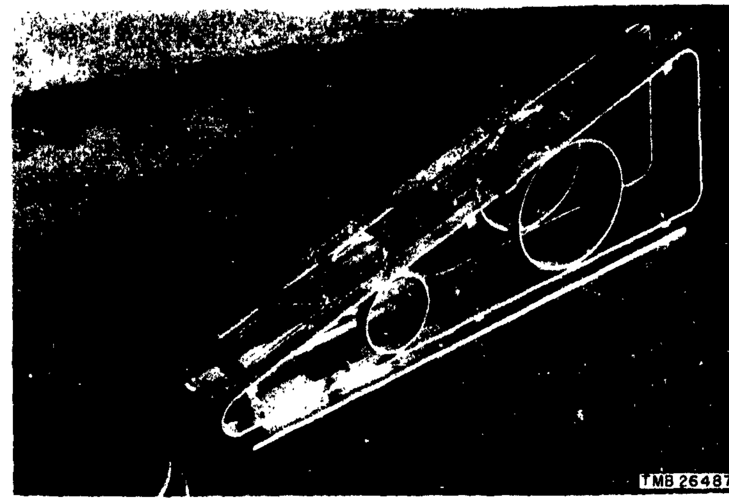
The depth-float method proved the easiest and quickest method of obtaining the horizontal velocity distribution. The depth float shown in Figure 3.31a consisted of a wooden block 2 1/4 inches square and having a length equal to the water depth in the channel. The float was hollowed to contain dry-cell batteries which were wired to an exposed flashlight bulb. The batteries were sealed in the block with beeswax. The block was weighted to float with 1/2 inch of its length exposed above water.

After the rough approximation of the velocity as explained in the section "Flow Control" a more refined adjustment of flow was made through the use of the three depth floats. The depth floats were gently lowered into the stream at the middle and at the quarter points of the channel and were then released. The time the floats took to travel 20 feet was noted; the path of their travel was noted. The discharge of the pumps was regulated by adjustment of the gate valves. When each float traversed 20 feet of the stream length in the required time and remained on the centerline and the quarter points during the run, the following tests were made with additional depth floats. For the smaller channel widths the depth floats were released at 1-foot intervals across the channel width; for the larger channel widths, the floats were released at 2-foot intervals across the channel width. The velocity variation at the measuring points had to be within plus or minus 10 per cent of the required stream velocity.

Figure 3.30a illustrates a record of a horizontal velocity distribution as obtained by the depth-float method.

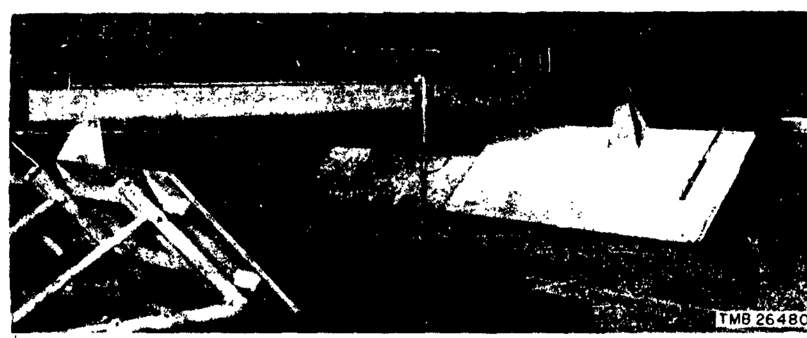
Although the depth float was satisfactory in determining the horizontal velocity distribution it gave no indication of a vertical distribution

a - Depth Float for Obtaining Velocity Distribution

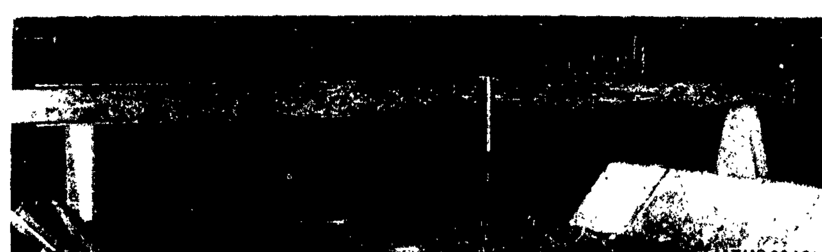


c - Manometer for Use with Pitot-Tube Transverse Equipment

b - Pitot-Tube Transverse Equipment, Showing Transverse Travel Head and Pitot-Tube Support Arm



d - Pitot-Tube Transverse Equipment Mounted on Steel Wall Units



e - Pitot-Tube Transverse Equipment Mounted on Concrete Wall Sections

Figure 3.31 - Flow-Measurement Equipment

of velocity. The pitot traverse equipment illustrated in Figure 3.31b was designed to obtain vertical as well as horizontal velocity traverses as illustrated in the graphs of Figure 3.30b.

A 4- by 4- by 8-inch I-beam 20 feet long bridged the channel. On the beam the transverse travel head was mounted on brass tracks fixed to the I-beam. A vertical member was attached to the transverse travel head. The vertical member was the pitot support arm on which the pitot tube was mounted. The pitot tube could be raised or lowered in the stream by motion along the pitot support arm. The movement of the transverse travel head along the I-beam positioned the pitot unit at a point in the width of the channel; the motion of the pitot tube on the support arm positioned the pitot tube at a point in the vertical section of the stream.

The transverse travel head with the pitot support arm is shown in Figure 3.31b. A scale for indicating the vertical position of the pitot tube was mounted on the support arm; a scale for indicating the horizontal position of the transverse travel head along the beam was mounted on the I-beam. It was possible for an operator, standing on a bridge across the canal, to set the pitot at any point in the cross section of the stream.

The pitot support arm could be turned about a vertical axis to align the pitot tube with the direction of the stream flow. To set the pitot tube for a measurement the transverse travel head was moved along the I-beam to the desired point and clamped; the pitot tube was lowered until it touched the bottom of the canal. The scale on the pitot support arm was adjusted to read "zero" with a pointer attached to the pitot tube. The pitot tube was raised until the pointer indicated the desired depth on the scale and then was clamped. In this position the pitot tube was set for taking measurements at the point desired in the cross section of the stream.

The differential manometer shown in Figure 3.31c was mounted on the I-beam and could be moved along the beam as desired by the operator. The manometer mounted on the I-beam is shown in Figure 3.31d and 3.31e.

The differential manometer was used to measure the height of water equivalent to the velocity pressure of the stream. The manometer U-tube was set at a 1-to-4 incline in order to indicate small changes in water level in the tubes. The scales were designed for direct reading of deviation in inches, tenths of an inch, and hundredths of an inch. An indicator similar to a slide-rule glass was mounted over each manometer tube and was used for sighting on the meniscus.

DISCUSSION

Considering the large number of test installations and the variables to be accommodated within each test setup, the equipment performed its functions satisfactorily. However, certain limitations should be noted in the event similar tests are made in the future.

All lights on the model ship used as references for the analysis of film records should be mounted on the centerline of the ship and directly over the forward and the after perpendiculars. This would permit a quicker and easier analysis of the speed and displacement of the vessel.

The field to be recorded photographically was not always adequately lighted to produce clear records. Further experimentation to determine the proper amount and application of light would improve the quality of the photographic records.

The electronic rudder-control system is superior to the servo-type rudder control used earlier in the tests.

If a radio-controlled model could be used instead of a ship requiring a power cable, any possible error due to the interference of the power cable would be eliminated.

Figure 3.13f illustrates the typical installations of a channel bend in the shallow basin. The water passage between the south wall of the basin and the south wall of the model channel is constricted as compared to the water passage between the north wall of the basin and the north wall of the model channel. Consequently, for the pump discharge necessary to move half of the water volume flowing through the bend in Figure 3.13d the water level outside of the south wall of the model channel was slightly over 30 inches at the bend. The height of concrete units from the basin floor was 30 inches. Therefore in order to prevent the water from spilling into the canal over the concrete unit, the height was increased by building a ridge on top of the wall with caulking cement. If further tests are scheduled this difficulty could be eliminated by increasing the height of the concrete channel-wall units to prevent water overflow.

In addition the water pressure, due to the conditions mentioned, caused the concrete units to separate and move into the canal. This was remedied by anchoring the blocks to the basin floor by means of bolts. In the future the concrete units should either be heavy enough to maintain their place in the channel wall or allowances should be made for the bolting down of the units.

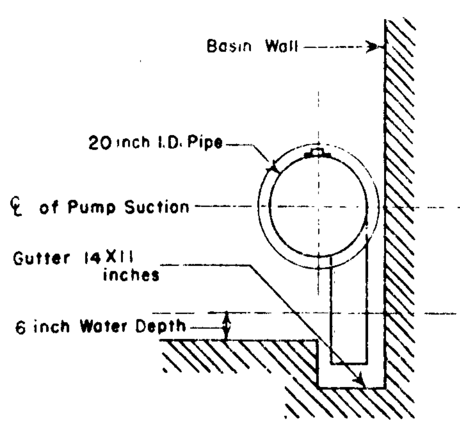
Another difficulty was presented by the water pressure just mentioned. The rubber gaskets between the basin floor and the concrete channel-wall units were forced out from under the concrete blocks. Bolting down the concrete channel wall kept the rubber seals in place and prevented water from entering the channel at the floor joint.

Figure 3.23d tabulates the pump discharges necessary for producing stream velocities in canals of the dimensions used.

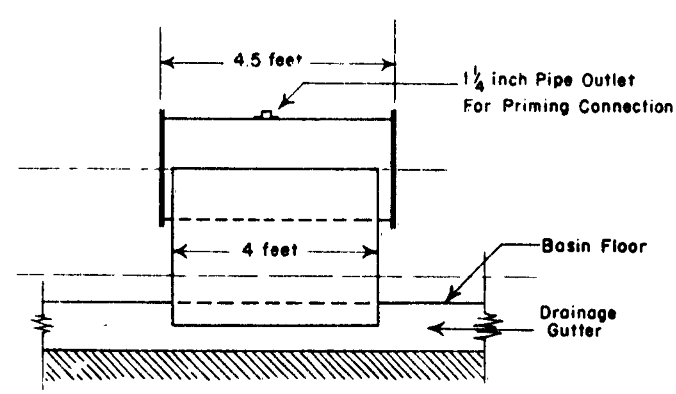
The ability of the pumps to deliver their full capacity depends on the design of the scoops which are attached to the suction side of the pump. The scoops as used were limited in the amount of water they could pick up at the very shallow water depths. The suction inlets should be designed similarly to the one indicated in Figure 3.32. The suggested design utilizes the additional depth afforded by the gutter along the side of the basin. Two such inlets flanged together pick up 12,500 GPM with an entrance velocity of 5 FPS. One unit would adequately serve to suck water from depths as small as six inches with low values of entrance velocity. The design of an inlet such as shown in Figure 3.32 would pick up the required water, be airtight, and need the minimum of basin space for installation.

The bad effect of the narrow water passage on the south wall of the basin and the large water passage on the north wall of the basin in relation to the velocity distribution in the canal might be alleviated by the installation of a series of adjustable guide vanes at the entrance to the channel. This would lessen the numerous adjustments of the pumps for setting the desired flow.

Time did not permit the measurement of the velocities and trend of the currents over the entire length of the channels. Future tests should include such records which could be made with a photographic installation similar to the one used for making the streak photographs. The 8- by 10-inch plate camera should have a device for exposing the plate for a set time



Transverse Section through a Portion of the Shallow Water Basin



Elevation with Basin Wall Removed

Figure 3.32 - Suggested Design for Improved Suction Inlet for the Allis-Chalmers Pumps

interval and for keeping the plate unexposed for a set time interval. The lighted depth floats, inserted at spaced intervals across the channel, would float with the current and record an interrupted streak on the photographic plate. From the record it would be possible to determine the trend of the current for any portion of the canal and the average velocity of the stream for any portion of the canal.

For vertical traverses of the stream velocity a current meter would permit a more rapid plot of the vertical current distribution. The rest of the pitot-traverse assembly could be used with the current meter.

The urgency with which the tests had to be carried out in order to meet the time schedule did not allow time for development of the improvements mentioned. It is felt that the points mentioned above should be weighed carefully in the event the tests are to be continued in the future.

The equipment was dismantled and stored for possible future use. The electronic rudder-control units, the pitot transverse-travel head, the pitot support arm, the pitot tube and the parabolic mirror and support are stored in a cabinet under the circulating-water channel. The 3-component dynamometer used in the force-measurement tests is stored in the circulating-water-channel building.

The Allis-Chalmers pumps, the steel and concrete channel-wall units, the platform frame and supporting structures, and the beam for the pitot-traverse equipment are stored near the east gate on the premises of the Taylor Model Basin.

The electric motors and their controls and the Nash vacuum pump are stored at the east end of the Basin Building.

All wooden structures such as platform floors, baffles, etc., were scrapped.

The trim gage is standard basin equipment and is under the cognizance of the basin manager. The beam for supporting the trim gage is stored with the pumps near the east gate.

SECTION 4

CONTROLLABILITY OF SHIPS IN ONE-WAY TRAFFIC IN STRAIGHT CHANNELS

ABSTRACT

The model tests reported in this section were conducted to determine the effect of channel dimensions on the relative controllability of selected ships under varied conditions of operation in one-way traffic in a straight channel. In some of the tests the linear ratio of both ship and channel was 35, in the others 45. The major test variables included the width and depth of the channel, ship speed, position of the ship in the channel, the type of ship represented, and the velocity and direction of the channel currents.

Fifteen channel sections ranging from 268 to 770 feet in width and from 45 to 80 feet in depth were tested. The major emphasis was on ship speeds between 5 and 10 knots with respect to the water. The channel currents ranged between 5 knots in following current and 5 knots in ahead current. The ships represented in the tests were selected because of their extreme size, their poor handling characteristics in restricted channels, or because they were representative of a large number of ships now using the Panama Canal.

The hydrodynamic phenomenon which is of major importance in this section of the report is popularly referred to as "bank suction." As a result of this phenomenon a ship underway in a restricted channel develops a tendency to sheer towards the far bank of the channel. In this report the magnitude of the bank suction is measured in terms of the rudder angle required to counteract it and also in terms of the yawing moment and total lateral force produced by it. Graphs have been prepared which show that these measures of bank suction are functions of the major test variables. Additional data were obtained by direct observation of the test runs and by analysis of photographic records of the test runs.

GENERAL CONSIDERATIONS

The tests discussed in this section were undertaken primarily to determine the effect of channel dimensions on the relative controllability of selected ships under varied conditions of operation in one-way traffic in a straight channel.

When a ship is underway in a restricted channel its movements and controllability are not the same as they are in open water. It will be recalled from Section 2 that navigation in restricted channels is difficult not only because of the limited space available but also because of three major hazards caused by the hydrodynamic phenomena.

Bank suction is the only one of the three major hazards of restricted-channel navigation which is of importance in this section of the report. It will be recalled that bank suction occurs when a vessel is closer to one side of a restricted channel than it is to the other or when the vessel passes projections in the channel. Its effect is to cause the vessel to sheer or deviate from its original course. It could be described as an interaction between the ship and the channel boundaries. The asymmetrical flow distribution which develops on the two sides of the vessel creates unbalanced forces which tend to force the vessel off its original course. If the vessel is underway in a restricted channel on a course parallel but to one side of the centerline of the channel the water surface between the bow and the near bank will build up above the level of the normal water surface, with the result that the bow is forced away from the near bank. As the water flows aft along both sides of the vessel to fill the void left by the stern, the level of the water surface drops below the normal surface level. The level of the water surface between the vessel and the near bank drops lower than the level on the other side, with the result that the stern of the vessel is forced toward the near bank. The net result of the difference in water level on the two sides of the vessel is to cause the ship to sheer away from the near bank. In some cases the sheer that results cannot be overcome by the rudder and the vessel strikes one of the banks. It is necessary to use a rudder setting which tends to turn the vessel toward the near bank to counteract bank suction. Thus, if a vessel were near the right bank it would be desirable to use right rudder to counteract this effect. If it were desired to return to the center of the channel the rudder could be eased off enough to allow the vessel to return slowly to the center. If, by using selected rudder angles, the longitudinal centerline of the vessel is maintained parallel to the bank while the vessel is off center in the channel, the resultant of all side forces acting on the vessel will be a force toward the near bank. If these conditions are maintained for a time the vessel will move bodily into the near bank. However, if the vessel is allowed to assume a slight angle of yaw away from the near bank and is given a rudder angle just sufficient to counteract the yawing moment, both the side force and the moment would be neutralized and the vessel would maintain a course parallel to the bank.

Another related hydrodynamic phenomenon which may be serious during the passage of vessels through restricted channels is the change of level of the vessel while underway with respect to its level while stationary in the same channel. This phenomenon is discussed in Section 7 of this report.

Another factor which might be of general interest, but which has been omitted from this investigation, is the resistance of ships in restricted channels. In the past, many investigators have concerned themselves with the resistance of ships in shallow water, but few have treated the problem of ship resistance in restricted channels. Some of the available information on ship resistance in shallow water is described in References (16), (64), and (65). References (66), (67), and (68) include most of the available information on ship resistance in restricted channels, although additional data on barges have been obtained.

An investigation of the controllability of ships in restricted channels is necessarily quite complex. It involves the effect of interaction between the vessel and the channel boundaries (bank suction), the steering characteristics of the vessel, and the effect of the restricted channel upon the steering characteristics of the vessel. If an attempt is made to maneuver the model in a manner similar to maneuvers of a full-scale vessel in a restricted channel the "human element," or skill of the pilot, becomes important. In an attempt to evaluate these factors, two general types of tests were set up. In each of these types it was planned to test several self-propelled ship models in channels with various cross-sectional dimensions.

One type of test, the so-called observational tests, consisted of observing and photographing the models while they were underway and completely unrestrained in a restricted channel. The other type, the force-measurement tests, consisted of the measurement of side forces which developed when the model was held at various transverse positions in a stream of water. The side force and the yawing moment were measured for various rudder angles and angles of yaw. In addition the rudder angle required to overcome the turning moment caused by bank suction was determined.

The terminology adopted to identify the specific types of tests is presented in the following outline of tests, and the specific types of tests are described as each type is discussed.

1. Observational tests
    a. Equilibrium-rudder-angle tests in still water,
    b. Equilibrium-rudder-angle tests in moving water,
    c. Maneuvering tests.
2. Force-Measurements tests
    a. Equilibrium-rudder-angle tests
    b. Total-lateral-force and yawing-moment tests at zero angle of yaw,

c. Tests to determine the rudder angle required to produce zero moment at zero angle of yaw for both self-propelled and towed models.

OBSERVATIONAL TESTS

The observational tests were of two general types, the equilibrium-rudder-angle tests and the maneuvering tests. The test apparatus and the test setup were the same for the two types of tests with the exception that no photographic apparatus was used for the equilibrium-rudder-angle tests. The test procedure was different for the two types of tests. The tests were conducted at a linear ratio of 45 in a facility known as the shallow water basin. This basin consists of a concrete-lined channel 52 feet wide, 10 feet deep, and approximately 300 feet long. Figure 4.1 which is a photograph of the basin, shows the test setup. The water depth can be set at any depth up to 10 feet. A towing carriage, which spans the basin, can be run in either direction at speeds up to about 8 knots. The functions of the towing carriage are a. to tow models which are being tested for resistance or other performance characteristics, b. to provide a movable observational and photographic platform and power supply, for studies of self-propelled models, and c. to accelerate self-propelled models to the desired speed in a short time. Two steel walls were placed on the floor of the 300-foot basin to form a smaller channel. The overall length of this channel was 180 feet, which is equivalent to 1.5 miles full scale. Its width could be varied from zero to 23 feet. The full-scale channels represented in these tests had bottom widths of 300, 500, or 700 feet. The side slope of the walls of the channel could be varied from an angle with the horizontal of 18.25 degrees to 90 degrees. During this phase of the tests the walls were set at an angle of 45 degrees. The test apparatus is fully described in Section 3.

SELECTION OF SHIP MODELS

Three TMB ship models, 3769, 4018, and 3748-4 were used in this part of the test program. These models were selected because of the navigation problems which their prototypes present. Model 3769, which was used in most of the tests, represents a 900-foot naval vessel which was selected because its extreme size makes restricted-channel navigation difficult even though the ship's steering qualities are excellent. Model 4018, representing a 720-foot tanker, was selected because a considerable number of accidents in the Panama Canal have involved large twin-screw, single-rudder ships; also, Panama Canal pilots consider large twin-screw, single-rudder ships very difficult to steer in restricted waters. The tanker model represents a ship somewhat larger than the majority of the twin-screw, single-rudder ships which

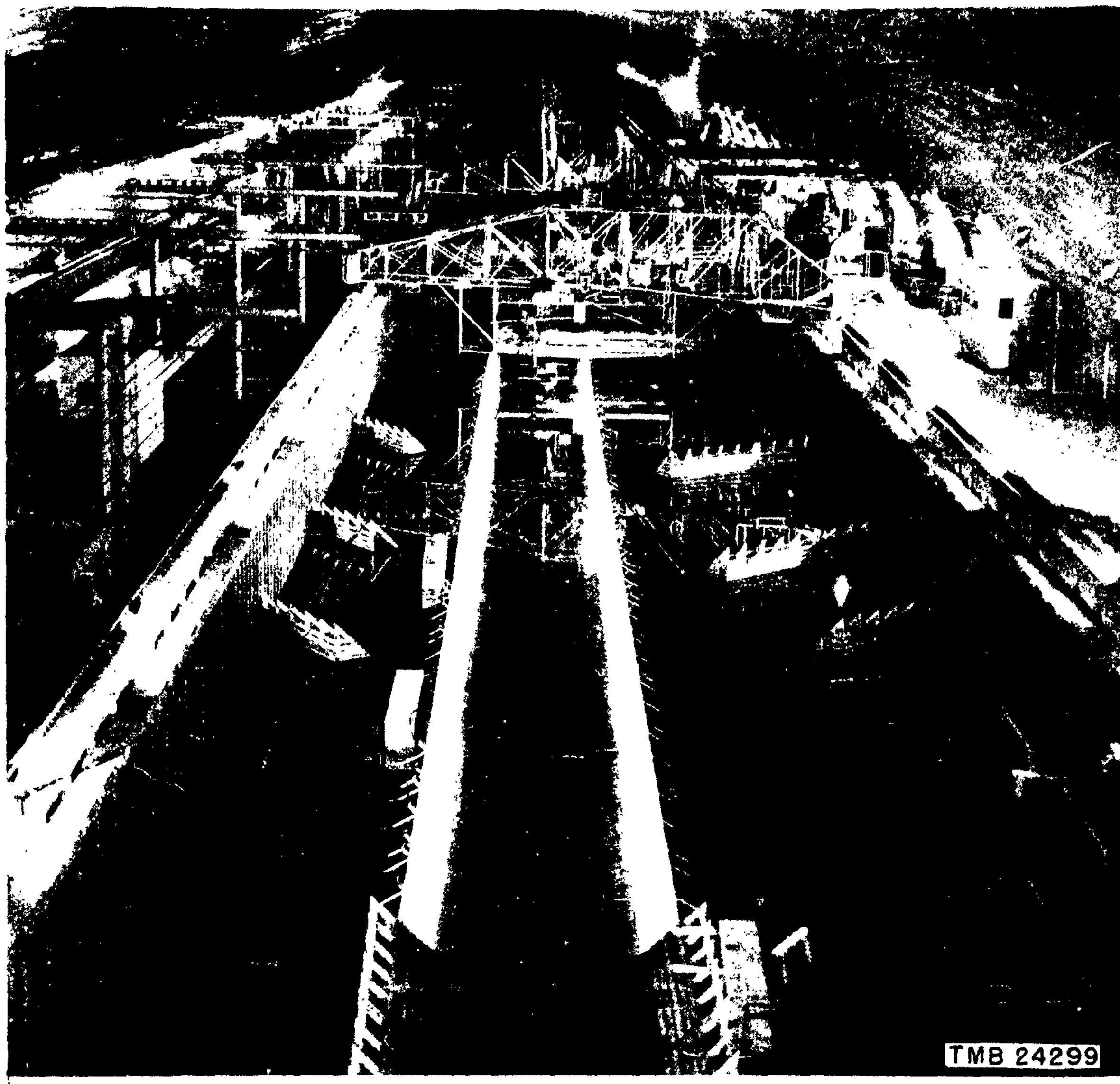


Figure 4.1 - General View of Basin Building, Showing Restricted-Channel Setup in Shallow Water Basin

The central portion of the restricted channel is made of steel sections with adjustable sides, so that the angle of slope can be set at 18, 30, 45, or 90 degrees to the horizontal.

The width of the channel can be varied by moving one or both sides along the basin floor. The depth of water is varied by changing the water level in the basin. The wooden slat structures outside the channel and at the near end are arranged to break up waves and surges set up by motion of the model.

The ship model, shown at the far end of the channel, is operated by distant control from the special platform under the towing carriage.

are transiting the Panama Canal at present. Model 3748-4, representing a modified Liberty ship, was selected because it is representative in size and operating characteristics of a large number of ships now transiting the Panama Canal.

Figure 2.1 summarizes the pertinent information with respect to the physical features of these ship models.

On the basis of Froude's law which was discussed in Section 2, the model speed during the tests was equal to the full-scale ship speed divided by the square root of 45, the linear ratio. For example, the model speed corresponding to 10 knots full scale was 10 divided by 6.71, or 1.49 knots.

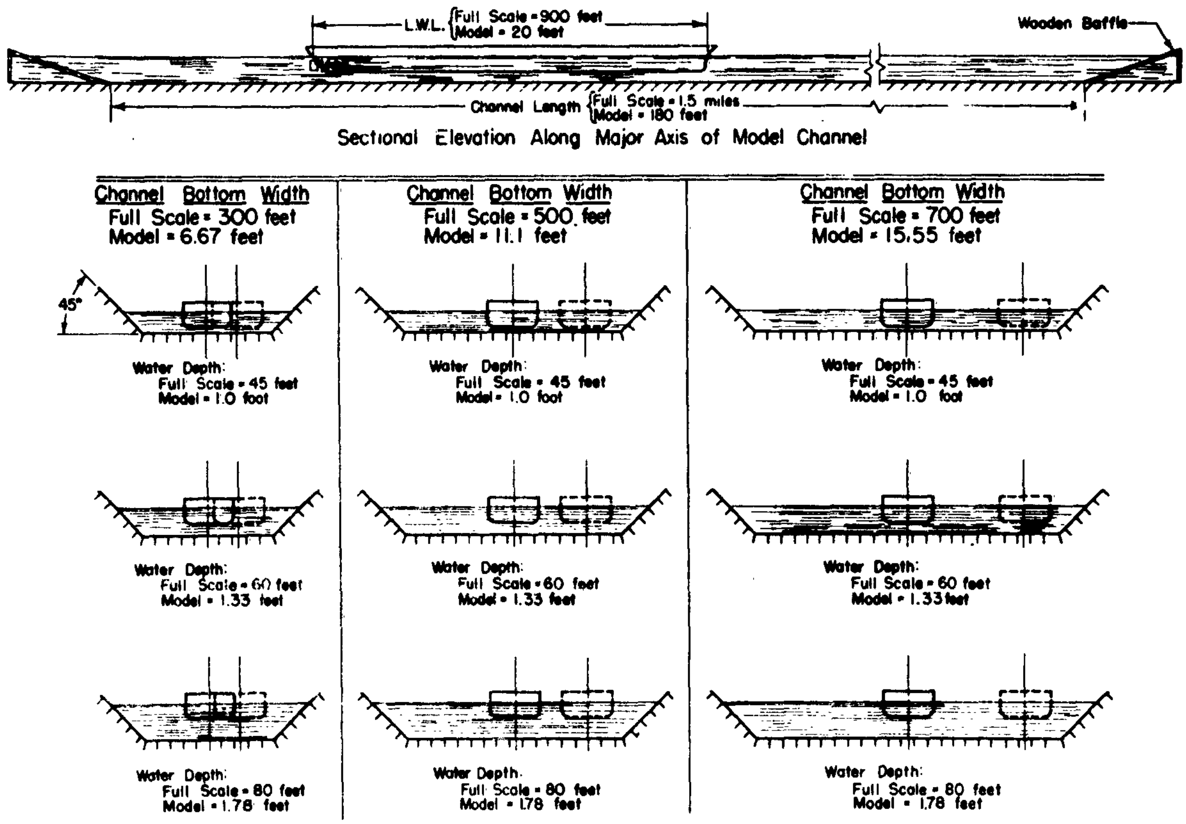


Figure 4.2 - Model and Full-Scale Dimensions of the Channels in Which Model 3769 Was Tested During the Observational Tests

On all of the cross-sectional sketches of the channels an outline of the hull of Model 3769 has been shown. The solid outline shows the model on the centerline of the channel. The dotted outline is the position nearest the wall for which the model was tested during the observational tests. The purpose of the wooden baffles at the ends of the channel was to dissipate waves.

EQUILIBRIUM-RUDDER-ANGLE TESTS IN STILL WATER

The still-water equilibrium-rudder-angle tests were conducted to obtain a comparison of the bank suction or interaction for various off-center positions of the ship in channels such as illustrated in Figure 4.2. The nature of the tests was such that the magnitude of the yawing moment caused by the bank suction was obtained in terms of the rudder angle required to counteract it.

A ship underway in a straight channel on a course parallel to but to one side of the channel centerline may be said to be in a condition of equilibrium. To maintain this condition the ship must be at an angle of yaw away from the near bank and the ship must have a rudder setting which tends to turn the vessel toward the near bank. For a particular test condition only a particular rudder setting and a particular angle of yaw will produce the condition of equilibrium. In this report these angles are referred to as the equilibrium rudder angle and the equilibrium angle of yaw.

Some question may be raised with regard to the advisability of expressing the yawing moment in terms of rudder angle rather than in a more orthodox form such as foot-pounds. One advantage of this method is that it expresses the moment in a term which is familiar to most people who are acquainted with the handling of ships. On the average ship the maximum rudder angle which can be used is in the vicinity of 35 degrees. Thus if the rudder angle required to counteract the bank suction for some specified condition is 25 to 30 degrees, it is obvious that the moment is quite large with respect to the maximum counteracting moment that can be developed by the rudder. A disadvantage of this method is that the lift developed by the rudder may not be directly proportional to the rudder angle at large rudder angles.

In the equilibrium-rudder-angle tests the model was attached to the towing carriage by two pins which held the longitudinal axis of the model parallel to the centerline of the model canal channel. The towing carriage was then accelerated to the desired speed and at the same time the propellers of the model were brought up to the RPM which would propel the model at the desired speed. The model was then released from all contacts with the towing carriage, with the exception of a light flexible cable which supplied power to the propeller- and rudder-motors. The path and heading of the model were observed from the towing carriage. A light source on the bow of the model cast a two-inch beam of light along an extension of the model centerline to a horizontal scale at the end of the channel. By observing the movement of the beam the observer could note instantly changes in the heading of the model. It should be noted that the purpose of the towing carriage was to accelerate the model in as short a distance as possible so as to leave a large section of the model channel available for observation of the unrestrained model. If the rudder on the model had been previously set at zero the course of the model would remain on the centerline of the channel for several model lengths before it deviated in either direction. Following this test the model was attached to the towing carriage on a line parallel to but to one side of the centerline. Again the carriage was accelerated to the desired speed, at which the model was again released. If the rudder had previously been set at zero it would be noted that the model sheered away from the near wall as soon as it was released from the carriage. As soon as this was observed, the model and carriage were stopped and the model was again attached to the carriage at the same off-center position. Before the model was released a second time the rudder would be set at an angle which would normally turn the model toward the near bank. If the model again sheered away from the near bank it would be returned to the carriage and the rudder angle increased. This procedure was repeated until a rudder angle was found which would just counteract the yawing moment caused by bank suction. After this rudder angle had been selected the procedure was repeated at several higher speeds. The model was then moved to a point farther off center and the complete procedure repeated. In this manner data were obtained for the rudder angles required to counteract interaction at various off-center positions, various ship speeds, and for channels with various widths and depths.

In each run, after the necessary observations were complete, the model was maneuvered by remote control so as to prevent damage to the model.

The basic data, showing the test spots for TMB Model 3769 tested by this method, are presented in Figures 4.3, 4.4, and 4.5. The distance between the centerline of the channel and the center of gravity of the ship, as well as the distance between the center of gravity of the ship and the near prism line, is indicated on the curves. In most instances the rudder angle for equilibrium was measured for three off-center positions of the ship. These positions were varied for each width of channel so as to cover the navigable range of the channels. For comparison, intermediate positions may be selected on cross-plots of the data. It will be noted that the equilibrium rudder angle almost always increases with ship speed and that the rate of increase is somewhat less in the wider and deeper channels. The tabulated data for the equilibrium-rudder-angle tests conducted in the shallow water basin are presented in Table 4.1.

The basic data in Figures 4.3, 4.4, and 4.5 have been plotted to show the variation of the equilibrium rudder angle with various pertinent parameters.

Figure 4.6 is a plot of the equilibrium rudder angle required to counteract bank suction against distance between the centerline of the channel

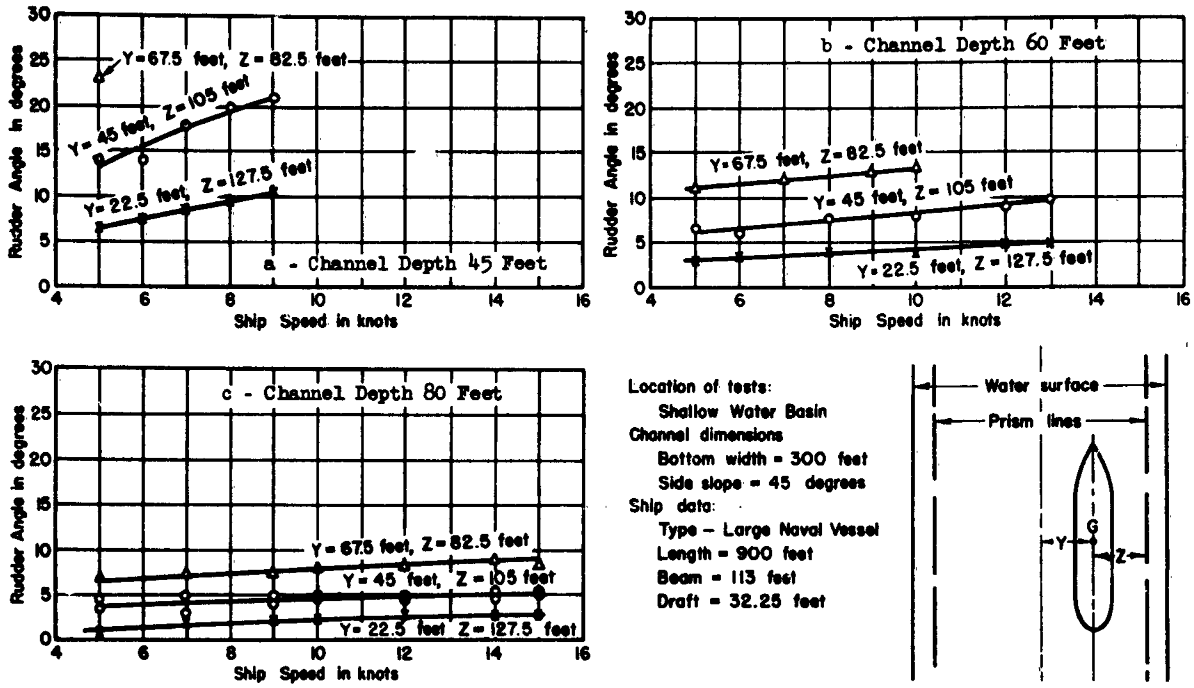


Figure 4.3 - Rudder Angle for Equilibrium as a Function of Ship Speed in a 300-Foot Channel

These rudder angles are required to counteract the yawing moment which exists when self-propelled Model 3769 is released parallel to and at various distances from the centerline of the channel.

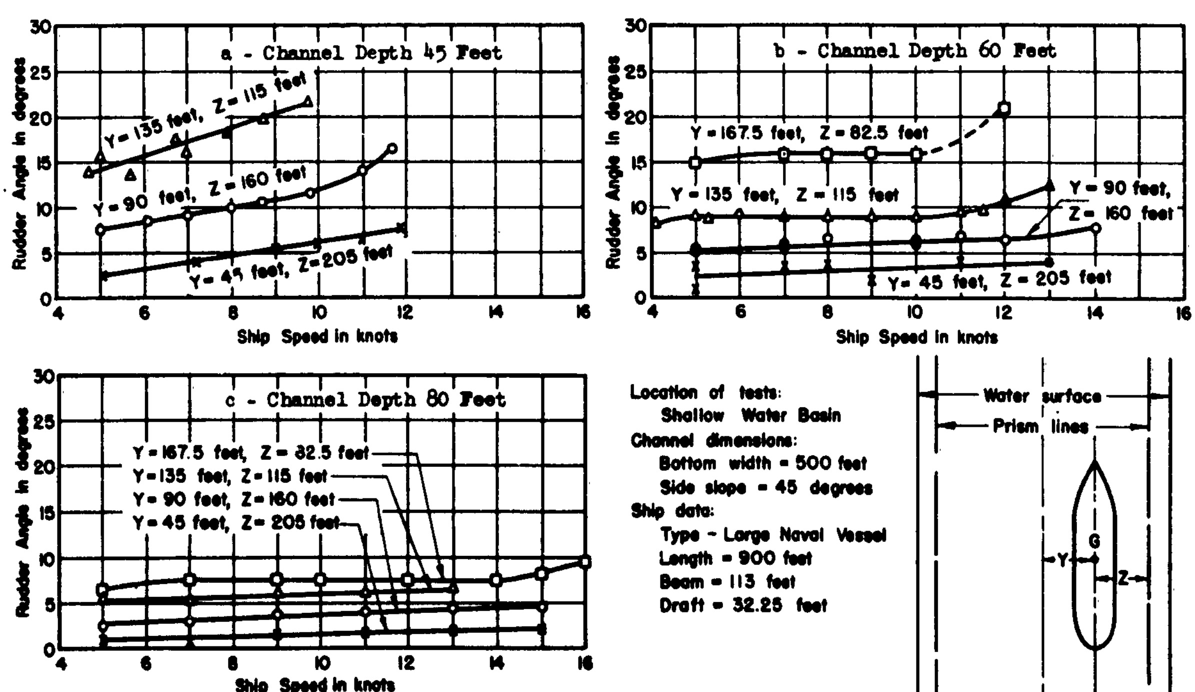


Figure 4.4 - Rudder Angle for Equilibrium as a Function of Ship Speed in a 500-Foot Channel

These rudder angles are required to counteract the yawing moment which exists when self-propelled Model 3769 is released parallel to and at various distances from the centerline of the channel.

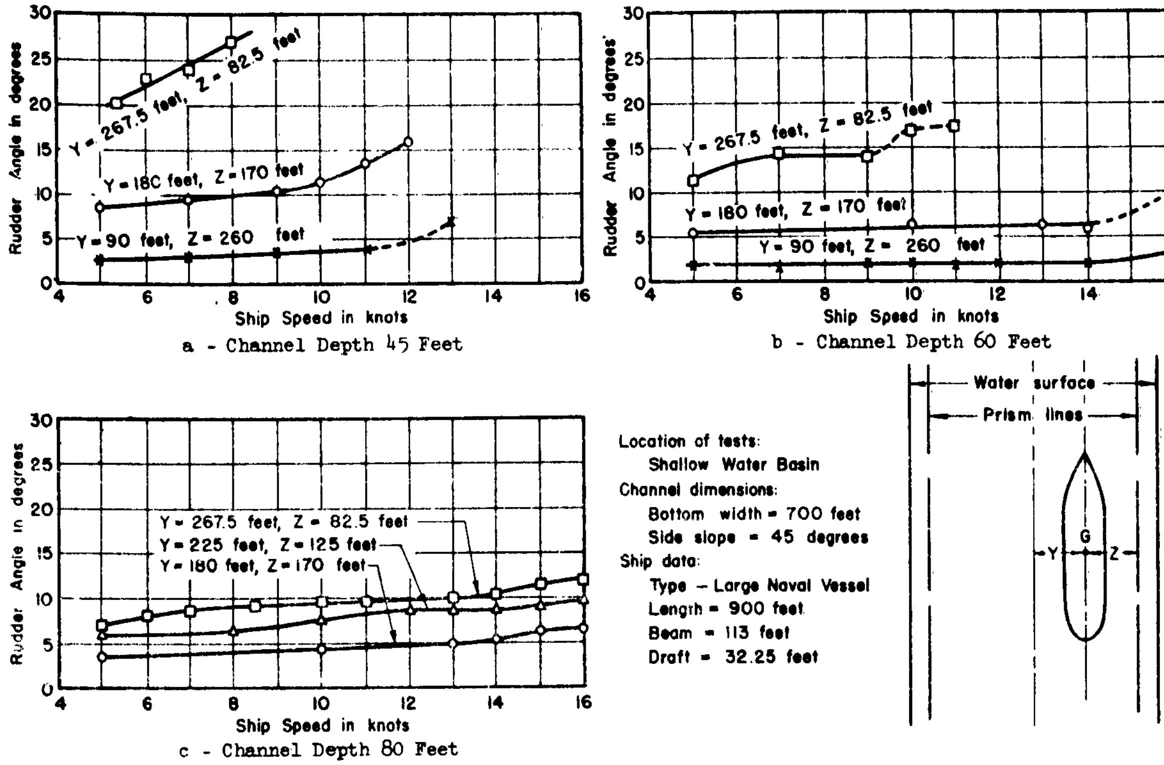


Figure 4.5 - Rudder Angle for Equilibrium as a Function of Ship Speed in a 700-Foot Channel

These rudder angles are required to counteract the yawing moment which exists when self-propelled Model 3769 is released parallel to and at various distances from the centerline of the channel.

and the center of gravity of the ship. Data for three channel widths and for several ship speeds are plotted on each graph for comparison. It will be noted that the slope of these curves, or the rate at which the rudder angle increases, is somewhat less for the wider and deeper channels. Given the ship's speed, the chart can be used to determine the distance between the centerline of the channel and the center of gravity of the ship for which a specified equilibrium rudder angle will be required. For example: In the 500- by 45-foot channel, at a speed of 9 knots, the ship requires 10 degrees of rudder when Y* equals 21 feet; whereas in the 500- by 60-foot channel a 10-degree rudder is not required until Y equals 135 feet. Thus the value of Y for which 10 degrees rudder is required has increased by a factor of approximately 7.

Figure 4.7, which was prepared by this method, presents both and Z curves for 5 and 7 degrees equilibrium rudder for channel depths of 45, 60, and 80 feet. It will be noted that the slopes of the Y curves at the 700-foot channel width are close to the theoretical slope for infinite W_B.

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* For notation see Figure 2.1

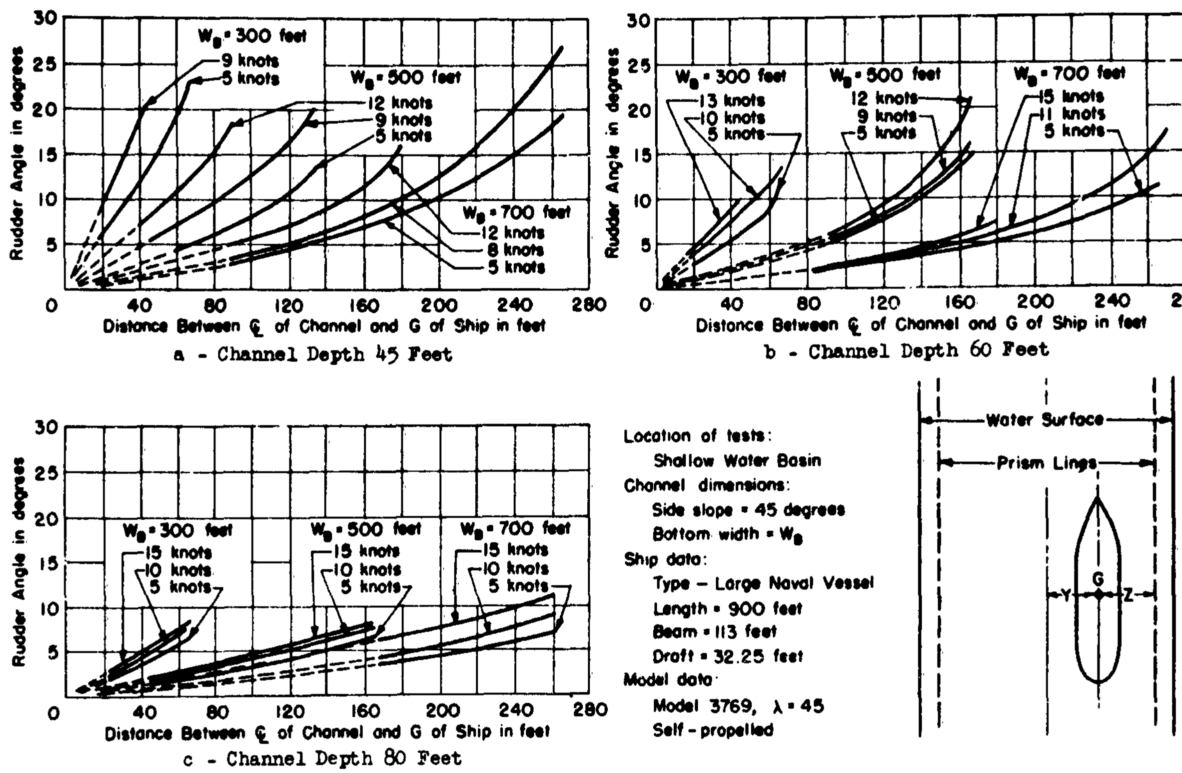
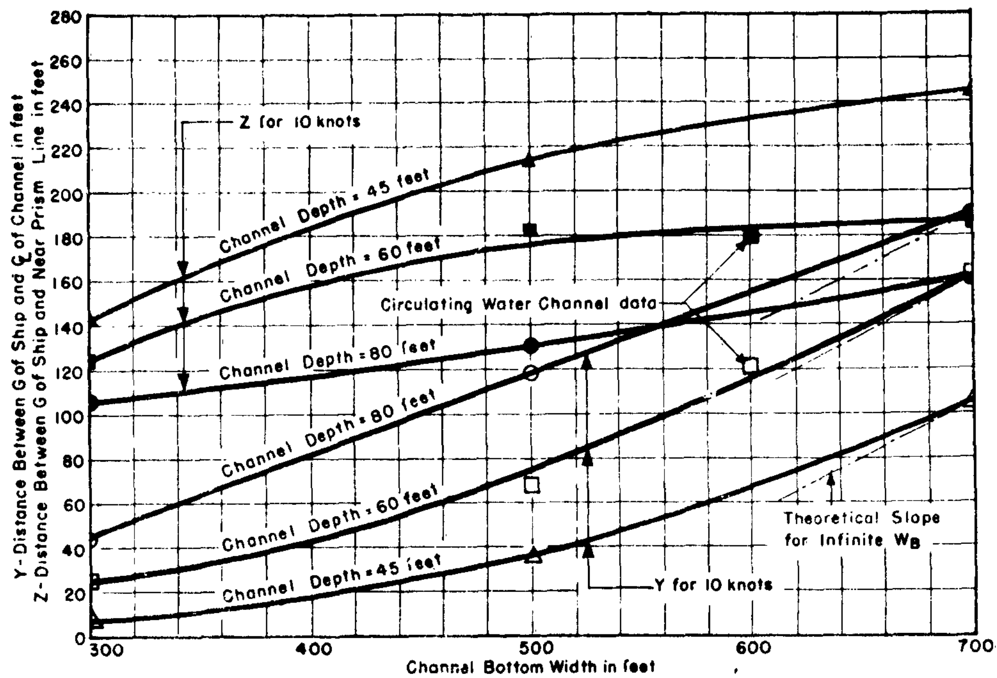


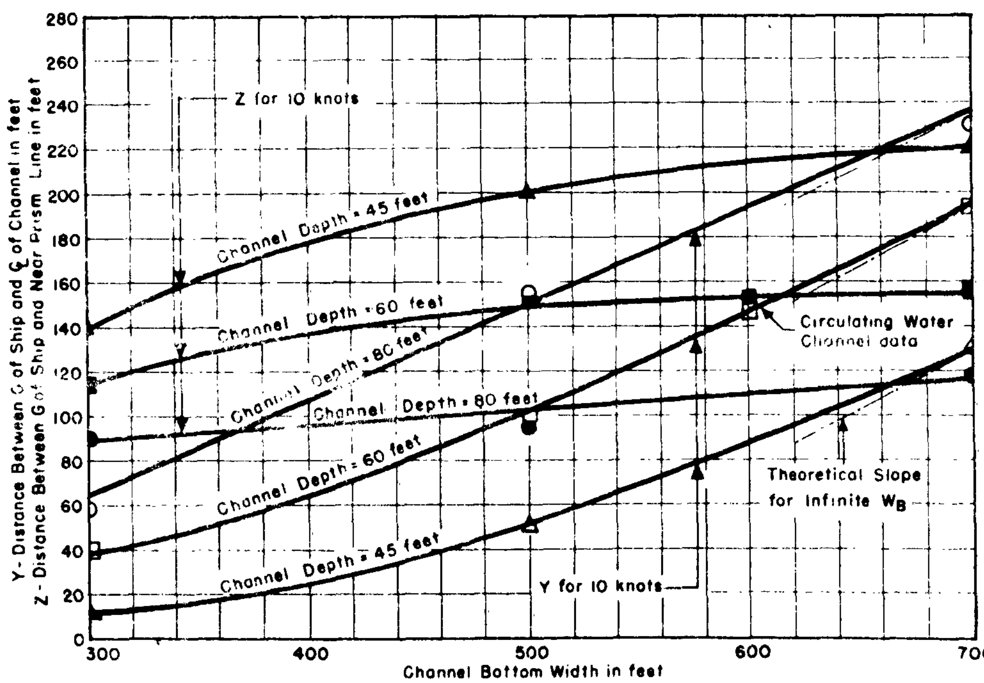
Figure 4.6 - Rudder Angle for Equilibrium as a Function of the Distance between the Centerline of the Channel and the Center of Gravity of the Ship

These rudder angles are required to counteract the yawing moment which exists when self-propelled Model 3769 is released parallel to and at various distances from the centerline of the channel.

The theoretical slope, is 1/2. This is the slope which results if W_B is so large that an increase of 2 feet in W_B causes Y to increase 1 foot. In effect this means that the far bank of the channel is so far away from the vessel that it has no effect on the flow pattern around the vessel, and thus the depth of the channel and the distance from the near wall determine the rudder angle required for equilibrium. It follows that for a given channel depth, Z approaches a constant as W_B increases. It is evident from this graph that this constant varies inversely with the channel depth. The test spots for the 600-by 60-foot channel obtained from equilibrium-rudder-angle tests, which were made in the circulating-water channel, are shown in Figure 4.7. These spots agree very well with the shallow-water-basin data. The curves in this figure provide valuable information as to the effects of bank suction in channels of different cross section.



a - 5-Degree Equilibrium-Rudder Angle



b - 7-Degree Equilibrium-Rudder Angle

Figure 4.7 - Values of *Y* and *Z* for 5-Degree and 7-Degree Equilibrium Rudder Angles as Functions of the Channel Cross Section for Model 3769

Location of tests: Shallow Water Basin
Model data: Model 3769, λ - 45, self-propelled
Channel dimensions: Side slope - 45 degrees

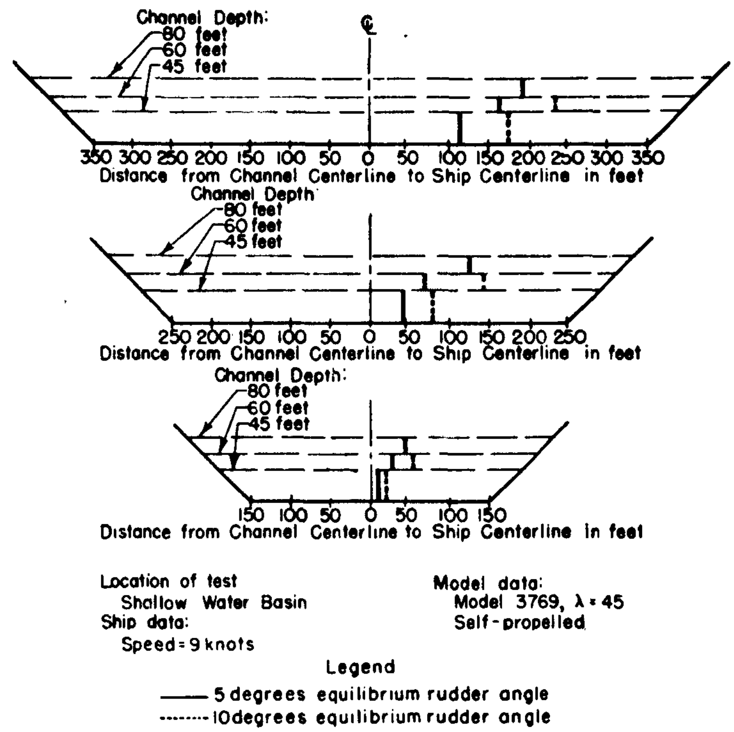
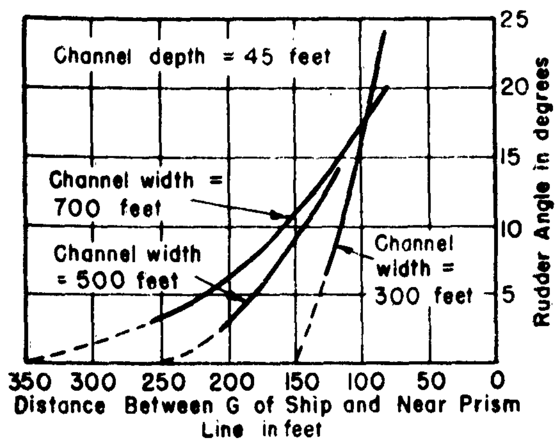


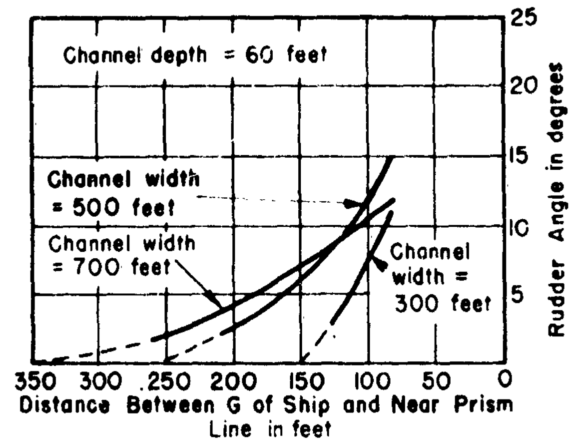
Figure 4.8 - The Effect of Channel Dimensions on the Off-Center Position, at Which a Ship Underway in a Restricted Channel Will Require Specified Equilibrium Rudder Angles

Figure 4.8, which presents somewhat similar information in its proper physical background, further illustrates the significance of this type of data.

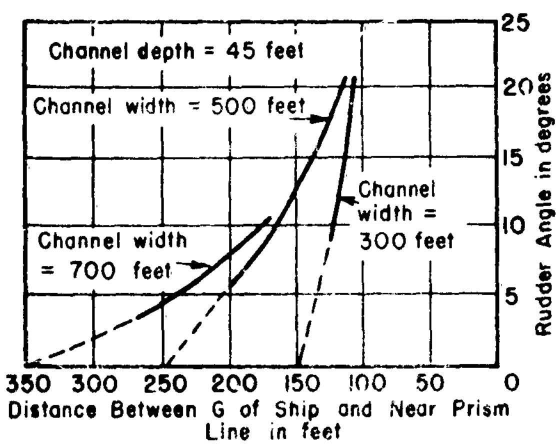
Figure 4.9 is a plot of basic data shown in Figures 4.3, 4.4, and 4.5 in terms of rudder angle against distance between the center of gravity of the ship and the nearer prism line. Separate graphs have been plotted for each channel depth and ship speed. These data are an indication of the approximate variation in the yawing moment caused by interaction for variations in the position of the ship with respect to the near prism line. The curves for equilibrium rudder angle for the three channel widths tend to converge when this ship is approximately 100 feet from the channel prism line. This tendency is explained by the fact that the near-wall effects have become much more important than the far-wall effects. It will be noted, however, that this is less true of the 300-foot channels than of the 500- and 700-foot channels.



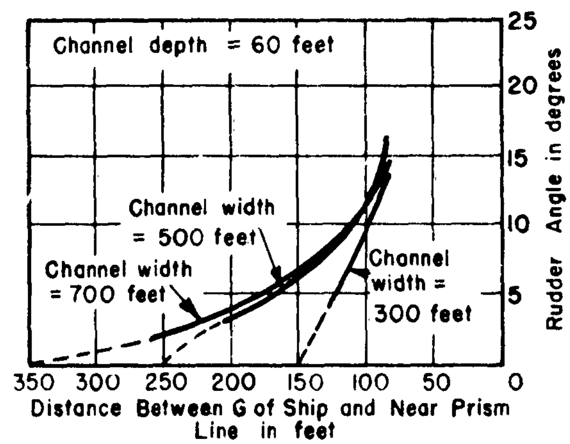
a - Ship Speed 5 Knots



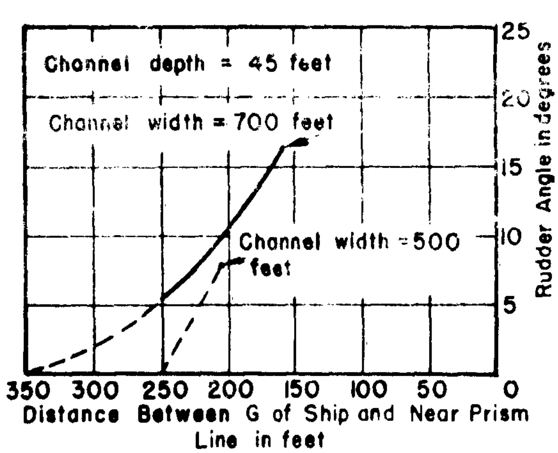
d - Ship Speed 5 Knots



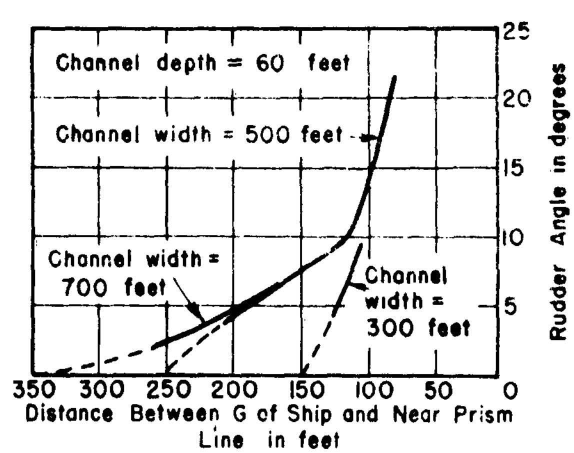
b - Ship Speed 9 Knots



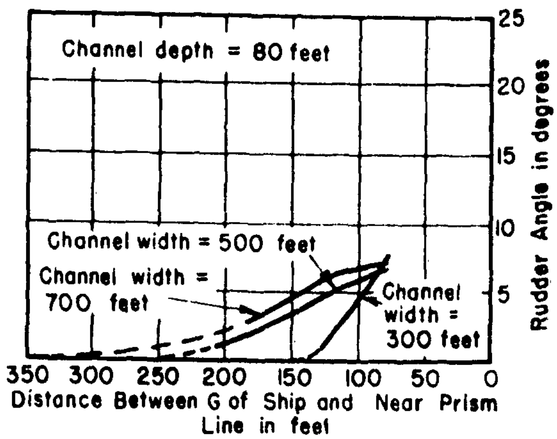
e - Ship Speed 9 Knots



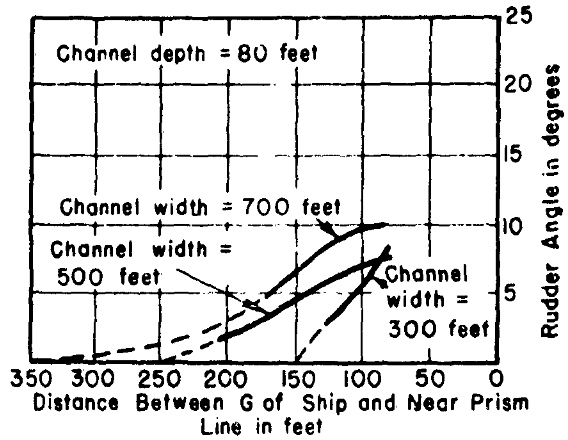
c - Ship Speed 12 Knots



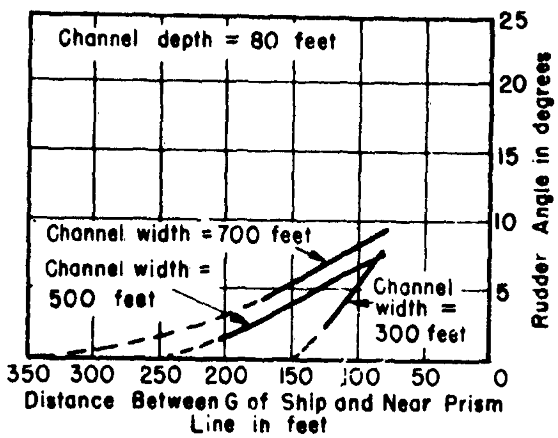
f - Ship Speed 12 Knots



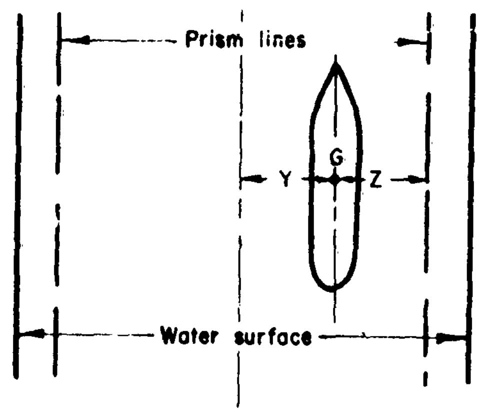
g - Ship Speed 5 Knots



i - Ship Speed 12 Knots



h - Ship Speed 9 Knots

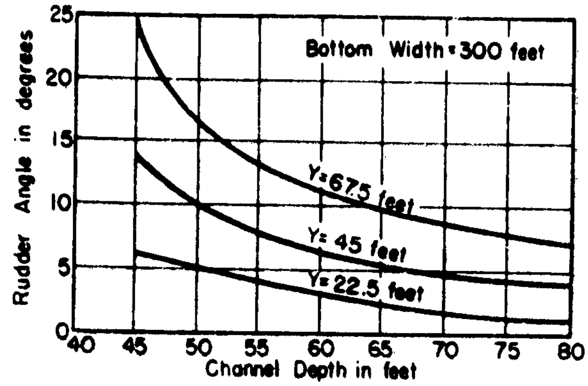


Location of tests:
Shallow Water Basin
Channel dimensions:
Bottom width = 300, 500, 700 feet
Depth = 45, 60, 80 feet
Side slope = 45 degrees

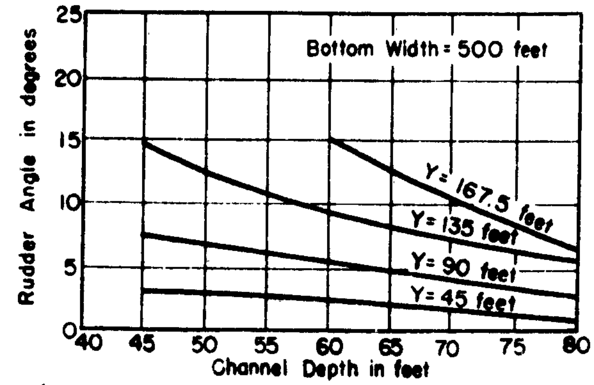
Model data:
Model 3769, λ = 45, self-propelled
Ship data:
Type – Large Naval Vessel
Length = 900 feet
Beam = 113 feet
Draft = 32.25 feet

Figure 4.9 - Rudder Angle for Equilibrium as a Function of the Distance between Center of Gravity of Ship and Near Prism Line of Channel

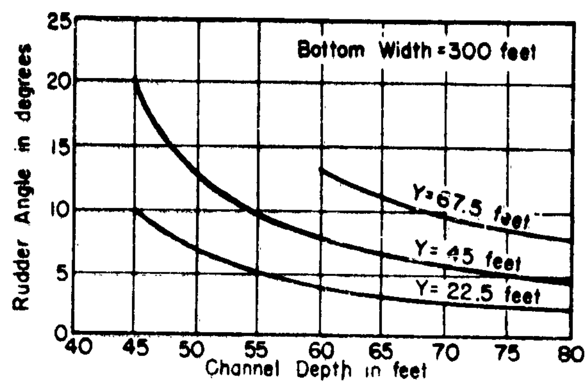
These rudder angles are required to counteract the yawing moment which exists when self-propelled Model 3769 is released parallel to and at various distances from the centerline of the channel.



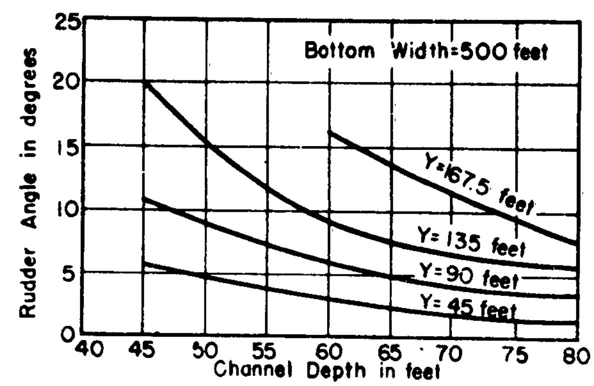
a - Ship Speed 5 Knots



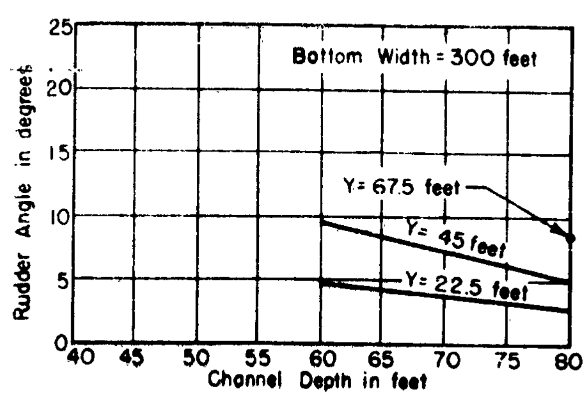
d - Ship Speed 5 Knots



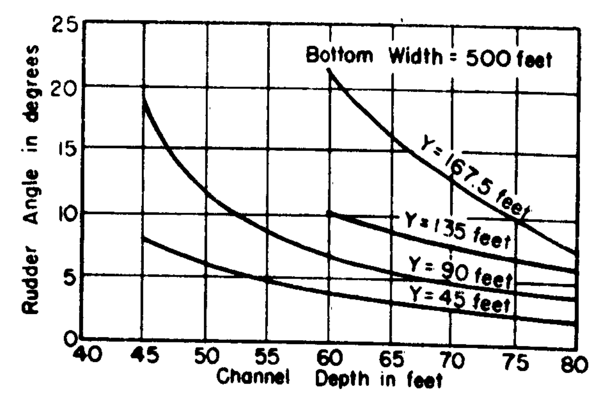
b - Ship Speed 9 Knots



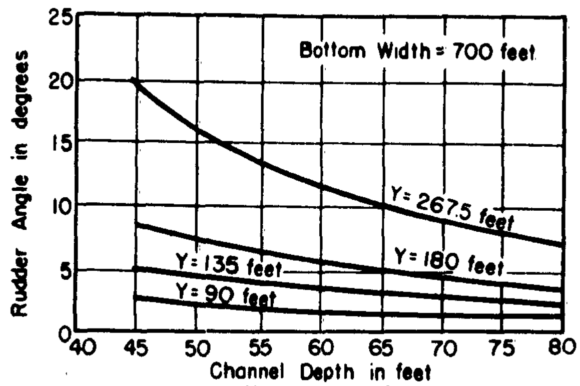
e - Ship Speed 9 Knots



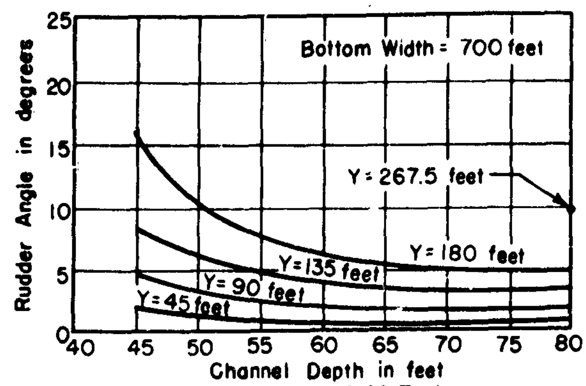
c - Ship Speed 12 Knots



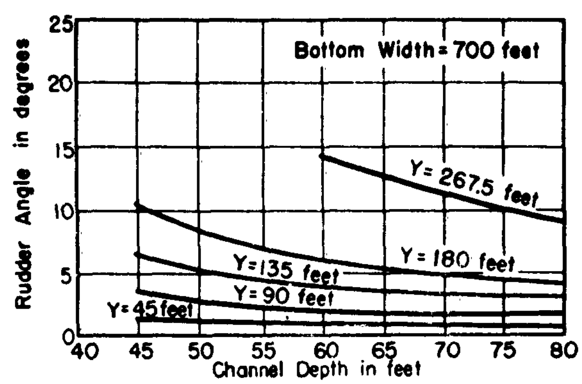
f - Ship Speed 12 Knots



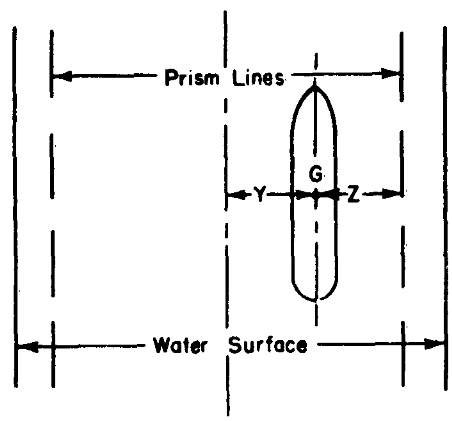
g - Ship Speed 5 Knots



i - Ship Speed 12 Knots



h - Ship Speed 9 Knots



Location of tests:
Shallow Water Basin

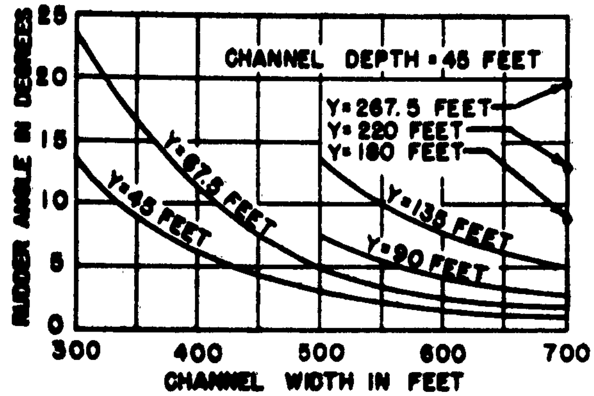
Channel dimensions:
Bottom width = 300, 500, 700 feet
Depth = 45, 60, 80 feet
Side slope = 45 degrees

Model data:
Model 3769, λ = 45, self-propelled

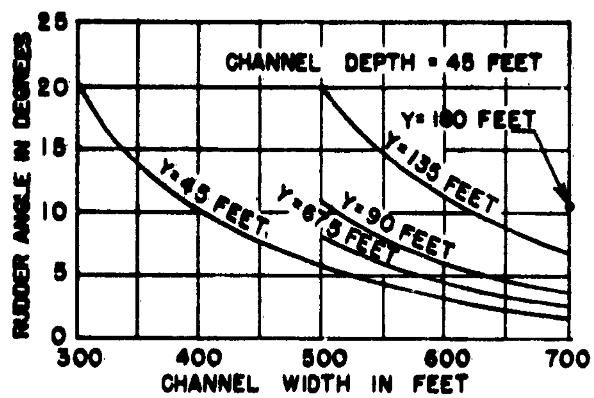
Ship data:
Type = Large Naval Vessel
Length = 900 feet
Beam = 113 feet
Draft = 32.25 feet

Figure 4.10 - Rudder Angle for Equilibrium as a Function of Channel Depth

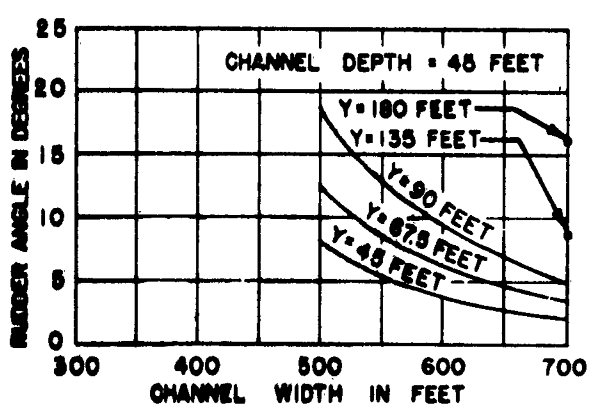
These rudder angles are required to counteract the yawing moment which exists when self-propelled Model 3769 is released parallel to and at various distances from the centerline of the channel.



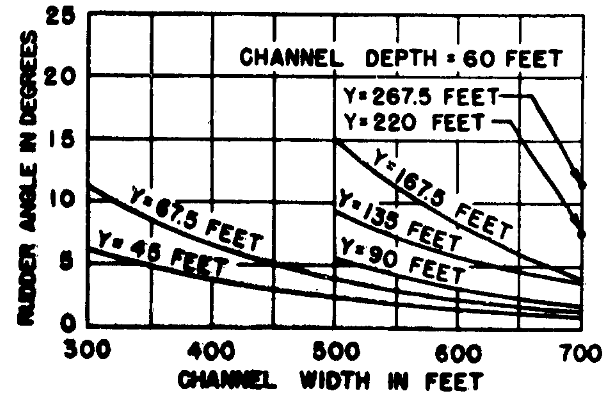
a - Ship Speed 5 Knots



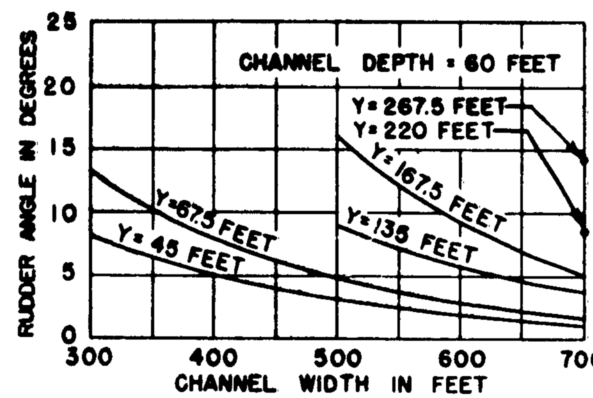
b - Ship Speed 9 Knots



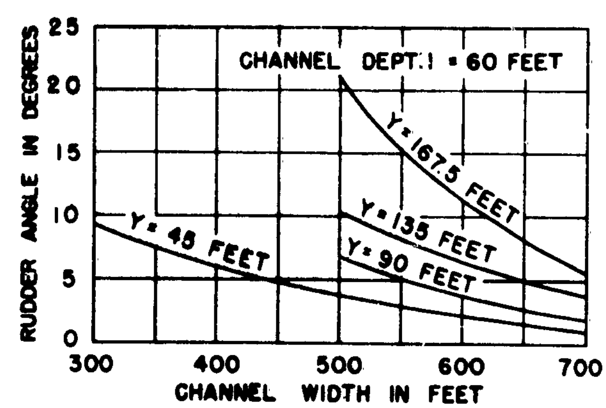
c - Ship Speed 12 Knots



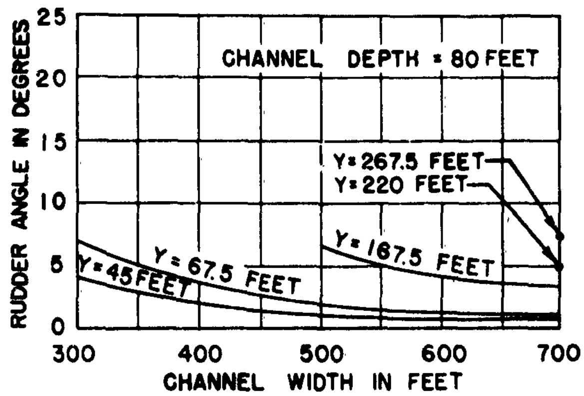
d - Ship Speed 5 Knots



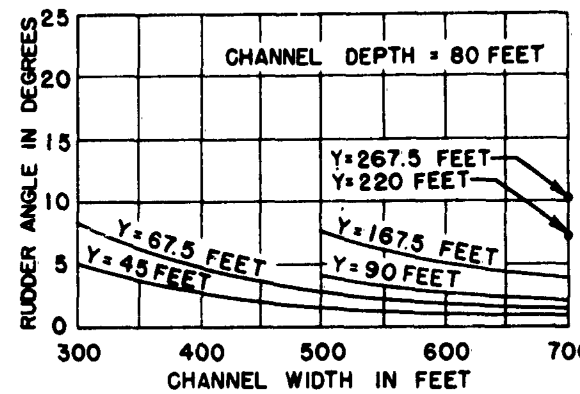
e - Ship Speed 9 Knots



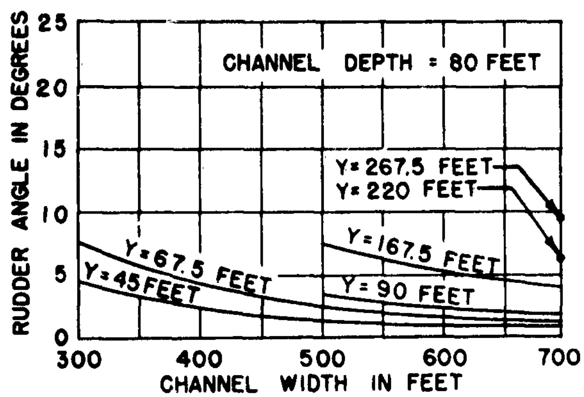
f - Ship Speed 12 Knots



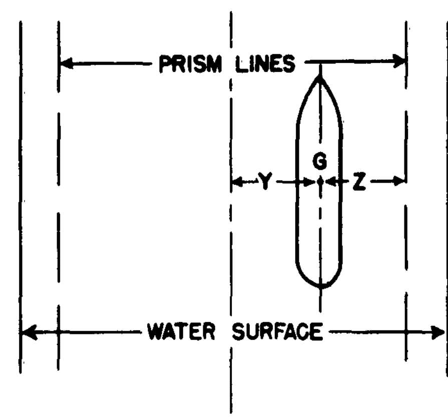
g - Ship Speed 5 Knots



i - Ship Speed 12 Knots



h - Ship Speed 9 Knots



LOCATION OF TESTS:
SHALLOW WATER BASIN

CHANNEL DIMENSIONS:
BOTTOM WIDTH = 300, 500, 700 FEET
DEPTH = 45, 60, 80 FEET
SIDE SLOPE = 45 DEGREES

MODEL DATA:
MODEL 3769, $\lambda = 45$, SELF-PROPELLED

SHIP DATA:
TYPE - LARGE NAVAL VESSEL
LENGTH = 900 FEET
BEAM = 113 FEET
DRAFT = 32.25 FEET

Figure 4.11 - Rudder Angle for Equilibrium as a Function of Channel Width

These rudder angles are required to counteract the yawing moment which exists when self-propelled Model 3769 is released parallel to and at various distances from the centerline of the channel.

In Figure 4.10 the same data have been plotted in the form of rudder angle against channel depth with parameters of ship speed and distance off center in the channel. For selected channel widths and ship speeds the curves furnished are indicative of the effect of channel depth on the yawing moment caused by interaction. It may be noted that for the 300-foot width the yawing moment caused by bank suction at a channel depth of 60 feet is less than half as great, in terms of rudder angles, as it is for the 45-foot depth. An increase in depth from 60 to 80 feet causes a further decrease in the required rudder angle but the additional change is much smaller. For channel widths of 500 and 700 feet there is a similar decrease in the required rudder angle with increasing depth, but the magnitude of this decrease is a function of ship speed and the distance between the centerline of the channel and the center of gravity of the ship.

In Figure 4.11 the same data have been plotted as a function of channel-bottom width. Separate graphs have been plotted for various ship speeds and channel depths. On some of the graphs the data are not complete for the 300-foot width. This is a result of excessive change of level of the ship or of the fact that some of the curves are for off-center positions which are beyond the physical limits of the 300-foot channel. This graph emphasizes the importance of channel width. For example: It may be noted that, for equal values of Y, the yawing moment, in terms of rudder angle, in a channel 500 feet by 45 feet is approximately 1/4 as much as it is in a channel 300 feet by 45 feet. In channels 500 feet by 60 feet and 300 feet by 60 feet the corresponding ratio is approximately 1/3.

EQUILIBRIUM-RUDDER-ANGLE TESTS IN CHANNEL CURRENTS

In addition to the tests just discussed, a limited number of observational tests were made to determine the effect of ahead and following currents on the equilibrium rudder angle and to determine a basis for comparing test results from the shallow water basin and the circulating-water channel.* The results of these tests are presented in Figures 4.12 and 4.13. The circulating-water-channel equilibrium-rudder data presented in Figure 4.12 were obtained by holding the model stationary at various transverse positions in a stream of water. The test method is described more fully in the discussion of "Force-Measurement Tests."

In Figure 4.12 a single curve has been drawn through all test spots obtained by testing the tanker, Models 3859 and 4018, in simulated still

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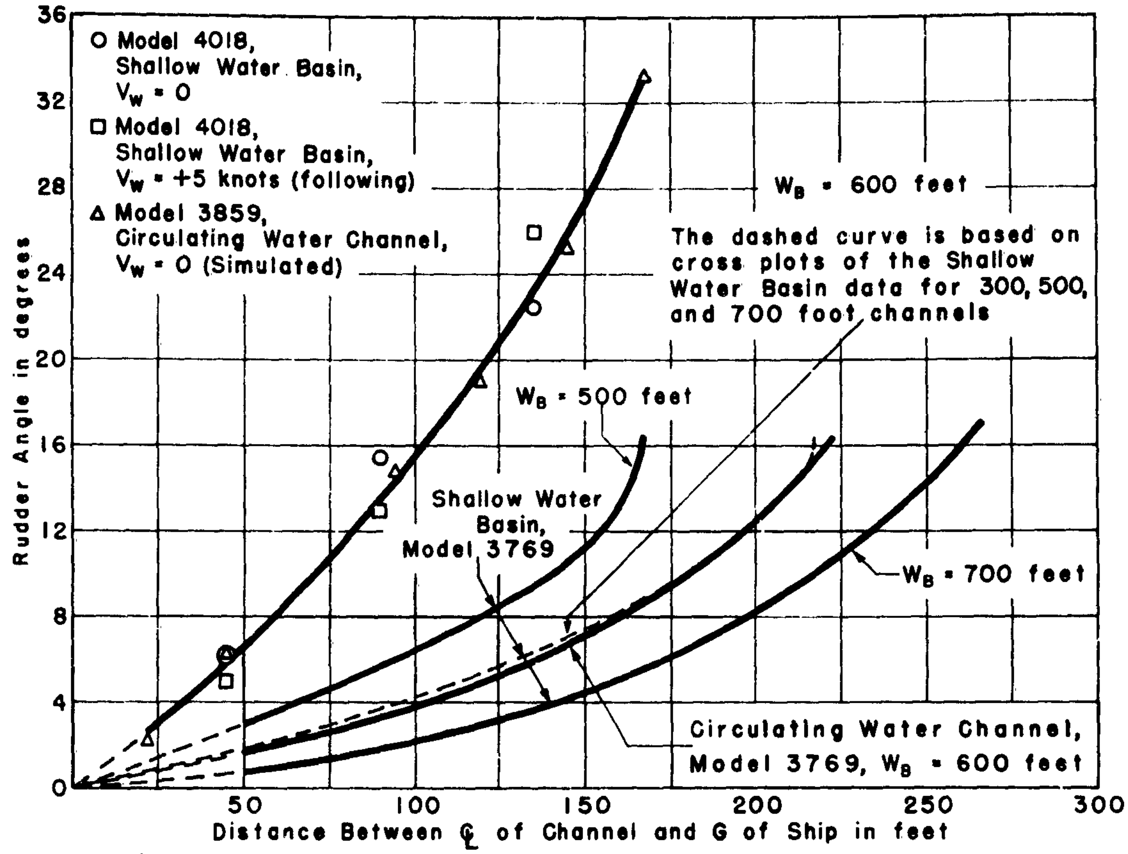
* The method of producing the channel currents and the calibration of these currents is discussed in Section 3.



	MODEL 3769	MODEL 3859	MODEL 4018	MODEL 3769
Location of tests:	Circulating Water Channel	Circulating Water Channel	Shallow Water Basin	Shallow Water Basin
Channel dimensions:				
Width =	600 feet	500 feet	500 feet	500, 700 feet
Depth =	60 feet	60 feet	60 feet	60 feet
Side Slope	Vertical	Vertical	45 degrees	45 degrees

Figure 4.12 - Comparison between Equilibrium Rudder Angles as Obtained from Tests in Circulating-Water Channel and Shallow Water Basin

Ship's speed with respect to water - 10 knots. Reduction 5.

water in the circulating-water channel and in still water and following currents in the shallow water basin. This indicates, first, that the two facilities produce very similar test results and, second, that the interaction between the ship and the channel boundaries, as measured by the equilibrium rudder angle, is apparently the same for both still water and following currents. In the same figure the curves for Model 3769, as tested in both facilities, for the still-water condition, give further support to the first conclusion.

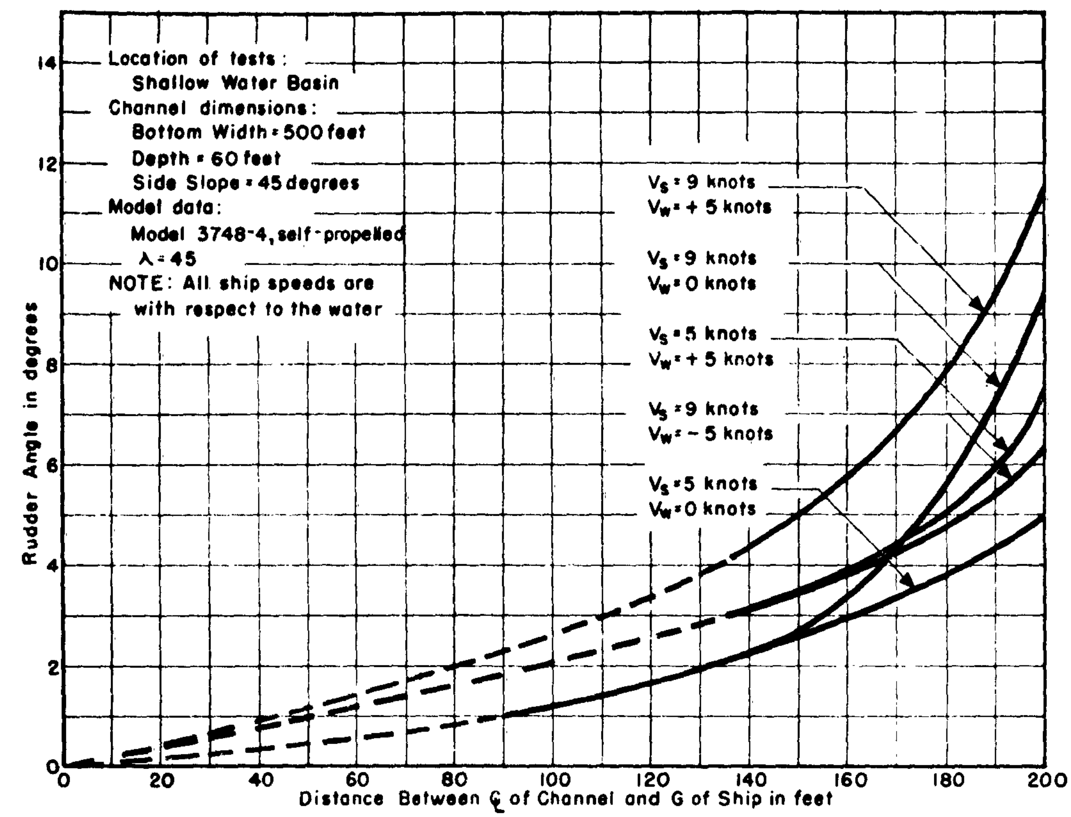


Figure 4.13 - Rudder Angles for Equilibrium as a Function of the Distance between the Centerline of the Channel and the Center of Gravity of the Ship for Model 3748-4

These rudder angles are required to counteract the yawing moment which develops when the ship is nearer one wall than to the other.

It should be noted, however, that the conclusion with respect to the similarity of test results in the two facilities is based on two assumptions; first that the differences in test results due to vertical side walls and side walls at 1-to-1 slope are not serious, and second that the differences in test results due to scale effect, resulting from the differences in the linear scale of Models 3859 and 4018 are negligible.

In respect to the first assumption it is realized that a more complete test program probably would indicate slight systematic differences in equilibrium rudder angle with variations in side slope. The difference in scale between Models 3859 and 4018 is not great and besides, the reliability of the Froude relationship is well established.

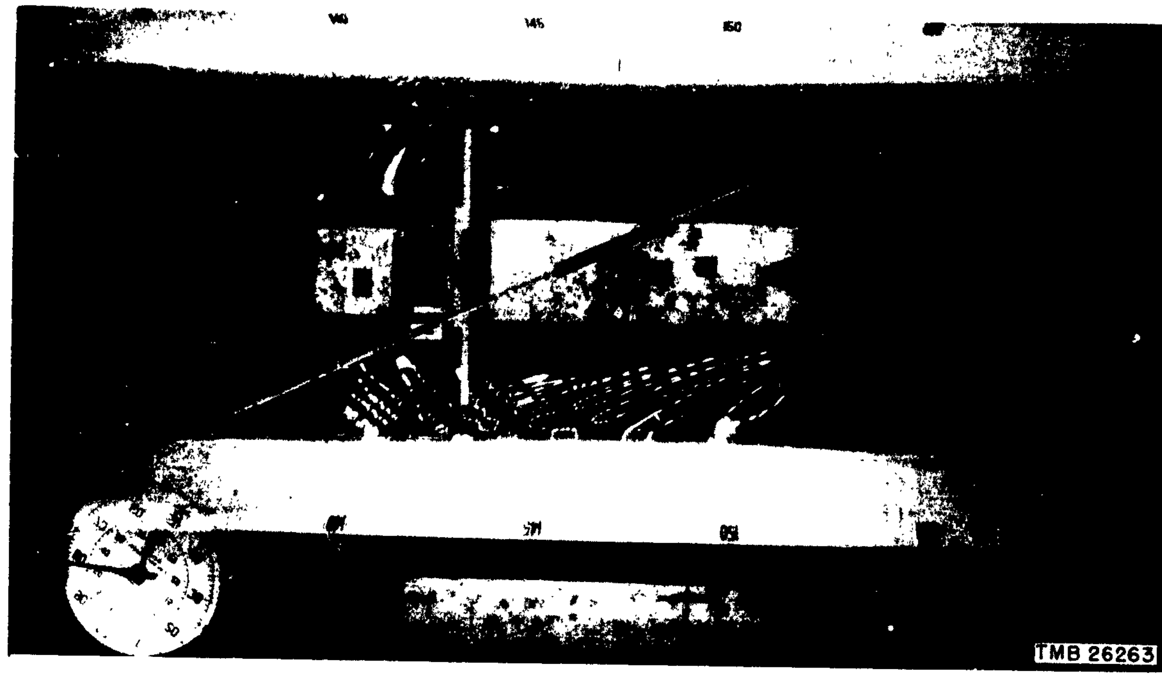


Figure 4.14 - One Frame of a Photographic Record of a Maneuvering Test

This photograph is a print of one frame of the photographic record taken by an overhead camera during the maneuvering tests. The camera was attached to a boom extending forward from the carriage which followed the model. The camera speed was approximately one frame per second. Each time it photographed the model it also photographed the dial of a clock. The time record was used in conjunction with the numbers along the channel walls to compute the speed of the model. An indicator mounted on the stern of the model gave a continuous indication of the rudder angle. In this particular test a model of a large naval vessel was being steered through a channel which represented a full-scale channel 80 feet deep and 300 feet wide at the bottom. The model speed was equivalent to 12 knots full scale.

Figure 4.13, based on a limited amount of data with a considerable scatter of test spots, apparently indicates some variation in the equilibrium rudder angle, for a Liberty ship, tested in still and in moving water. However, considering the circumstances and considering the fact that the maximum differences between the curves for practical operating conditions is only about 3 degrees and also because of the contrary evidence presented in Figure 4.12, it is believed that the equilibrium rudder angle is not materially affected by changes from still-water to moving-water conditions.

Figure 4.12 indicates that the equilibrium rudder angle for Model 4018 is more than twice that required for Model 3769 when both are tested at the same off-center position in a 500- by 60-foot channel at a speed of 10 knots. The fact that Model 4018 represents a twin-screw ship with a single rudder located between the screws, whereas Model 3769 represents a four-screw ship with twin rudders located almost directly behind the inner screws, probably accounts for a considerable part of the difference, although the differences in hull design and the differences in rudder area are certainly contributing factors.

MANEUVERING TESTS IN ONE-WAY TRAFFIC IN A STRAIGHT CHANNEL

The maneuvering tests are the second type of observational tests. The purpose of these tests was to obtain further information as to the effect of channel dimensions on the relative controllability of selected ships under varied conditions of operation. This information was obtained by direct observation of the tests and by analysis of photographic records. As stated previously the test setup was similar to that used in the equilibrium-rudder-angle tests.

In these tests, Model 3769, a self-propelled model, was maneuvered by remote control. Throughout the tests an effort was made to duplicate full-scale operating conditions as closely as possible.

Test Procedure

The Panama Canal pilots participated in the tests by observing and commenting on the performance of the ship models, by piloting the ship models, and by their expert advice on all phases relating to their work.

The model was attached to the towing carriage by two pins which held the longitudinal axis of the model parallel to the centerline of the model canal channel. The towing carriage was then accelerated to the desired speed and at the same time the propellers of the model were brought up to the RPM which would propel the model at the desired speed. The model was then released from all contacts with the towing carriage, with the exception of a light flexible cable which supplied power to the propeller and rudder motors. By closing a double-throw switch on the towing carriage the rudder on the model could be moved to any desired setting. This setting could be altered as frequently as desired throughout the run. A large indicator was mounted on the stern of the model, which showed the instantaneous rudder angle at all times. In addition, the rudder angle was indicated by a Selsyn system on the model-control panel of the towing carriage. A light source on the bow of the model cast a two-inch beam of light along an extension of the centerline of the model to a horizontal scale at the end of the channel. By observing the movement of the beam the "pilot" could note instantly changes in the heading of the model. During the run the pilot attempted to maintain the model on a course parallel to or on the centerline of the channel. The quartermaster, upon orders from the pilot manipulated the controls which actuated the rudder. Soon after the model was released from the carriage it was photographed at intervals of about one second by an overhead camera. The camera provided a record of the path of the model, its speed, and the rudder angles used.

During this phase of the tests it was attempted to maintain a course parallel to and at specified distances to one side of the centerline, as well as directly on the centerline of the channel. This differs somewhat from actual full-scale operating conditions in that the pilots usually attempt to stay on the centerline of a canal except when meeting another ship. However, it was thought that the off-center runs might provide additional information. Maneuvering runs were made at about 3 transverse positions in channels with bottom widths of 300 and 500 feet and with depths of 45, 60, and 80 feet. Some maneuvering runs were also made in the 700- by 45-foot channel. It was attempted to conduct separate runs for various speeds ranging from 5 to 15 knots but in numerous instances it was not possible to reach the top speeds because of excessive change of level of the model or other hazardous operating conditions.

Test Results

During this phase of the tests it was noted that for a specified width the depth of water was very important with regard to ease of handling. At the 60- and 80-foot depths it was much easier to control the model and to maintain a course parallel to the bank at greater distances off center than was possible at the 45-foot depth. This was especially noticeable at channel widths of 300 and 500 feet. The width of the channel was also important in the controllability of the model in that it was possible to maintain a desired course farther off center with the greater channel widths.

It was noted that during some of the off-center runs the model developed a sheer which could not be overcome by the rudder, with the result that the model struck one of the banks. In some instances the model was being maneuvered on a course parallel to the near bank and carrying 10 to 15 degrees rudder angle to counteract the bank suction. If the bow was allowed to swing a few degrees too far away from the near bank there was a sudden drop in the water surface between the stern and the near bank. At about the same time the bow would start to swing rapidly away from the near bank. Even if the rudder was put hard over it could not overcome the swing until the model had advanced across the centerline of the channel and the stern was well clear of the bank. This sometimes resulted in grounding on one of the banks either as a result of the original sheer or of overcorrection in an attempt to control the sheer. Quite frequently during off-center runs it was noticed that if the longitudinal centerline of the model was maintained exactly parallel to the banks, by using a suitable rudder angle, the model would drift toward the near bank. As it moved toward the wall the yawing moment became larger and it was necessary to increase the rudder angle in order to maintain the longitudinal centerline of the model parallel to the bank. Eventually the model would ground unless the yawing moment became so large that a sheer developed.

As stated in the appendix to Section 1, the photographic records for the straight-channel one-way-traffic maneuvering runs and the pertinent test schedules constitute Addendum 3 and 4 to this report. Figure 4.14 is a sample print of one frame taken from the photographic record of a maneuvering run. The symbol I-A is used to identify all one-way-traffic maneuvering runs. The run number, such as 90, is given next and this is followed by 3769, the model number. The complete test conditions can be determined by reference to the test schedule.

These films were analyzed to learn more about the relative controllability of a ship in channels of different cross sections. Figure 4.15 is a sample of data taken from the complete film records for three maneuvering runs. The paths of the bow and stern have been plotted and the rudder angles used during the course of the run have been indicated. Work charts similar to Figure 4.15 were prepared for about 168 maneuvering runs.* None of the film records from the 700- by 45-foot channel were plotted. Some of the film for the 300- and 500-foot channels could not be read and other film records were not analyzed because it was believed that the additional information to be gained would not justify the considerable time and cost involved. However, all readable film is included in the addenda.

The natural variation in the character and quality of runs made under the same test condition is such that it was not feasible to choose and present typical runs in Figure 4.15. However, significant trends which apply to this ship are evident from an examination of the figure.

The rudder angles used when the ship is underway along the channel centerline are not large even in the 300- by 45-foot channel. In attempting to maintain a course parallel to but to one side of the channel centerline, the rudder angles used are larger and they tend to vary about the equilibrium rudder angle for that position rather than about the midship position as occurs in the centerline runs. Also, in this example, the rudder angles used in the 500- by 60-foot channel are in general less than in the 300- by

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* These work charts, which were prepared in pencil, are on file at the Taylor Model Basin.

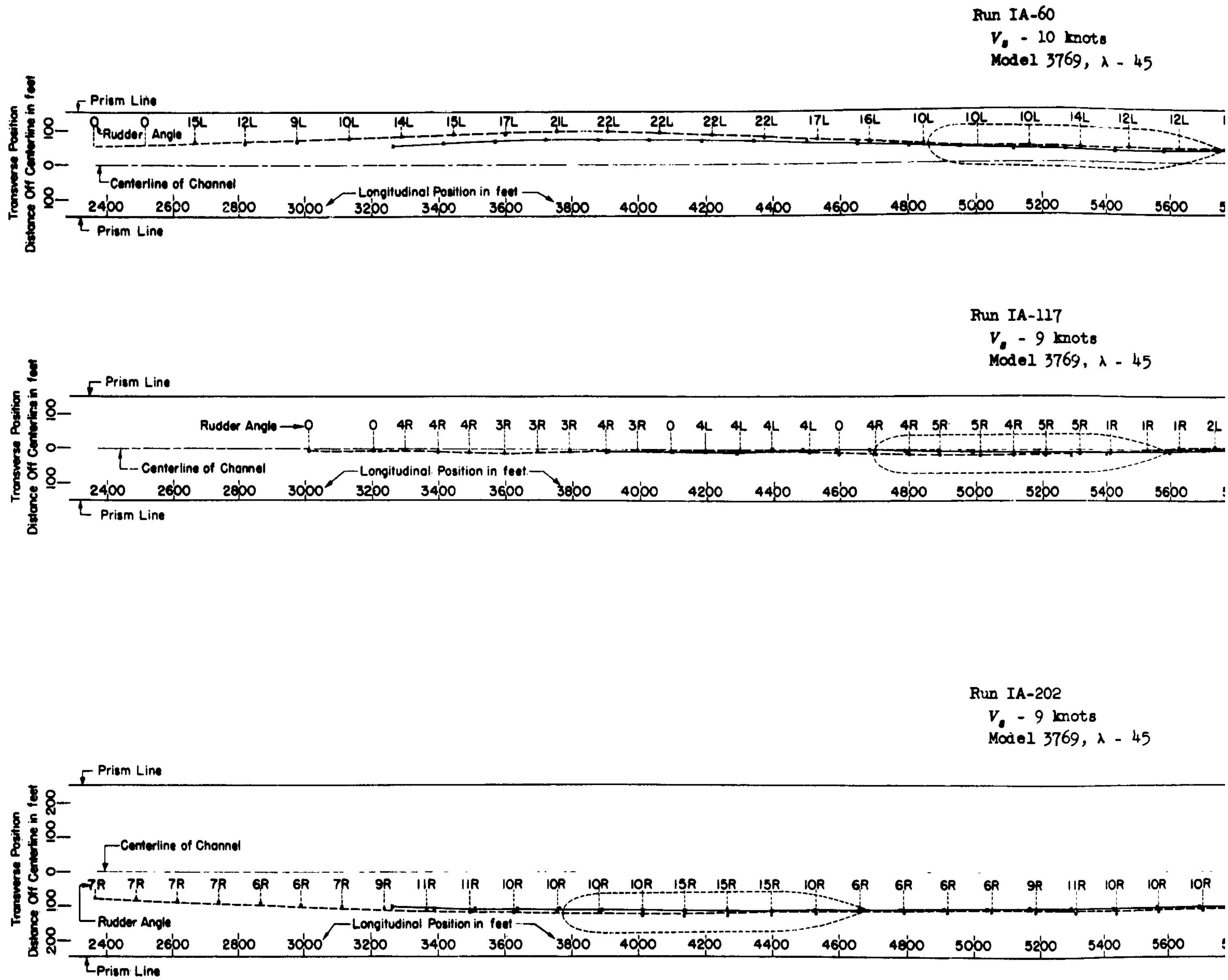


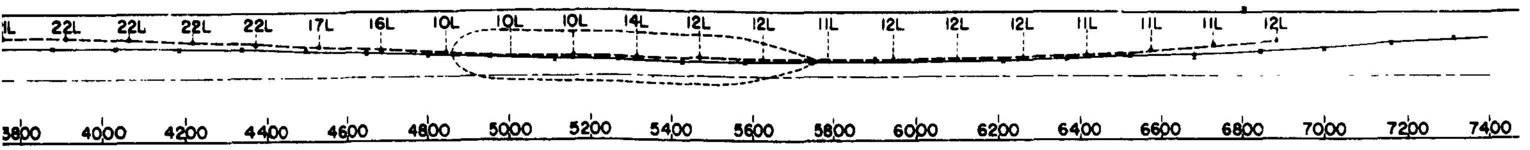
Figure 4.15 - Sample Plots of Maneuvering Runs

The plots represent the path of a self-propelled model which was steered by remote control through a restricted channel.

The data are plotted to represent the equivalent path of the bow and the stern of a full-scale ship.

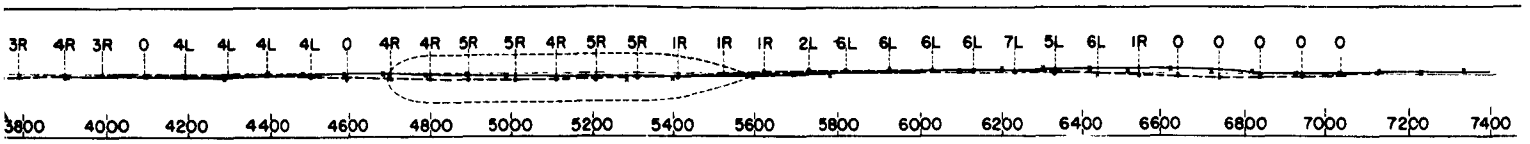
Run IA-60
V_s - 10 knots
Model 3769, λ - 45

Channel-bottom width - 300 feet
Channel depth - 60 feet
Desired course - parallel to and 45 feet to the left of the channel centerline.



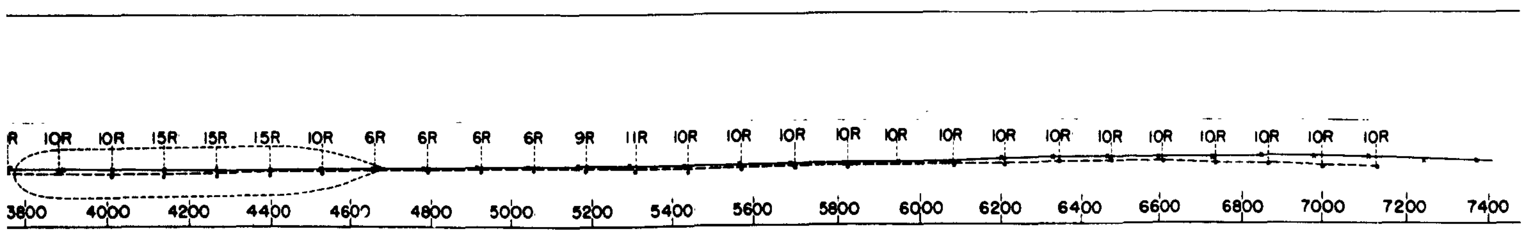
Run IA-117
V_s - 9 knots
Model 3769, λ - 45

Channel-bottom width - 300 feet
Channel depth - 45 feet
Desired course - channel centerline



Run IA-202
V_s - 9 knots
Model 3769, λ - 45

Channel-bottom width - 500 feet
Channel depth - 60 feet
Desired course - parallel to and 90 feet to the right of the channel centerline.



Maneuvering Runs

ich was steered by remote control through a

the bow and the stern of a full-scale ship.

60-foot channel even though the *Y* distance is nearly twice as large in the 500-foot channel. In comparison with the other runs presented in Figure 4.15 Run IA-60 indicates considerable difficulty in controlling the model. Difficulties such as this appear to occur more frequently in the smaller channels than in the larger channels.

Figures 4.16, 4.17, 4.18, 4.19 and 4.20 present data obtained from the work charts. Figures 4.16 and 4.17 are scatter diagrams which show the range and scatter of extreme rudder angles used in the maneuvering runs in the various channel cross sections at various off-center positions. These diagrams indicate that the extreme rudder angles used vary about the equilibrium rudder angle and that the range of rudder angles used is less for the wider and deeper channels. Also, the range of rudder angles used tends to increase as the ship's distance from the channel centerline increases. It is realized that the human element plays a part in the range and scatter of rudder angles used. For example, some pilots prefer to use large rudder angles for a short period of time whereas other pilots prefer to use smaller rudder angles for longer periods of time. In this connection it should be stated that three or four Panama Canal pilots were usually on duty at the same time. Ordinarily each pilot called the orders to the quartermaster for one or more runs for each test condition so as to minimize effects due to the human element. The remote-control rudder system used in the straight-channel one-way traffic maneuvering tests did not always permit exact setting of the rudder in response to the pilots' orders and as a result the range of angles used may in some instances be several degrees greater than it would otherwise have been. The limited number of runs plotted for each test condition and the limitations previously discussed do not appear to warrant any specific conclusions beyond the general trends already mentioned.

If the total of all rudder angles used for a given run are averaged arithmetically and plotted against the average distance between the centerline of the channel and the center of gravity of the ship during the run, the resultant curves closely approximate the equilibrium-rudder-angle curves which were obtained in the first part of the observational tests. In Figure 4.18 the two sets of curves have been plotted for various channel dimensions for comparison. The test points for the maneuvering runs are shown on the graphs.

Figures 4.16, 4.17 and 4.18 are important, first because they substantiate the fact that the equilibrium rudder angles derived in the first part of the tests are an indication of the yawing moment caused by bank suction *under conditions similar to normal operations*; and second, because they clearly show that, in terms of rudder angles actually used, the ship is

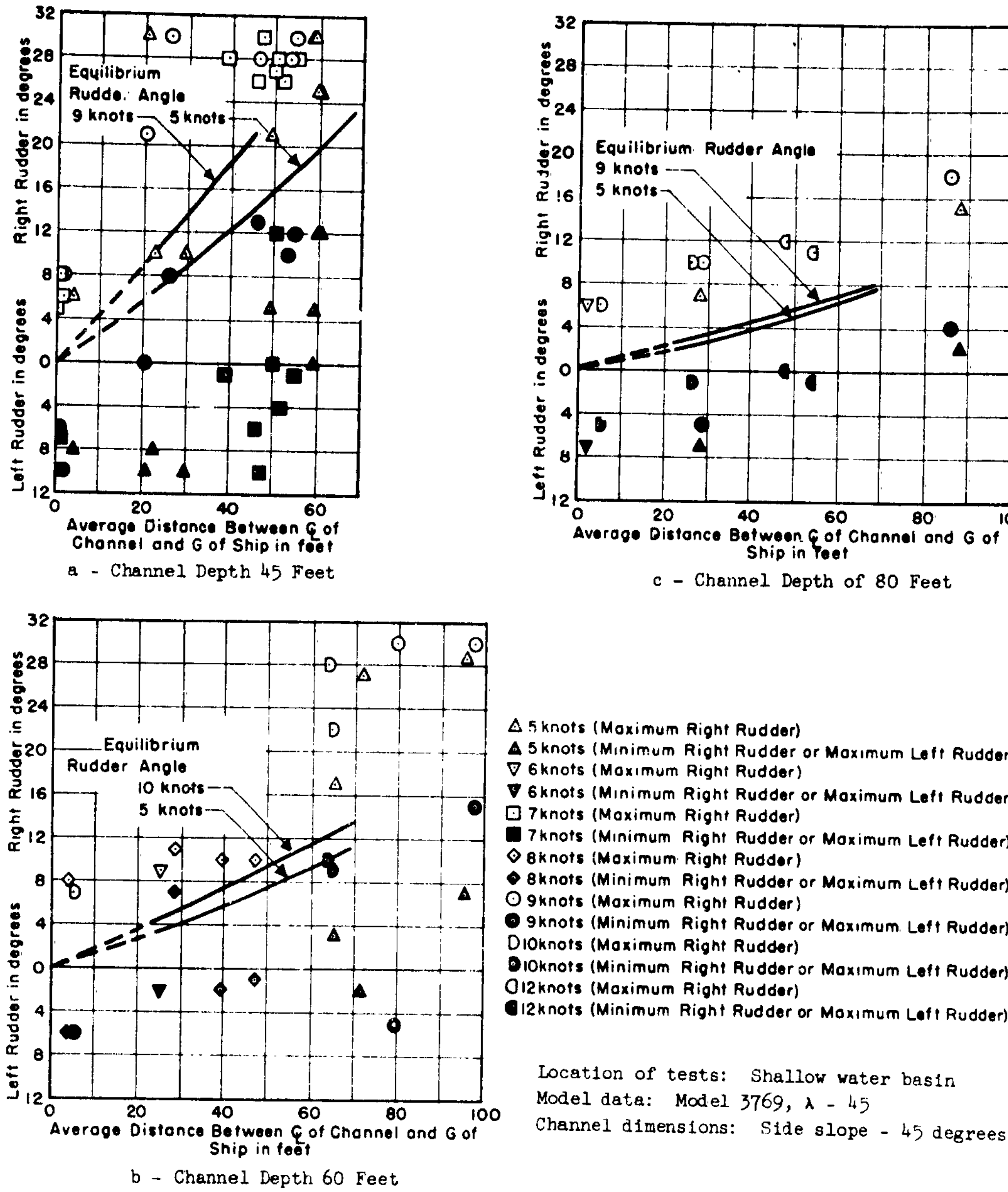


Figure 4.16 - Range and Scatter of Extreme Rudder Angles Used in Maneuvering Runs in 300-Foot Channels

The equilibrium-rudder-angle curves were plotted to show how the extreme rudder angles used in the maneuvering runs tend to range about the equilibrium rudder angle.

considerably more controllable in the wider and deeper channels even though maneuvering further from the channel centerline.

Figures 4.19 and 4.20 are scatter graphs which show the maximum width of path of Model 3769 at various off-center positions in the 300- and the 500-foot channels for speeds below 10 knots.* The maximum width of path

* Similar graphs for speeds above 10 knots are presented in Figures 4.35 and 4.36 of the Appendix.

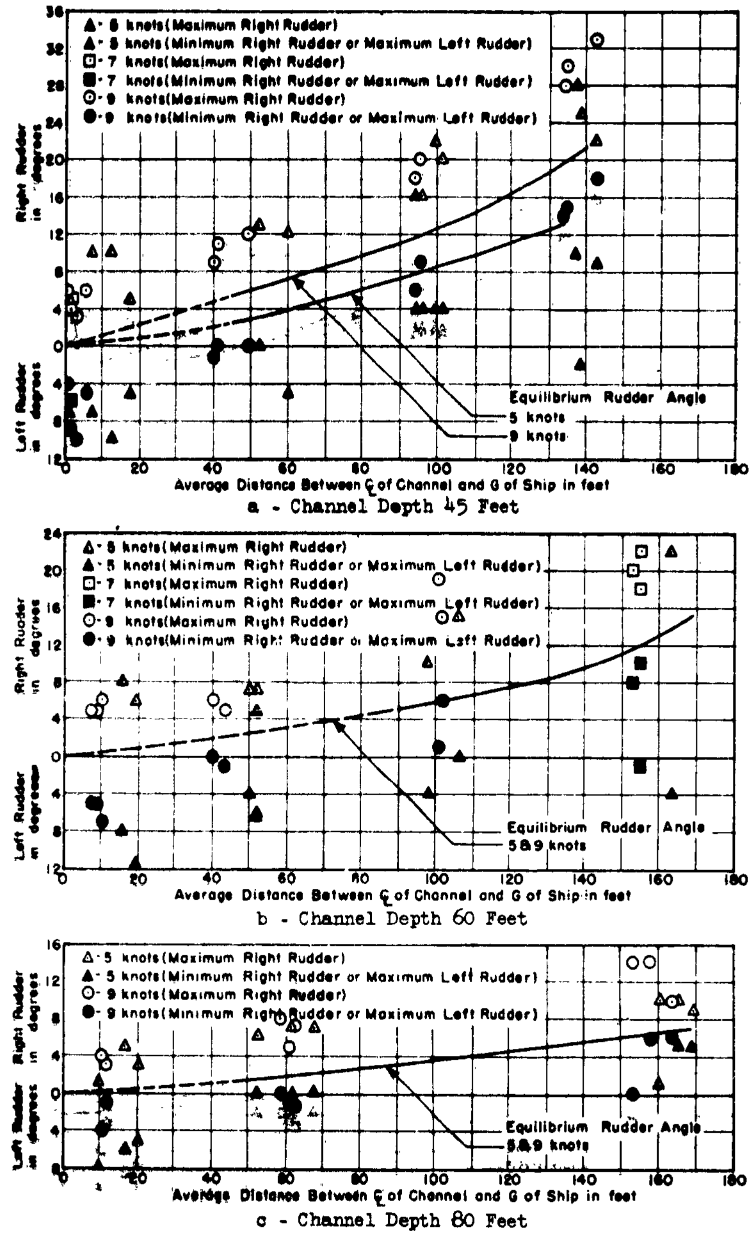
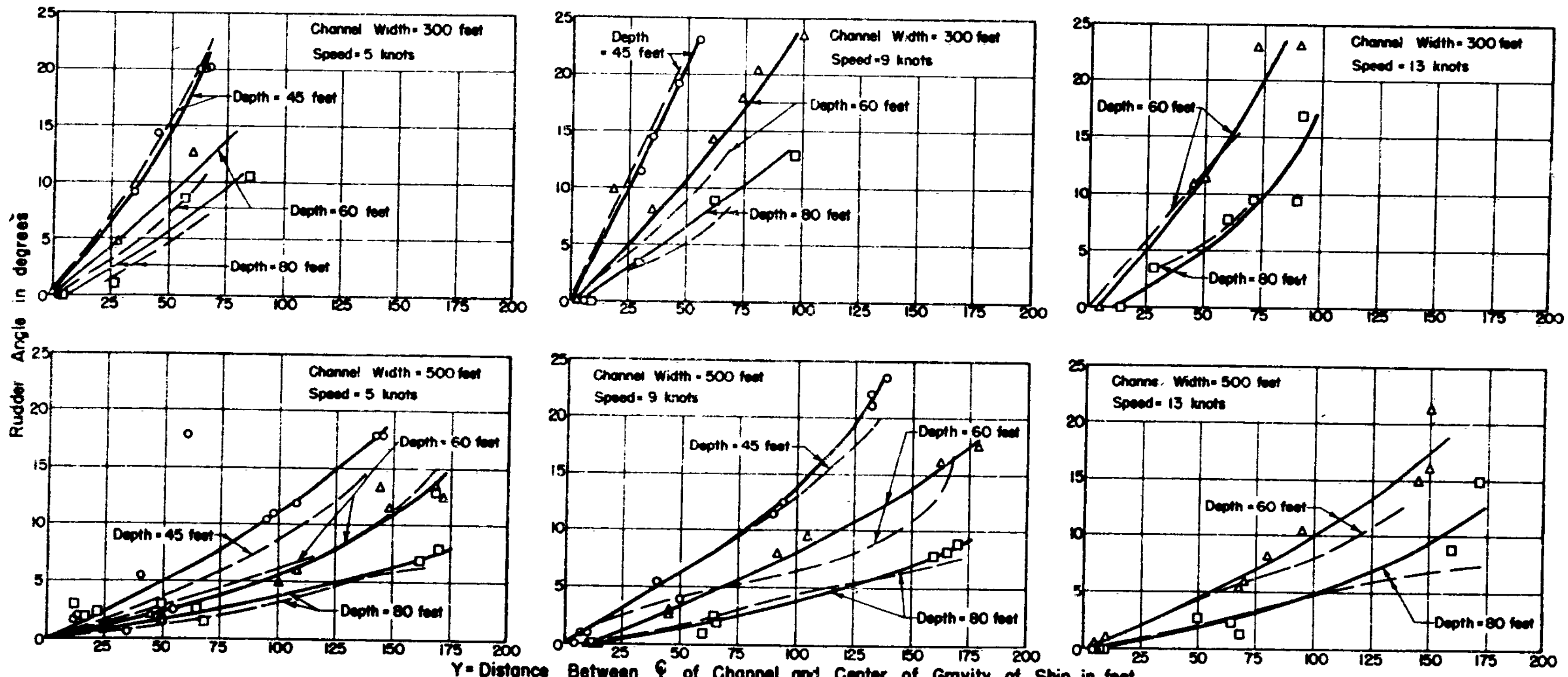


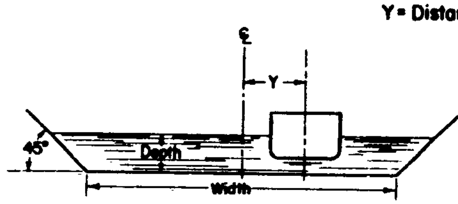
Figure 4.17 Range and Scatter of Extreme Rudder Angles Used in Maneuvering Runs in the 500-Foot Channels

The equilibrium-rudder-angle curves were plotted to show how the extreme rudder angles used in the maneuvering runs tend to range about the equilibrium rudder angle. Since the 5- and 9-knot data are nearly identical in the deeper channels a single curve has been drawn in b and in c.

Location of tests: Shallow water basin Model data: Model 3769, λ - 45
Channel dimensions: Side slope - 45 degrees

was obtained by noting the extreme lateral positions of the forward and after perpendiculars as shown by the work chart, and then determining the lateral distance between the extreme positions without regard to whether they were due to bow or stern perpendiculars and to this distance the beam of the ship was added. This method was easy to apply and because of small variations in





Location of tests: Shallow Water Basin

Ship data: Type - Large Naval Vessel
Length - 900 feet
Beam - 113 feet
Draft - 32.25 feet

Legend: o Channel Depth - 45 feet
Δ Channel Depth - 60 feet
□ Channel Depth - 80 feet

Figure 4.18 - Comparison of Rudder Angles for Equilibrium and the Average of All Rudder Angles Used during Maneuvering Runs, for Various Distances between the Centerline of the Channel and the Center of Gravity of the Ship

The broken lines in the graphs represent the rudder angles required to counteract the yawing moment caused by interaction between the ship and the channel boundaries. The solid lines represent the average of all rudder angles used while maneuvering the model, by remote control, through a restricted channel.

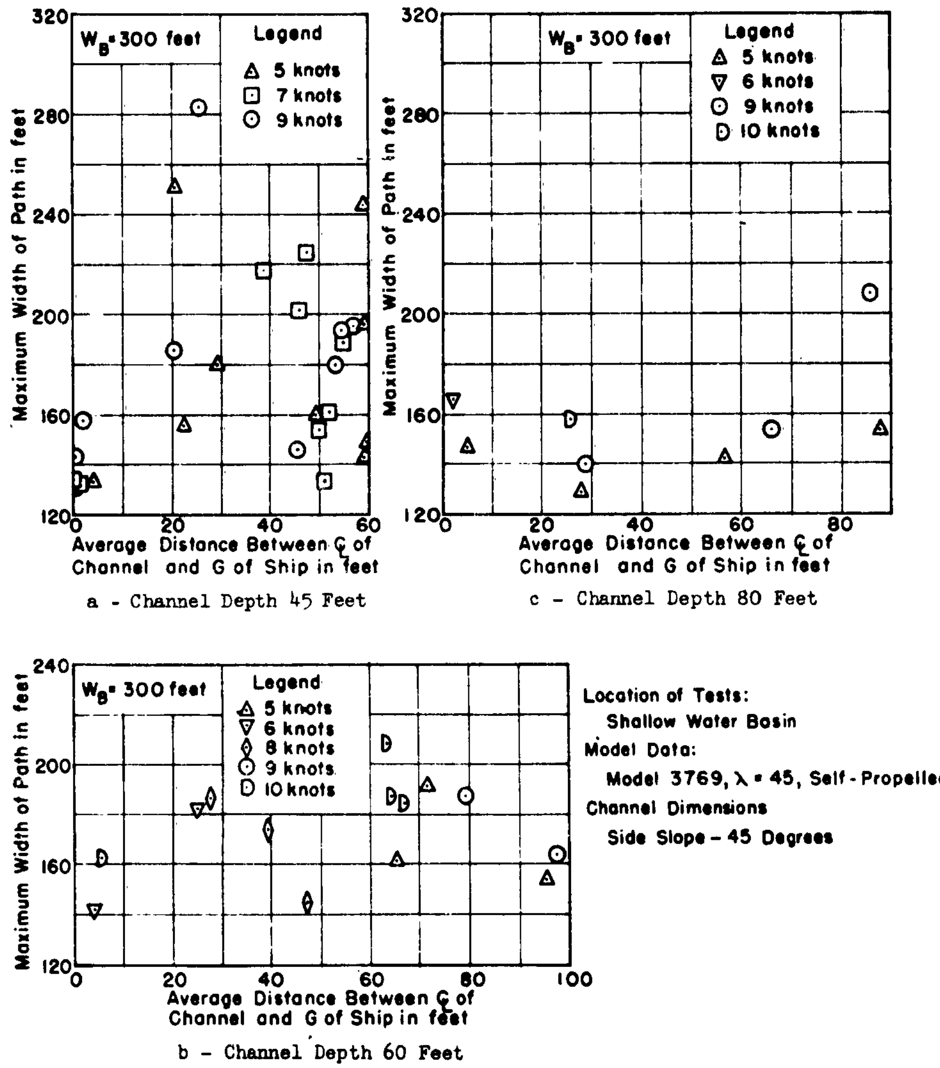
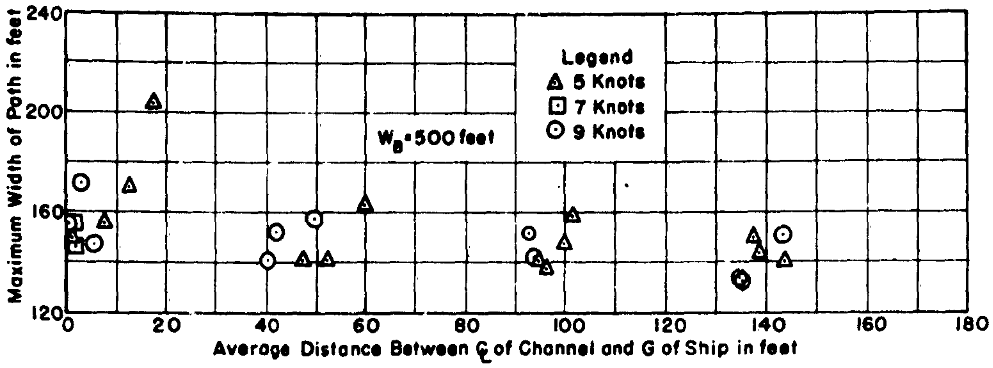


Figure 4.19 - Maximum Width of Path for Maneuvering Runs at Speeds of 10 Knots or Less in the 300-Foot Channels

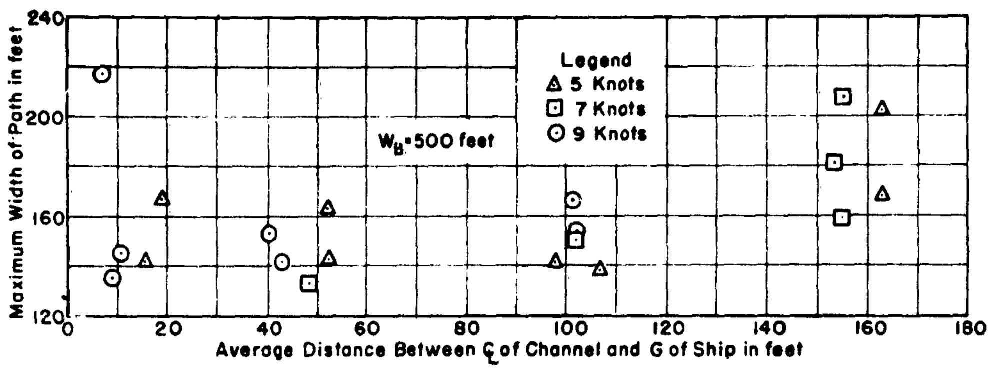
The method of obtaining the width of path is explained in the text.

the angle of yaw it provides a conservative estimate of the width of path. It will be noted that for a given channel the maximum width of path is not materially affected by the distance between the center of gravity of the ship and the centerline of the channel except when the ship's course is close to one of the banks.

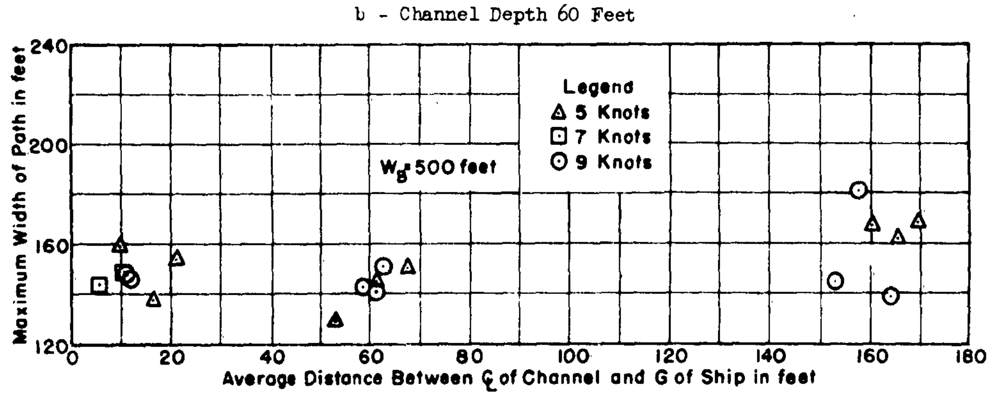
The range and scatter of maximum-width-of-path data is considerably greater for the 300- by 45-foot and the 300- by 60-foot channels than it is for the 300- by 80-foot or any of the 500-foot channels. The maximum width of path is only slightly affected by ship speed over the 5 to 10 knot speed range; however, the extreme maximum width of path of all runs in a given



a - Channel Depth 45 Feet



b - Channel Depth 60 Feet



c - Channel Depth 80 Feet

Figure 4.20 - Maximum Width of Path for Maneuvering Runs at Speeds of 10 Knots or Less in the 500-Foot Channels

The method of obtaining the width of path is explained in the text.

Location of tests: Shallow water basin
Model data: Model 3769, λ - 45, self-propelled
Channel dimensions: Side slope - 45 degrees

channel was usually obtained from a 9 or 10 knot run. The scatter diagrams give a fair indication as to the trends discussed. However, the range of maximum width-of-path data would doubtless increase slightly if more runs were plotted.

The maneuvering tests discussed in this section were intended primarily to indicate some of the general characteristics of bank suction under conditions similar to full-scale operation. It should be noted that only one model, that is, Model 3769, was used in the straight-channel one-way-traffic maneuvering tests. It would undoubtedly have been desirable to obtain information on the effect of varying the cross-sectional dimensions of the ship while holding the length constant as well as information on a variety of ship types and designs. However, a program of this type was considered too extensive for the present investigations.

FORCE-MEASUREMENT TESTS

The purpose of the force-measurement tests was to supplement the observational tests as a means of evaluating the various factors affecting the controllability of ships in restricted channels. As the name implies, the tests consisted in measuring the forces acting on ships in restricted channels, particularly those forces which result from interaction between the ship and the channel boundaries. The tests were conducted in a Taylor Model Basin facility known as the circulating-water channel. This facility is similar in principle to a wind tunnel. It consists of a test section 22 feet wide, 9 feet deep, and 60 feet long, a return channel underneath which passes the water from the downstream end of the test section back to the entrance of the test section and pumps in the downstream vertical leg to force the water around this circuit, and related equipment. The water depth in the channel can be varied from zero to 9 feet. Movable walls may be placed in the test section to vary the width of the channel. Figure 4.21 illustrates the test section with these walls in place. The water speed in the channel may be varied as desired up to 10 knots. Section 3 contains a detailed description of the test setup.

The basic difference between these tests and the observational tests is that the model can be held stationary while the water flows past, whereas in the observational tests the water is stationary and the model is moved. The advantage of this type of facility is that readings can be taken continuously for as long a period as is desired, whereas in the towing basin the length of time available for the observation of a given run is limited by the length of the channel.

It should be noted that the force-measurement tests are static tests and involve a different method of analysis than the observational tests, which are of the dynamic type. In the force-measurement tests the model was restrained while the forces which tended to make it move were measured. It

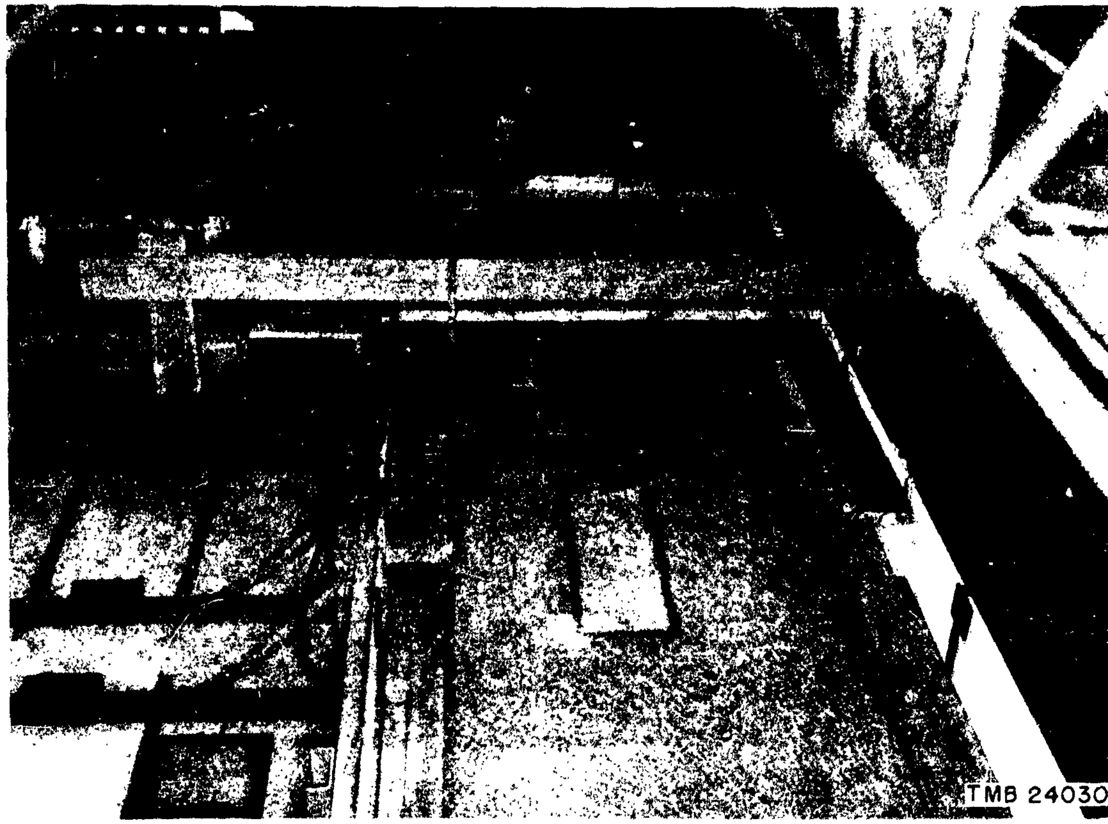


Figure 4.21 - View of the Test Section of the Circulating-Water Channel during the Force-Measurement Studies

This photograph illustrates the test setup for force-measurement studies in the circulating-water channel. The model is held stationary at various transverse positions in a channel and the forces acting on it are measured as the water flows through the channel. The channel walls, which are 7.66 feet apart, may be seen on both sides of the ship model in the center of the photograph. The arrangement shown represents a large tanker in a channel 268 feet wide and 45 feet deep.

is recognized that this is an artifical condition, with respect to a normal operating condition for the full-scale ship but the data obtained provide background for an analysis of the dynamic tests.

The self-propelled models were tested at various off-center positions in channels with various cross-sectional dimensions and at the equivalent full-scale speeds of 4.5 to 10 knots. The side walls of all channels tested in the circulating water channel were vertical. The dynamometer available for these tests could not withstand the forces imposed upon it at speeds in excess of 10 knots. Figure 4.22 is a sketch of the various channels in which the tests were conducted. During the tests the model was attached to the dynamometer in the desired position by means of three arms which extend downward from the dynamometer. Two of the arms were 2.5 feet forward and 2.5

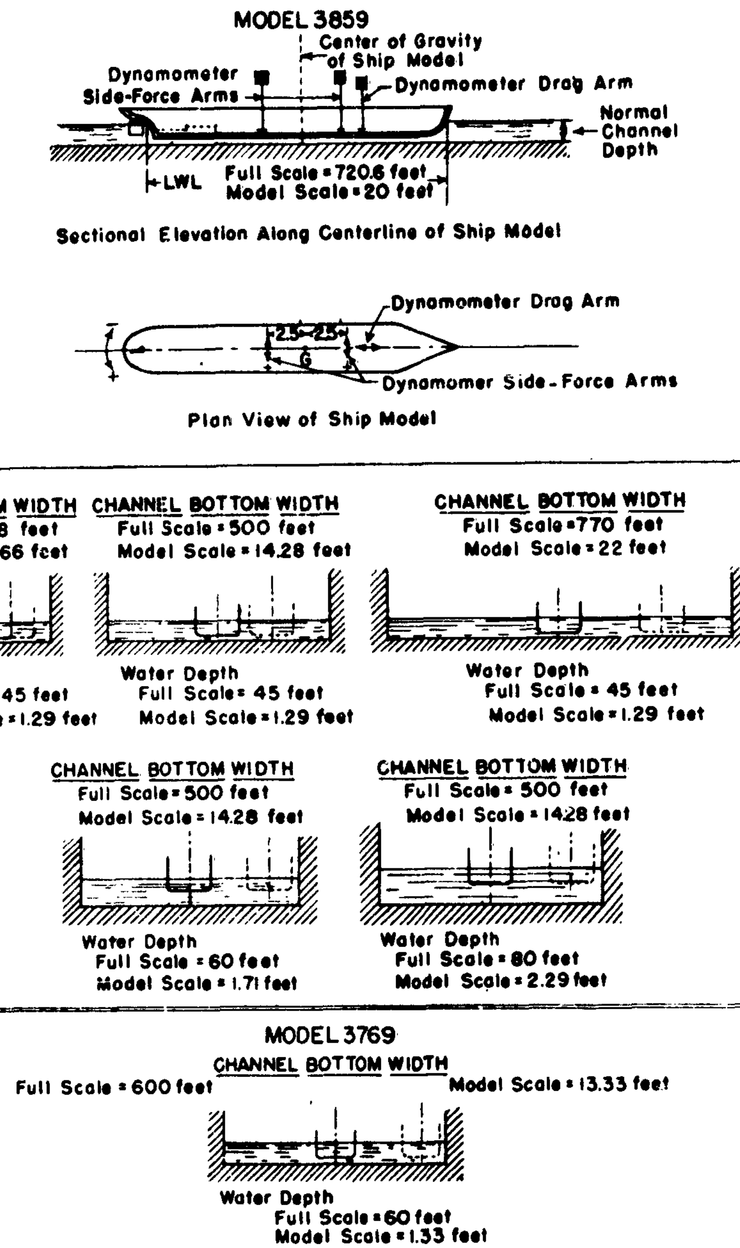


Figure 4.22 - Model and Full-Scale Dimensions of the Channels in Which Models 3859 and 3769 Were Tested during the Force-Measurement Tests

On all the cross-sectional sketches of the channels an outline of the hulls of Model 3859 or 3769 is shown. The solid outline shows the model on the centerline of the channel. The dotted outline is the position nearest the wall for which the model was tested during the force-measurement tests. The sectional elevation and plan view of the model show the location of the dynamometer side-force and drag arms with arrows indicating the direction and sign of the forces that were measured.

feet aft, respectively, of the center of gravity of the model. These two arms measure the side force acting on the model and restrain any movement laterally. The third arm, referred to as the drag arm, was located forward of the other two and measured any fore-and-aft force acting on the model. The dynamometer was designed so that the model could be attached at any desired transverse position in the channel. When it was desired to give the model an angle of yaw the whole dynamometer was turned. Thus all forces acting on the model were measured parallel or perpendicular to the centerline of the model regardless of its angle of yaw.

Three general types of force-measurement tests were conducted. These types of tests are identified as follows:

a. Equilibrium-rudder-angle tests.

b. Total-lateral-force and yawing-moment tests at zero angle of yaw.

c. Tests to determine the rudder angle required to produce zero moment at zero angle of yaw for self-propelled and for towed models.

The equilibrium-rudder-angle tests are the most complete and perhaps the most important of the force-measurement tests. These tests are quite similar to the equilibrium-rudder-angle tests run in the shallow water basin. The tests in b and c were made to provide background information and understandings necessary to make a proper evaluation of the test results.

EQUILIBRIUM-RUDDER-ANGLE TESTS

As previously discussed, when a ship is off center in a restricted channel the side forces acting on it tend to make it sheer away from the near wall. In the observational tests the rudder angle required to counteract the yawing moment caused by these forces was determined by trial and error which involved successively releasing the model at a specified distance from the centerline and trying various rudder angles until equilibrium was obtained. It was also pointed out that in order to produce a true condition of equilibrium it was necessary not only that the rudder be set at the equilibrium angle but also that the ship be at the equilibrium angle of yaw. In the force-measurement tests equilibrium rudder angles were determined by varying the rudder angle and angle of yaw until both the yawing moment and the side force became zero.

In order to facilitate making these adjustments and in order to quickly recognize the equilibrium condition a system of lights was installed. These lights indicated the direction of the forward and after lateral forces. The circuits were automatically broken and all lights went out when the

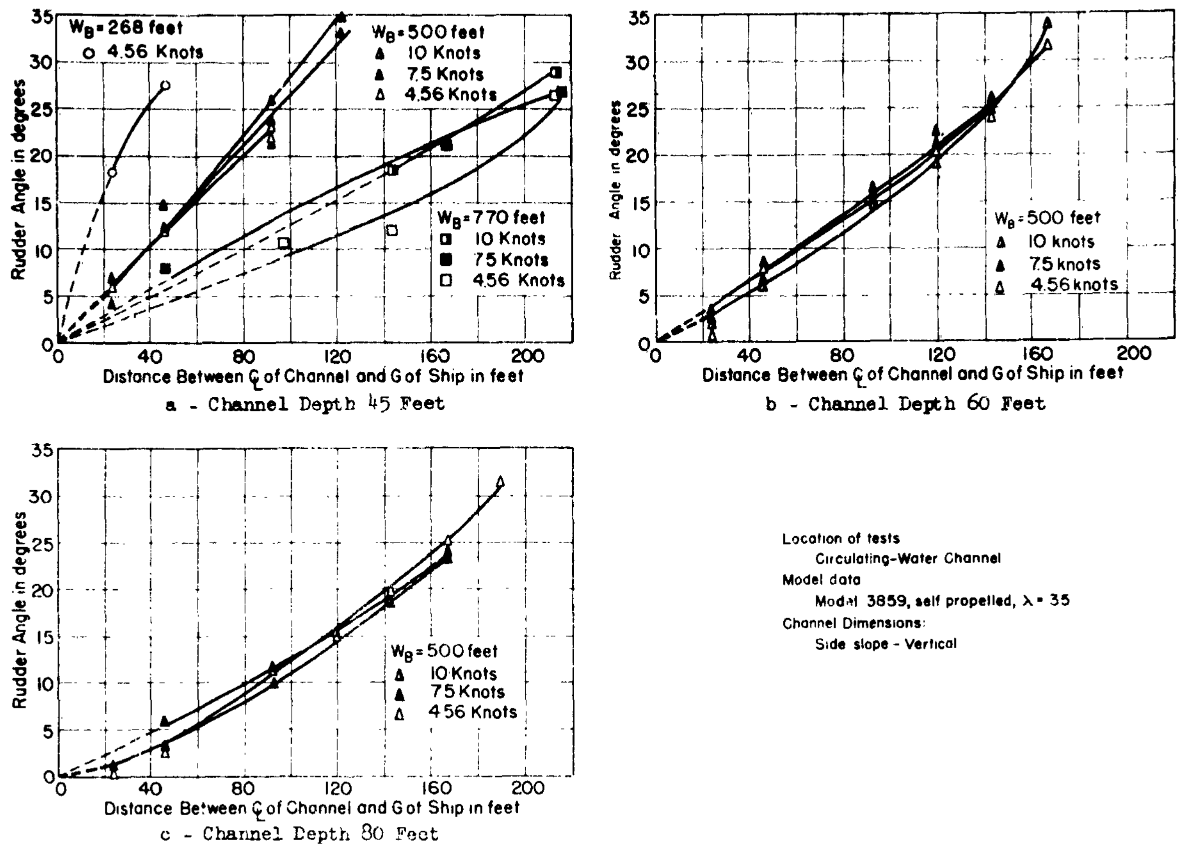


Figure 4.23 - Rudder Angle for Equilibrium as a Function of the Distance between the Centerline of the Channel and the Center of Gravity of the Ship for Model 3859

equilibrium condition was attained. The test schedules and the raw data for the circulating-water-channel equilibrium-rudder-angle tests as well as for all other force-measurement tests are presented in Table 4.2.

The basic data, showing the test spots, for TMB Model 3859 tested by this method are presented in Figure 4.23. It may be noted that the equilibrium rudder angle is not greatly affected by ship speed, and that in the majority of cases the required rudder angle slightly increases as the ship's speed increases. The slope of these curves, or the rate at which the rudder angle increases, is steeper for the shallower depths and narrower widths. This is in accord with the conclusions previously reached with respect to the equilibrium-rudder-angle tests with Model 3769 in the shallow water basin.

Figure 4.24 is a plot of the same data for rudder angle against distance between the center of gravity of the ship and the near wall of the channel. In this graph a single curve has been drawn through the test spots

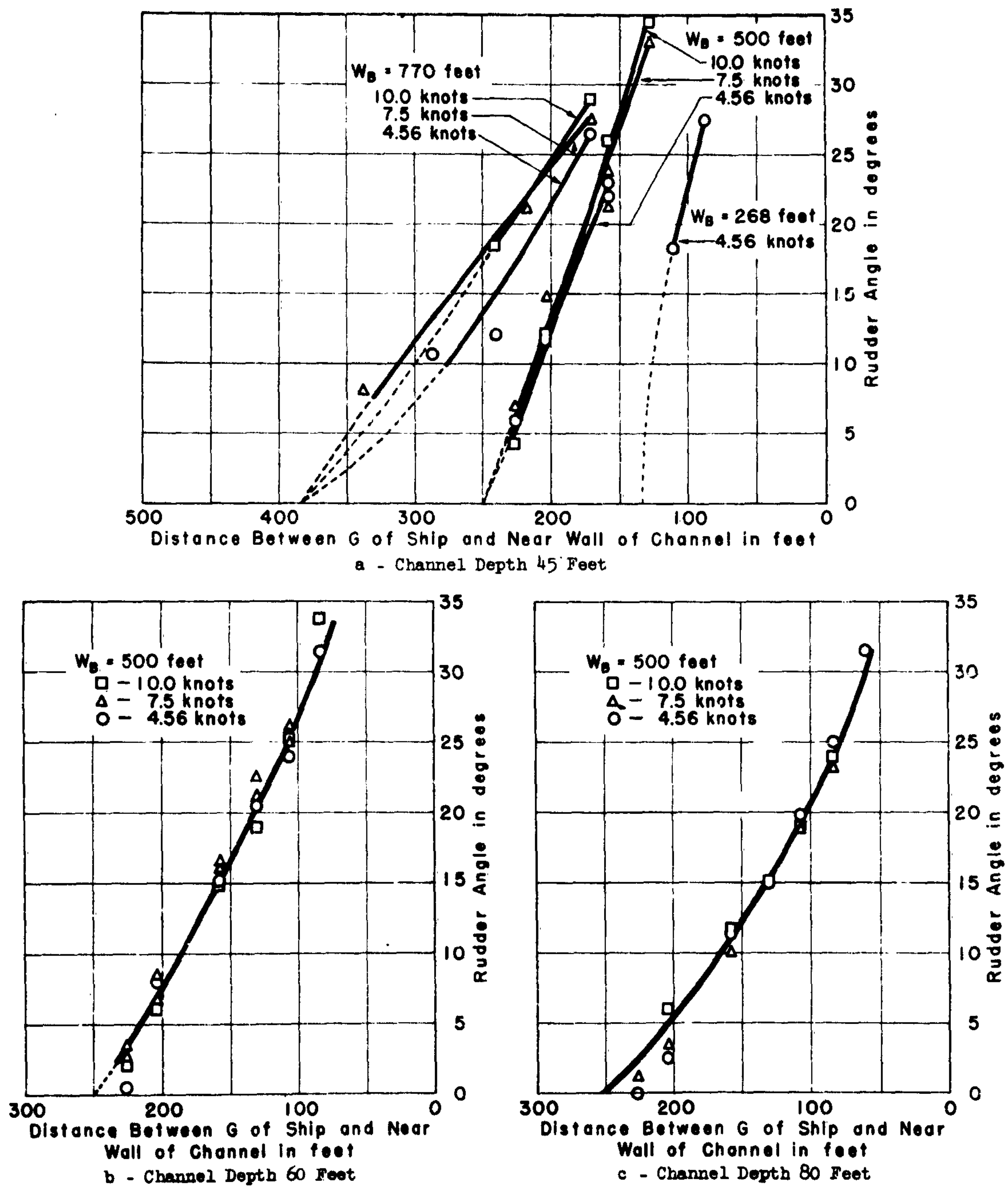


Figure 4.24 - Rudder Angle for Equilibrium as a Function of the Distance between the Near Wall of Channel and the Center of Gravity of the Ship for Model 3859

Since the 4.56-, 7.5- and 10-knot data are nearly identical in the deeper channels single curves have been drawn in b and c.

Location of tests: Circulating-water channel
Model data: Model 3859, λ - 35, self-propelled
Channel dimensions: Side slope - vertical

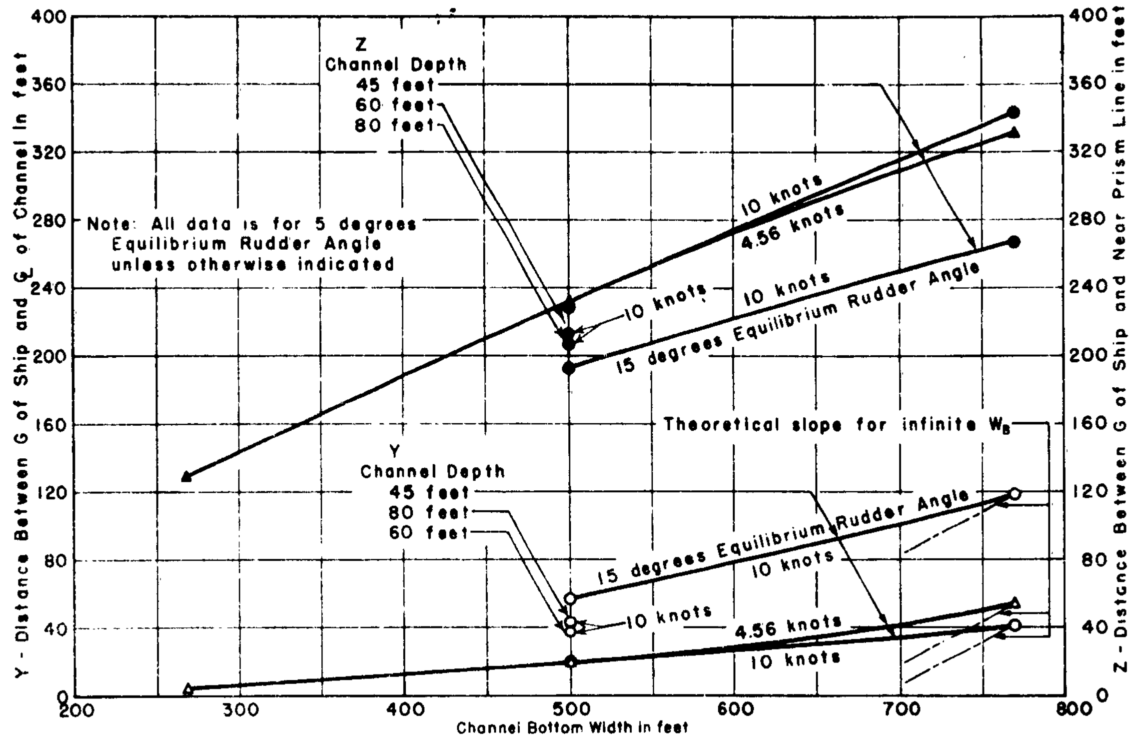


Figure 4.25 - Values of Y and Z for 5-Degree and 15-Degree Equilibrium-Rudder Angles as Functions of Channel Cross Section for Model 3859

Location of tests: Circulating-water channel
Model data: Model 3859, self-propelled, λ - 35
Channel dimensions: Side slope - vertical

obtained from the 4.5-, 7.5- and 10-knot runs for the channel depth of 60 feet. This procedure was repeated for the 80-foot channel depth.

Figure 4.25 shows the variation in Y and Z for 5 and 15 degrees equilibrium rudder angles in the various channels. By reference to this figure and Figure 4.7 it will be noted that the Z values for Model 3859 are larger than the Z values for Model 3769 tested under similar conditions in the shallow water basin. The slopes of the Y curves for Model 3859 in the 770-foot channel are much further from the theoretical slope for infinite W_B than are the Y curves for Model 3769 in the 700-foot channel. The Z curves for Model 3859 indicate that the values of Z for 5 and 15 degrees rudder are still increasing rapidly with increases in channel width even at the 770-foot width in the 770- by 45-foot channel.

The basic data for the equilibrium-rudder-angle tests with Model 3769,* tested in the same manner, are presented in Figure 4.26. It will be

* A limited amount of similar data for Model 3673-A tested in a 979- by 60-foot channel is presented in Figure 4.37.

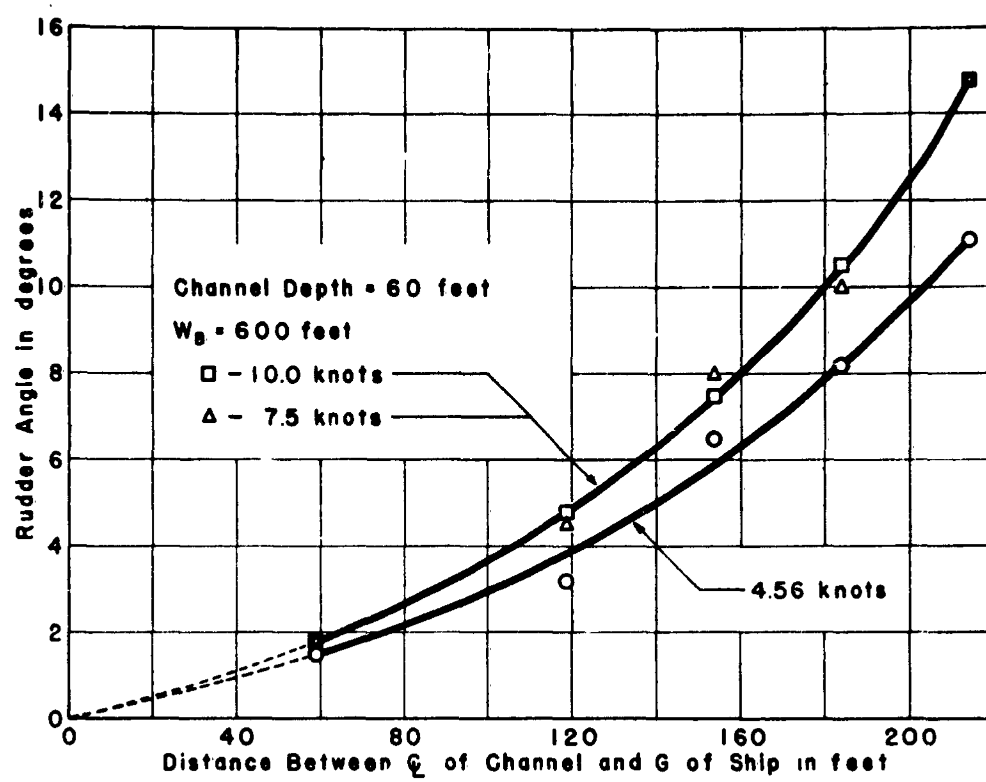


Figure 4.26 - Rudder Angle for Equilibrium as a Function of the Distance between the Centerline of the Channel and the Center of Gravity of the Ship for Model 3769

Since the 7.5-knot and the 10-knot data are nearly identical a single curve has been drawn for these speeds.

Location of tests: Circulating-water channel
Model data: Model 3769, λ - 45, self-propelled
Channel data: Side slope - vertical

noted that all tests were made in a 600- by 60-foot channel with vertical side walls. A single curve has been drawn through the test spots for 7.5 and 10 knots. In general, the limited data shows the same trends previously discussed.

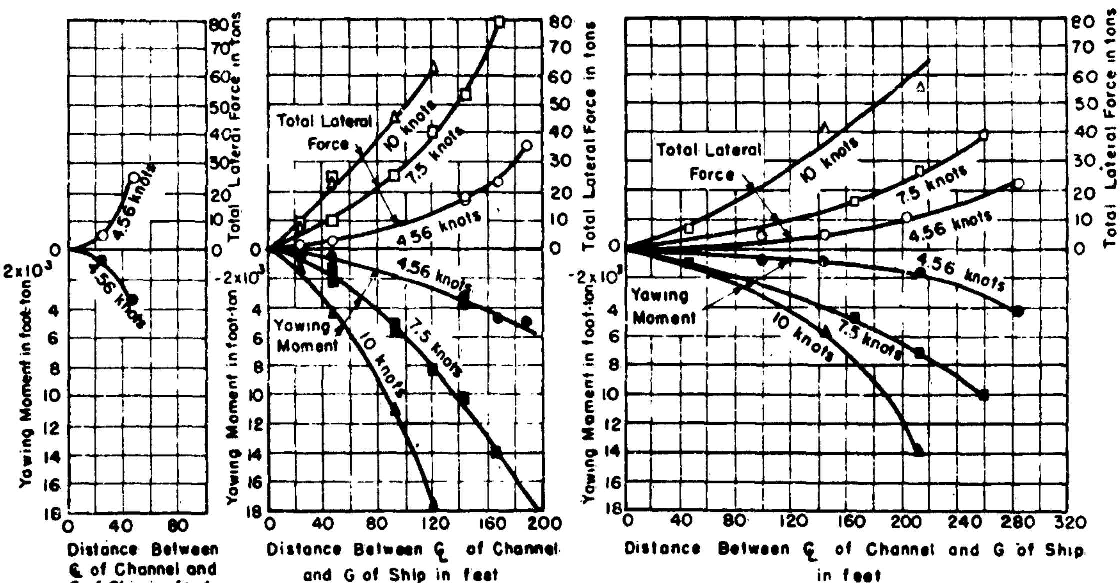
TOTAL-LATERAL-FORCE AND YAWING-MOMENT TESTS AT ZERO ANGLE OF YAW

In the total-lateral-force and yawing-moment tests the ship models were held parallel to the channel centerline and at various transverse position in the channel. It should be noted that the ship was not held at the equilibrium angle of yaw and therefore the forces and moments due to bank suction are not the same as they would be for the equilibrium position of the ship.

The model was self-propelled and the rudder was set amidship. Measurements were then taken of the fore and aft side forces. Some of these tests were repeated with the propellers removed. These tests were conducted to determine the magnitude of the interaction or bank suction in terms of forces and moments as opposed to the preceding tests which indicate the magnitude of these effects in terms of the rudder angle and angle of yaw required to counteract them. The yawing moment and the total lateral force were computed and plotted with respect to the center of gravity of the ship.

Figures 4.27 and 4.28 are graphs showing the estimated lateral force and yawing moment acting on the tanker at various transverse positions in five different channel sections for three speeds.*

As might be expected, Figures 4.27 and 4.28 indicate that the yawing moment and the total lateral force are greatly affected by ship's speed even in the wider and deeper channels. It will be remembered that the equilibrium rudder angles are only slightly affected by ship's speed in the wider



a - Channel Width 268 Feet

b - Channel Width 500 Feet

c - Channel Width 770 Feet

Figure 4.27 - Yawing Moment and Total Lateral Force as Functions of the Distance between the Centerline of the Channel and the Center of Gravity of the Ship for a Channel Depth of 45 feet

The data are plotted for the condition with the ship to starboard of channel centerline. The rudder angle was set at zero degree when the yawing moment and lateral force were measured.

Location of tests: Circulating-water channel
Model data: Model 3859, self-propelled, λ - 35
Channel dimensions: Side slope - 45 degrees

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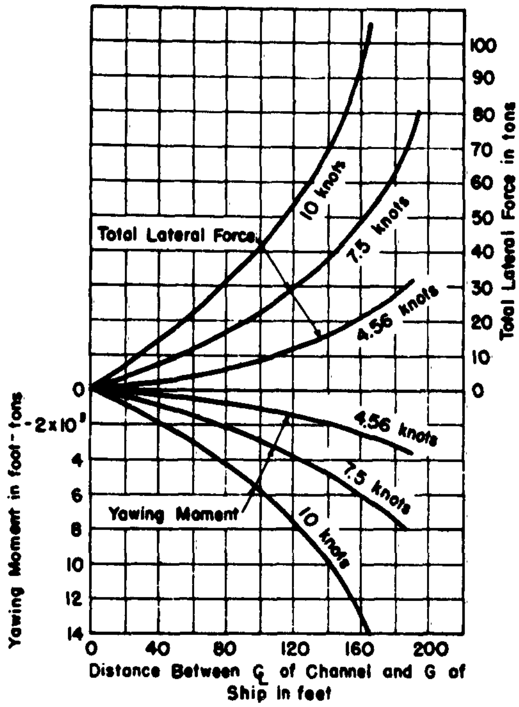
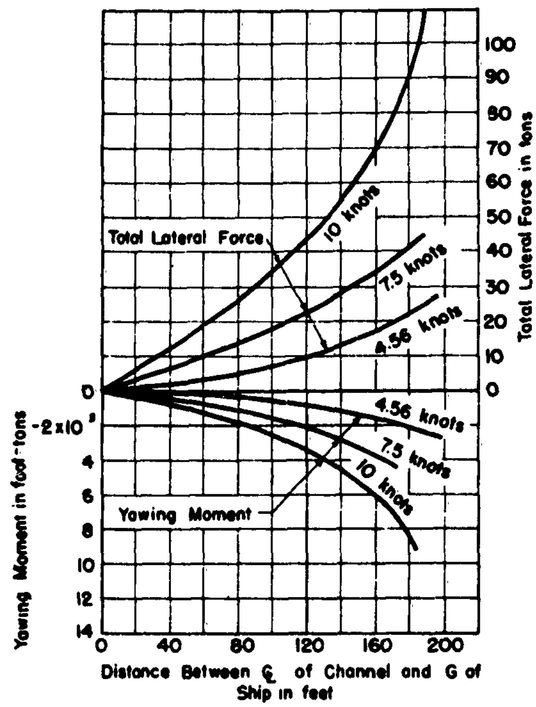
* A limited amount of similar date for Model 3769 is presented in Figure 4.41.



a - Channel Depth 60 Feet



b - Channel Depth 80 Feet

Figure 4.28 - Yawing Moment and Total Lateral Force as Functions of the Distance between the Centerline of the Channel and the Center of Gravity of the Ship for Channel Depths of 60 and 80 feet

The data are plotted for the condition with the ship to starboard of channel centerline. The rudder angle was set at zero degree when the yawing moment and lateral force were measured.

Location of tests: Circula.ing-water channel
Model data: Model 3859, λ - 35, self-propelled
Channel dimensions: Bottom width - 500 feet
Side slope - vertical

and deeper channels. This difference is accounted for by the fact that both the turning moment produced by the rudder and the turning moment produced by the bank suction increase roughly as the square of the ship speed. In the smaller channels the yawing moment due to bank suction increases more rapidly than the square of the ship's speed.

Data obtained by repeating these tests with the propellers removed is more conveniently presented and discussed in connection with the following paragraphs.

TESTS TO DETERMINE THE RUDDER ANGLE REQUIRED TO PRODUCE ZERO MOMENT AT ZERO ANGLE OF YAW FOR SELF-PROPELLED AND FOR TOWED MODELS

A series of tests to determine the rudder angle required to produce zero moment at zero angle of yaw were conducted with the self-propelled Models 3859 and 3769. These tests were conducted to furnish a basis for comparing the rudder angles and yawing moments at zero angle of yaw and to determine the effect of the angle of yaw on the rudder angle required to produce zero moment. A number of these tests were repeated with the propellers removed in order to determine the comparative effect of propeller action on the rudder angle required to produce zero moment at zero angle of yaw for the two models.

Figure 4.29 presents sample curves showing the comparison between yawing moments at zero angle of yaw and the rudder angle required to counteract yawing moment at zero angle of yaw for the tanker at 10 knots speed. It will be noted that the yawing-moment and rudder-angle curves are quite similar. A single curve has been drawn through the test spots obtained from yawing-moment tests with and without propellers. This indicates that the yawing moment caused by bank suction is not greatly affected by propeller action. The total lateral force acting on the ship at zero angle of yaw with the rudder amidship has also been plotted. A single curve has been drawn through the test spots obtained from the tests with and without propellers.

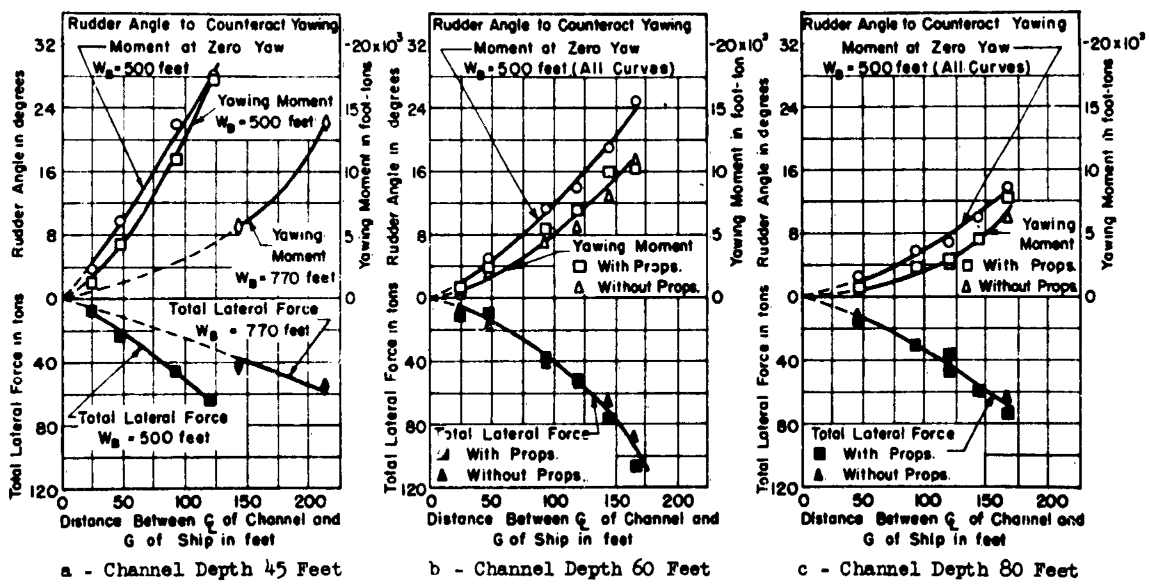


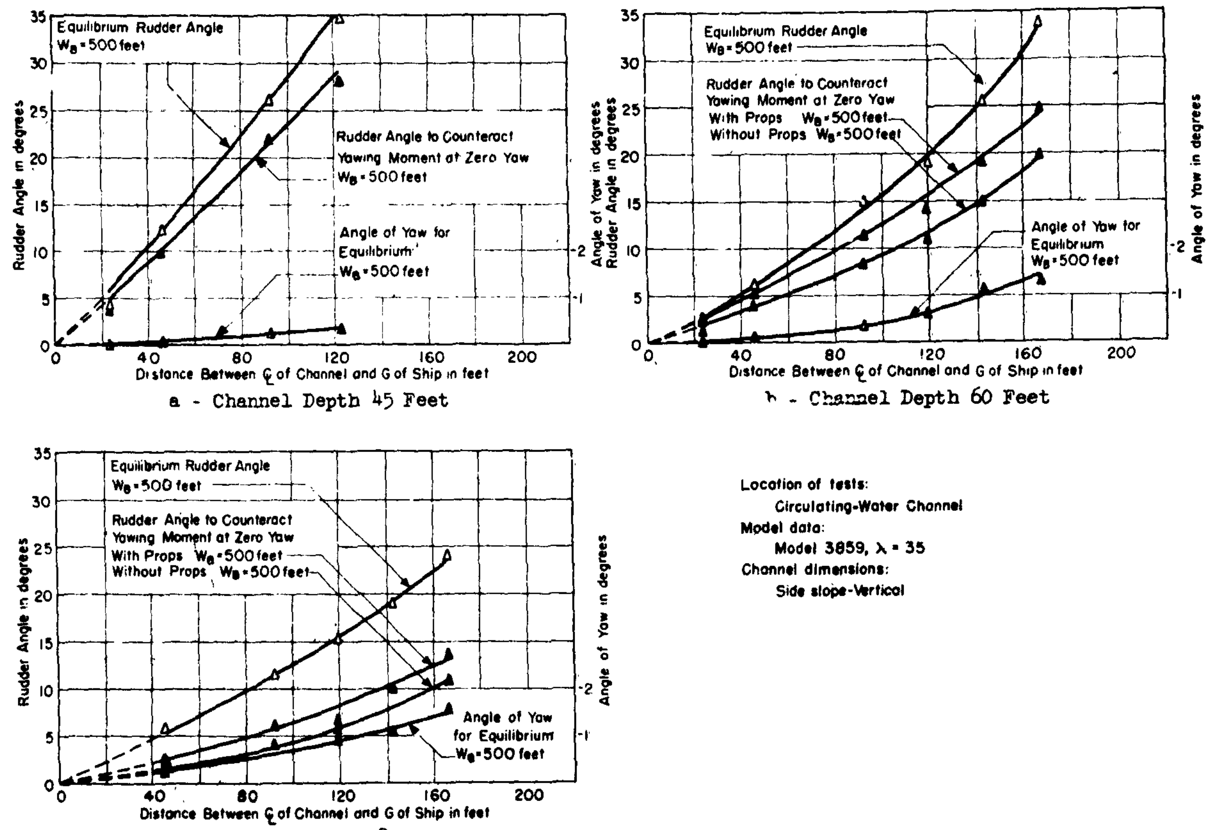
Figure 4.29 - Rudder Angle, Yawing Moment, and Total Lateral Force as Functions of the Distance between the Centerline of the Channel and the Center of Gravity of the Ship for a Ship Speed of 10 Knots

Yawing moment and total lateral force are measured with the self-propelled model at zero angle of yaw unless otherwise stated. For these measurements the rudder was set at zero degrees.

Location of tests: Circulating-water channel
Model data: Model 3859, λ - 35
Channel dimensions: Side slope - vertical

A complete set of graphs for all data similar to that in Figure 4.29 is presented in Figures 4.38, 4.39, 4.40, and 4.41 of the Appendix to this section.

Figure 4.30 presents sample curves for comparison of the equilibrium rudder angles with the rudder angles to counteract yawing moment at zero yaw both for the self-propelled and for the towed condition.* The curves are based on tests with Model 3859 at a speed of 10 knots in channels 45, 60, and 80 feet deep These graphs also show the angle of yaw for equilibrium as a function of the distance between the centerline of the channel and the center of gravity of the ship. The curves indicate that the equilibrium rudder



a - Channel Depth 45 Feet

b - Channel Depth 60 Feet

c - Channel Depth 80 Feet

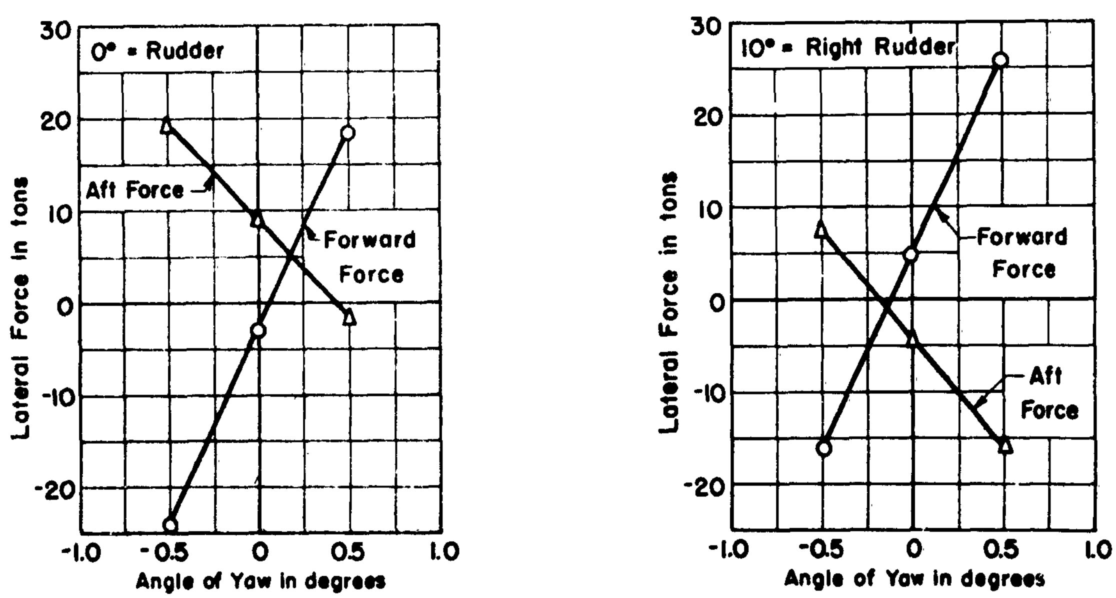
Figure 4.30 - Rudder Angle for Equilibrium and Rudder Angle for Zero Moment at Zero Angle of Yaw as Functions of the Distance between the Centerline of the Channel and the Center of Gravity of the Ship for a Ship Speed of 10 Knots

Rudder angle to counteract yawing moment at zero angle of yaw is measured with propellers unless otherwise stated.

* The complete set of graphs for all tests of this type with Model 3859 is presented in Figures 4.42, 4.43, and 4 44.

angles are larger than the rudder angles to counteract yawing moment for the self-propelled model at zero angle of yaw. It may seem strange that the rudder angles required to counteract yawing moment at zero angle of yaw were decreased considerably when the propellers were removed. In this connection it will be remembered from Figure 4.29 that the removal of the propellers did not materially change the yawing moment acting on the ship itself. It seems, therefore, that the reduction in the required rudder angle when the propellers were removed is caused by an increase in the moment produced by the rudder. This is not unreasonable if we consider the fact that the tanker is a twin-screw ship with a single rudder located between the screws, and that therefore the propeller action may tend to create a dead-water area surrounding the rudder.

It will be noted that the equilibrium angle of yaw is actually very small and that it increases with an increase in Y. It is apparent from these graphs that an accurate setting of the equilibrium yaw angle is of considerable importance in determining accurate values for the equilibrium rudder angle in the circulating-water-channel tests. Some of the scatter of the circulating-water-channel data may well be caused by slight errors in setting the angle of yaw.



a - Rudder Set at Zero Degrees

b - Rudder Set at 10 Degrees Right

Figure 4.31 - Forward and Aft Lateral Force as Functions of the Angle of Yaw and Rudder Angle

Location of test: Circulating-water channel
Model data: Model 3859, λ - 35, self-propelled
V_s - 7.5 knots (full-scale)

Channel dimensions:
Channel-bottom width - 770 feet
Channel depth - 45 feet
Side slope - vertical

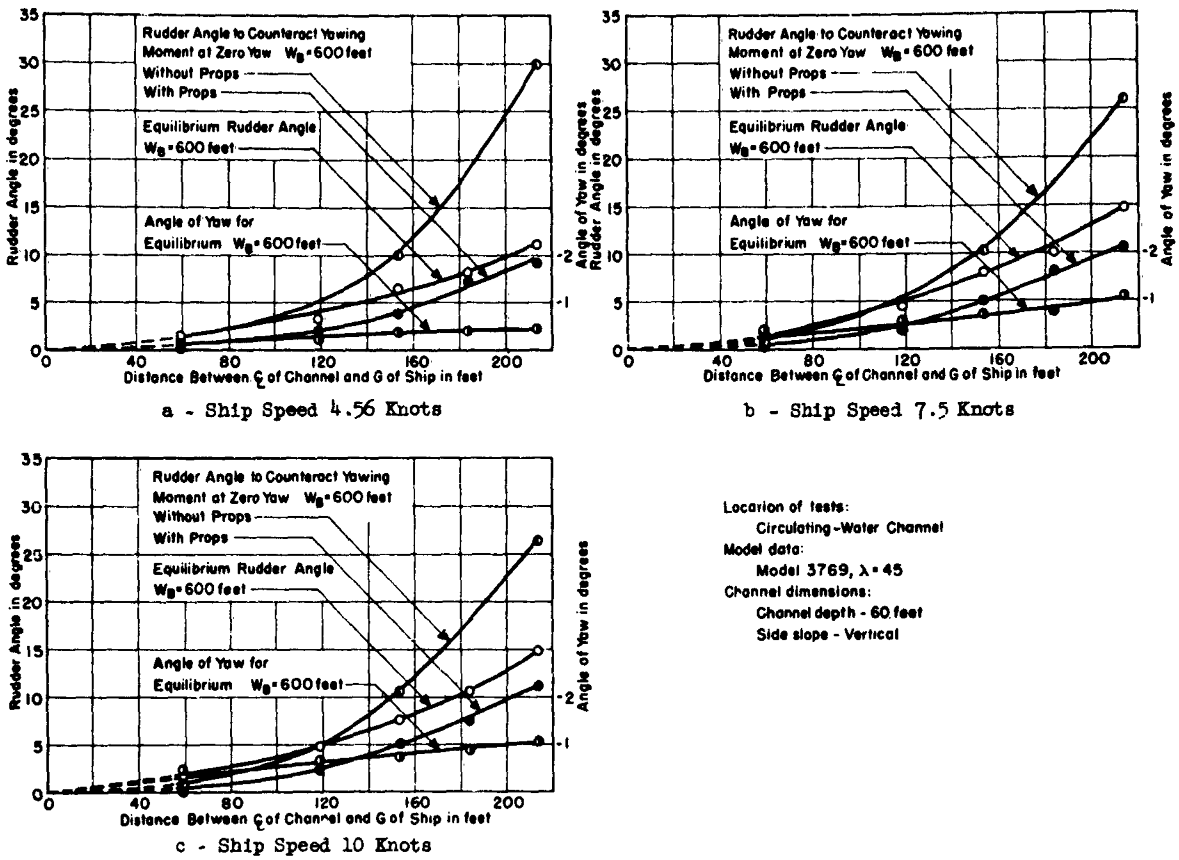


Figure 4.32 - Rudder Angle for Equilibrium and Rudder Angle for Zero Moment at Zero Angle of Yaw as Functions of the Distance between the Centerline of the Channel and the Center of Gravity of the Ship for Model 3769

In this connection Figure 4.31 shows the change in direction and in magnitude of the forward and aft lateral forces with small changes in the angle of yaw and with changes in the rudder angle. These curves are for the tanker at a ship speed of 7.5 knots on a course 46.6 feet off the centerline of a channel 770 feet by 45 feet. The coordinates of the points of intersection of the curves in Figures 4.31a and 4.31b indicate the angle of yaw for zero moment. Before equilibrium is attained, however, the total lateral force must also be zero. It is evident from Figures 4.31a and 4.31b that the equilibrium rudder angle is about 8.5 degrees and that the equilibrium angle of yaw is about 0.08 degree for this condition. These tests are static tests; however, the forces and moments could exist momentarily if the ship happened to be at the given angle of yaw and was not swinging.

Figure 4.32 presents data for Model 3769 which is similar to that presented for Model 3859 in Figure 4.30. These curves, as in the case of Model 3859, indicate that the equilibrium rudder angles are considerably larger than the rudder angles required to counteract yawing moment if the self-propelled model is set at zero angle of yaw. The rudder angles required to counteract yawing moment at zero angle of yaw were greatly increased when the propellers were removed from Model 3769. It will be remembered that this is opposite to what occurred with Model 3859 when its propellers were removed. This difference is explained by the fact that Model 3769 is a four-screw twin-rudder ship with the rudders located in the race from the inboard propellers. The rudder is thus more effective when Model 3769 is self-propelled than when it is not self-propelled. This difference between the two models helps to explain the comparatively large equilibrium rudder angles for Model 3859.

SUMMARY OF OBSERVATIONAL AND FORCE-MEASUREMENT TESTS

According to the original test program for the investigation of ship performance in restricted channels, models of two different ships were to be tested under identical conditions during the straight-channel one-way-traffic studies. The two models selected for the tests were a large naval vessel and a large twin-screw, single-rudder tanker. In accordance with this program both models would have been subjected to both observational and force-measurement tests. At the request of the Special Engineering Division, The Panama Canal, the observational studies on the tanker were cancelled in order to expedite two-way-traffic and bend studies. Observational studies were completed on the model of a naval vessel for channel-bottom widths of 300, 500, and 700 feet and channel depths of 45, 60, and 80 feet. Most of the force-measurement tests were performed with the tanker model. These tests were made in channels with vertical side walls for channel cross sections of 268- by 45-foot, 500- by 45-foot, 770- by 45-foot, 500- by 60-foot and 500- by 80-foot.

A limited number of force-measurement tests were made with Model 3769 in a 600- by 60-foot channel.

In both the observational and force-measurement tests, the rudder angle required to counteract the yawing moment caused by the interaction between the ship and the channel boundaries was determined. It is thought that an expression of the effect of interaction in terms of rudder angle will be of considerable practical value in the study of the controllability of ships in restricted channels. The magnitude of the required rudder angle is a function of the channel dimensions, the size, lines, and characteristics of the rudders and propellers of the ship, the ship speed, and the position of the ship in the channel. Thus, the rudder angles required by two different ships for a specified off-center position will be strongly affected by the steering characteristics of the ship.

The tanker requires more than twice as much rudder to maintain equilibrium when tested under the same conditions as Model 3769. The tests of the tanker with the propellers removed help to explain the inefficiency of the rudder on this ship. The result of tests with the tanker are such as to explain why large twin-screw single-rudder ships are involved in an unusually large number of accidents in canal traffic.

An investigation to determine the rudder angles required for many different ships might be of interest, for the purpose of ship design and for use in connection with the operation of ships in restricted channels. However, for the immediate purpose of indicating the necessary size and proportions of the canal channel, it is believed that study of Model 3769 and of the large tanker should provide sufficient information. The smaller and easier-handling ships should not present a problem in channels which are designed to handle ships of the types tested. The Naval vessel, represented by Model 3769, was originally selected for study in these tests because of its great size, although its steering characteristics are excellent. The tanker was selected as being representative of a type of large twin-screw single-rudder ships whose steering characteristics in restricted waters are very poor.

The yawing moment due to bank suction, as measured by the equilibrium rudder angle, is not materially affected by ahead or following current up to 5 knots provided that the ship speed with respect to the water remains the same and provided that the ship is in the portion of the channel normally used in navigation.

From a practical standpoint the test results obtained from the shallow water basin and from the circulating-water channel are nearly identical as evidenced by the equilibrium-rudder-angle tests in the two facilities.

The data have been plotted to facilitate a comparison of the effect of width and depth upon the magnitude of the effects caused by interaction between the ship and the channel boundaries. It is thought that the rudder angles required to counteract bank suction provide a comparison of the actual difficulty the pilots might have in controlling the ship under the various conditions. In general, it is believed that a condition requiring the use of a relatively high rudder angle would be a dangerous operating condition for the ship.

Certain differences between prototype operating conditions and model-test operating conditions should be considered in evaluating the test results. No attempt was made to simulate either weather conditions or the irregularities which normally occur in full-scale canals. The time scale in the maneuvering runs required that the pilot and the quartermaster act about 7 times faster than full-scale operations require in order to simulate full-scale conditions. The difference in time scale tends to make the test results conservative whereas the other two differences have the opposite effect. It is believed that these differences do not materially affect the value of the tests. However, tests to determine the effect of irregularities in the channel might produce results of value in connection with the design of a canal. The pilot was not located on the vessel; however, it is believed that the light-beam system used in the tests enabled the pilots to judge the action of the model ship nearly as well as they can judge the action of the full-scale ship.

The concepts developed and the data presented in this section are of major importance in connection with the overall summary and recommendations which are presented in Section 8. Also, the concepts developed provide a necessary background for the proper evaluation of the tests discussed in the remaining sections of the report.

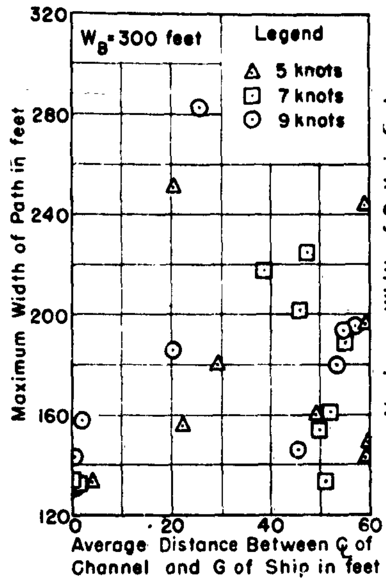
APPENDIX 4.1

The tabulated data for the shallow-water-basin tests are presented in Table 4.1. Table 4.2 presents the tabulated data for the force-measurement tests in the circulating-water channel. The graphs presented in this report do not exhaust the possibilities for interesting graphical representation of the data in Tables 4.1 and 4.2. However, it is believed that the most significant comparisons have been made.

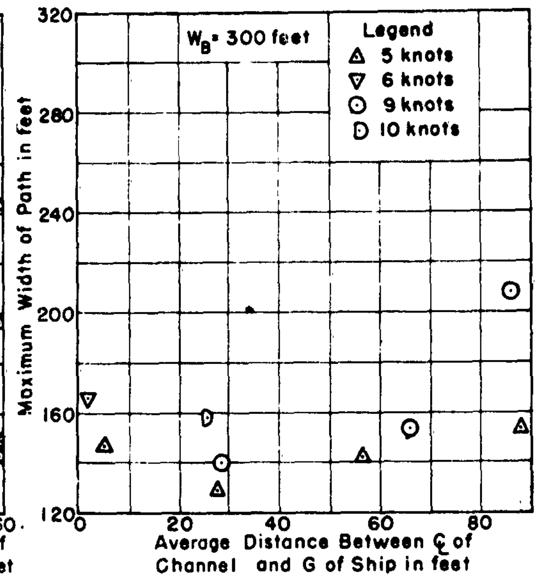
This appendix contains complete sets of graphs for those types of data for which only sample graphs were presented in the text. These sets of graphs and the brief discussion which follows emphasize the generality of the conclusions stated in the text.

Figures 4.33, 4.34, 4.35, and 4.36 present the maximum-width-of-path data for all the maneuvering runs which were plotted. The limited data for speeds above 10 knots show the same general trends discussed in the text for speeds of 10 knots and below.

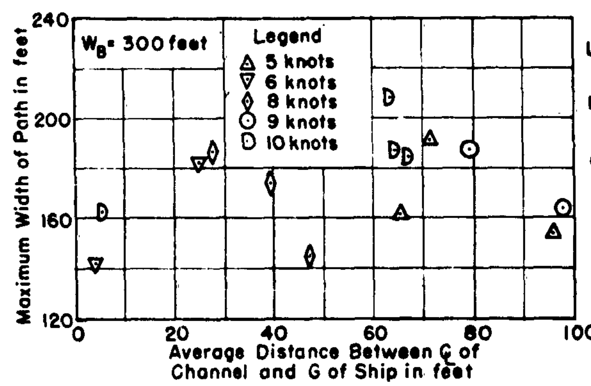
Figure 4.37 presents all the test data obtained with Model 3673-A. Tests with this model were discontinued because the model was not suited for continuous use. The results are presented because they show a very large ship in a very large channel.



a - Channel Depth 45 Feet



c - Channel Depth 80 Feet



b - Channel Depth 60 Feet

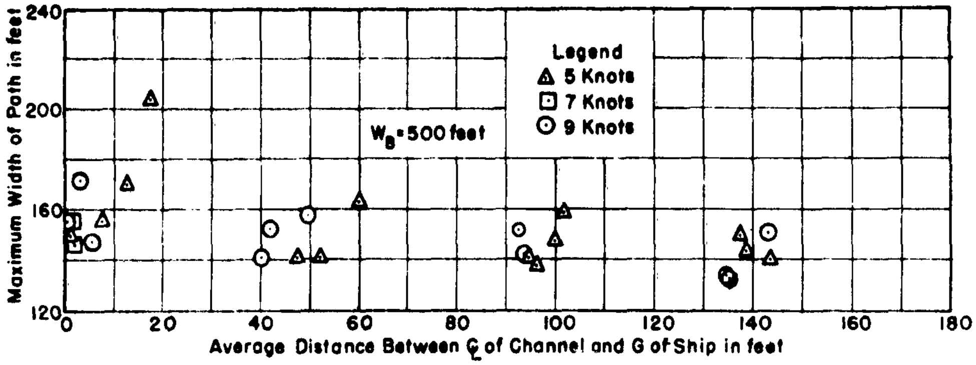
Location of Tests:
Shallow Water Basin
Model Data:
Model 3769, λ = 45, Self-Propelled
Channel Dimensions
Side Slope - 45 Degrees

Figure 4.33 - Maximum Width of Path for Maneuvering Runs at Speeds of 10 Knots or Less in the 300-Foot Channels

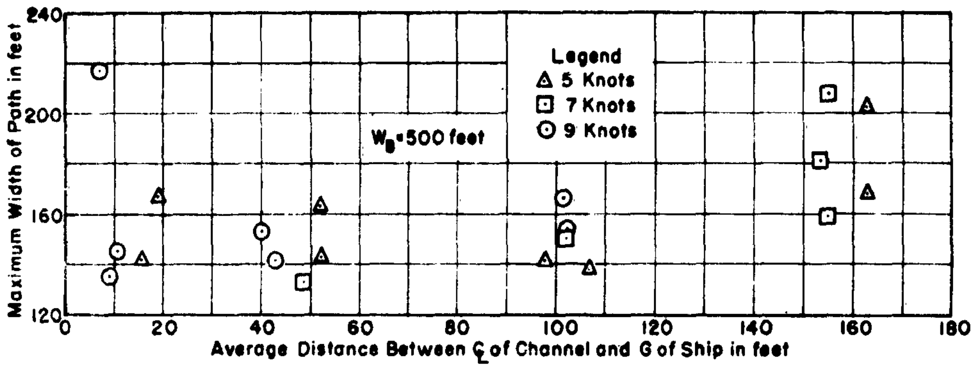
The method of obtaining the width of path is explained in the text.

Figures 4.38, 4.39, and 4.40 present all the data showing the comparison between the yawing moment and the rudder angle to counteract yawing moments for Model 3859 at zero angle of yaw.

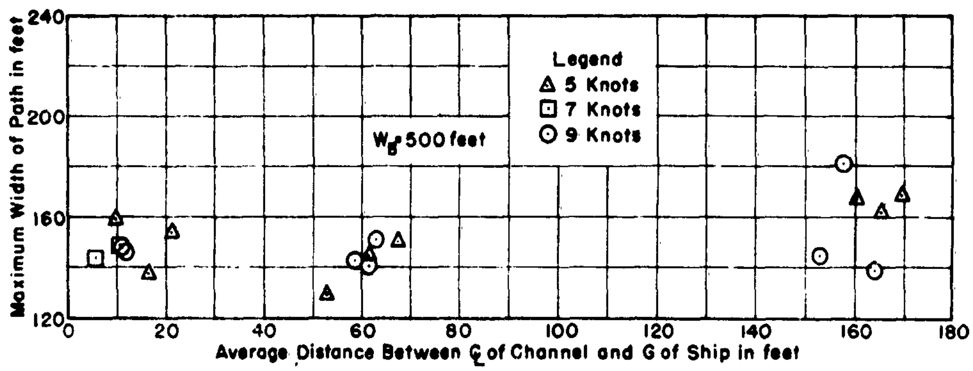
The rudder angle to counteract yawing moment at zero angle of yaw is only slightly affected by ship speed. This is accounted for by the fact that the yawing moment due to the rudder increases with speed at roughly the same rate as the yawing moment due to bank suction. The width and depth of the channel affect the magnitude of this rudder angle in much the same way as they affect the equilibrium rudder angle. The bank suction for the larger



a - Channel Depth 45 Feet



b - Channel Depth 60 Feet

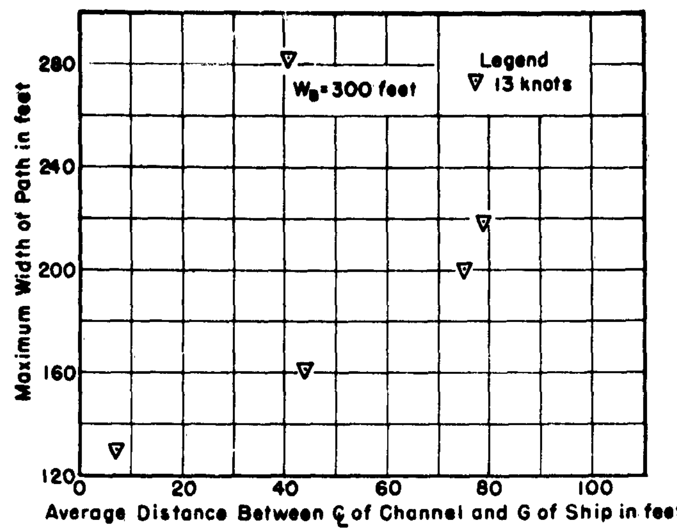


c - Channel Depth 80 Feet

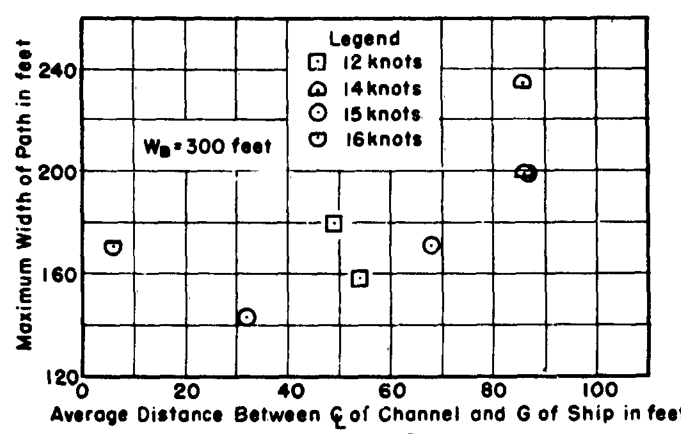
Figure 4.34 - Maximum Width of Path for Maneuvering Runs at Speeds of 10 Knots or Less in the 500-Foot Channels

The method of obtaining the width of path is explained in the text.

Location of tests: Shallow water basin
Model data: Model 3769, λ - 45, self-propelled
Channel dimensions: Side slope - 45 degrees



a - Channel Depth 60 Feet

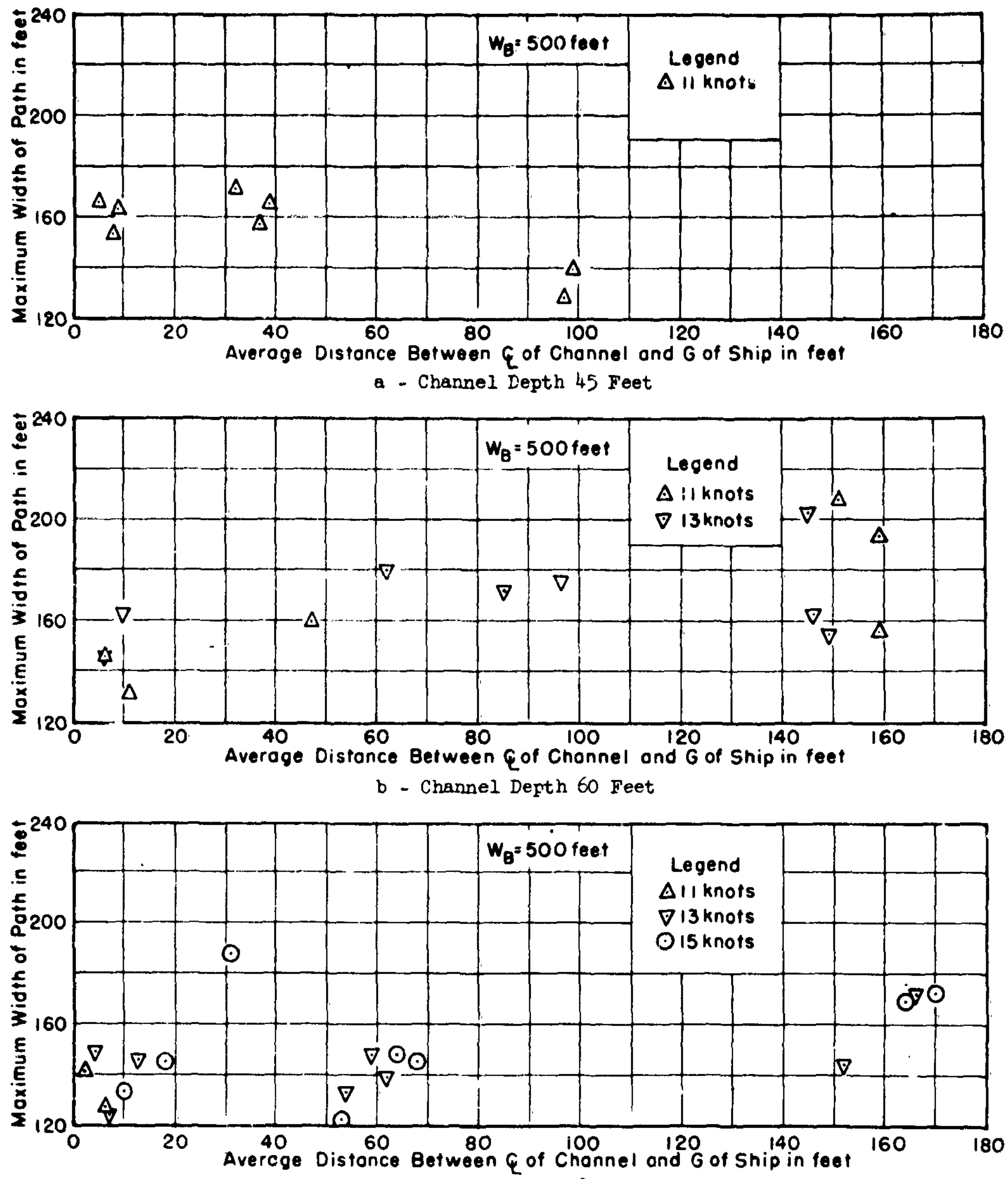


b.- Channel Depth 80 Feet

Figure 4.35 - Maximum Width of Path for Maneuvering Runs at Speeds above 10 Knots in the 300-Foot Channels

The method of obtaining the width of path is explained in the text.

Location of tests: Shallow water basin
Model data: Model 3769, λ - 45, self-propelled
Channel dimensions: Side slope - 45 degrees



a - Channel Depth 45 Feet

b - Channel Depth 60 Feet

c - Channel Depth 80 Feet

Figure 4.36 - Maximum Width of Path for Maneuvering Runs at Speeds above 10 Knots in the 500-Foot Channels

The method of obtaining the width of path is explained in the text.

Location of tests: Shallow water basin
Model data: Model 3769, λ - 45, self-propelled
Channel dimensions: Side slope - 45 degrees

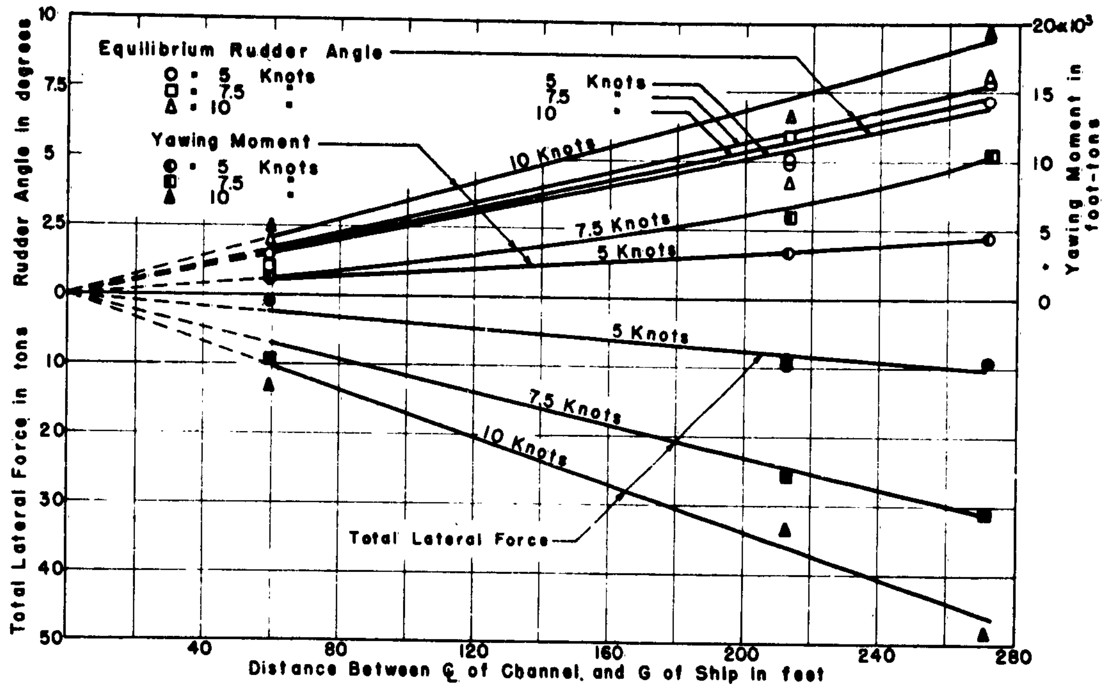


Figure 4.37 - Rudder Angle for Equilibrium, Yawing Moment, and Total Lateral Force as Functions of the Distance between the Centerline of the Channel and the Center of Gravity of the Ship for Model 3673-A

Yawing moment and total lateral force are measured with the model at zero angle of yaw. For these measurements the rudder was set at zero degrees.

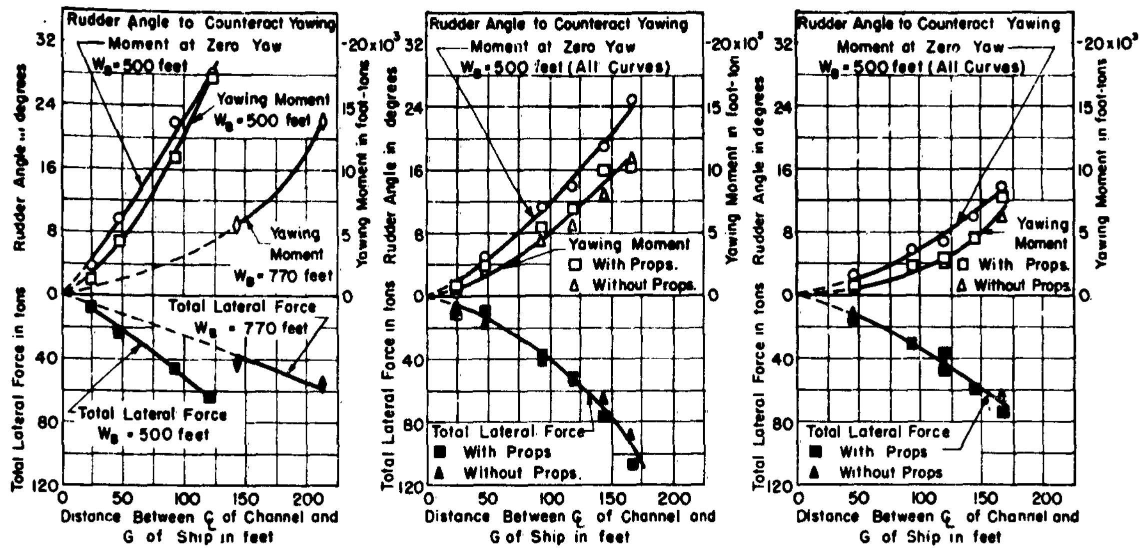
Location of tests: Circulating-water channel
Model data: Model 3673-A, λ - 44.5, self-propelled

Channel dimensions:
Channel width 979 feet
Channel depth 60 feet
Side slope - vertical

channels, in terms of yawing moment at zero angle of yaw, increases roughly as the square of the ship speed, and for the same off-center position, yawing moment increases with a decrease in the channel width or depth.

Figure 4.41 presents similar data for Model 3769, tested in a 600- by 60-foot channel. The effect of ship speed is the same as discussed in the previous paragraph.

Figures 4.42, 4.43, 4.44, and 4.45 present all the data for comparison of the equilibrium rudder angles with the rudder angles to counteract yawing moment at zero angle of yaw for Models 3859 and 3769. A study of these graphs together with Figures 4.38, 4.39, and 4.40 leads to the following

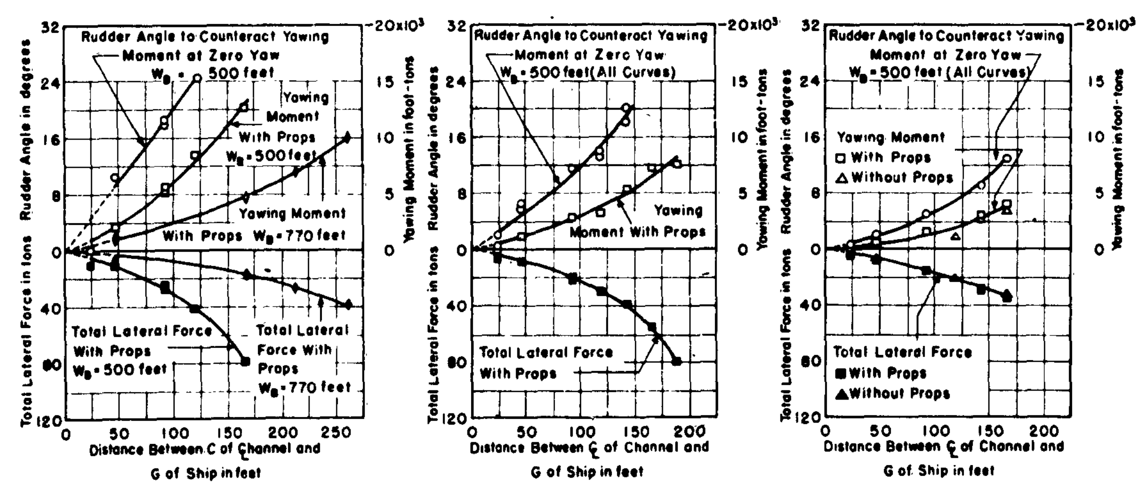


a - Channel Depth 45 Feet   b - Channel Depth 60 Feet   c - Channel Depth 80 Feet

Figure 4.38 - Rudder Angle, Yawing Moment, and Total Lateral Force as Functions of the Distance between the Centerline of the Channel and the Center of Gravity of the Ship for a Ship Speed of 10 Knots

Yawing moment and total lateral force are measured with the self-propelled model at zero angle of yaw unless otherwise stated. For these measurements the rudder was set at zero degrees.

Location of tests: Circulating-water channel
Model data: Model 3859, λ - 35
Channel dimensions: Side slope - vertical

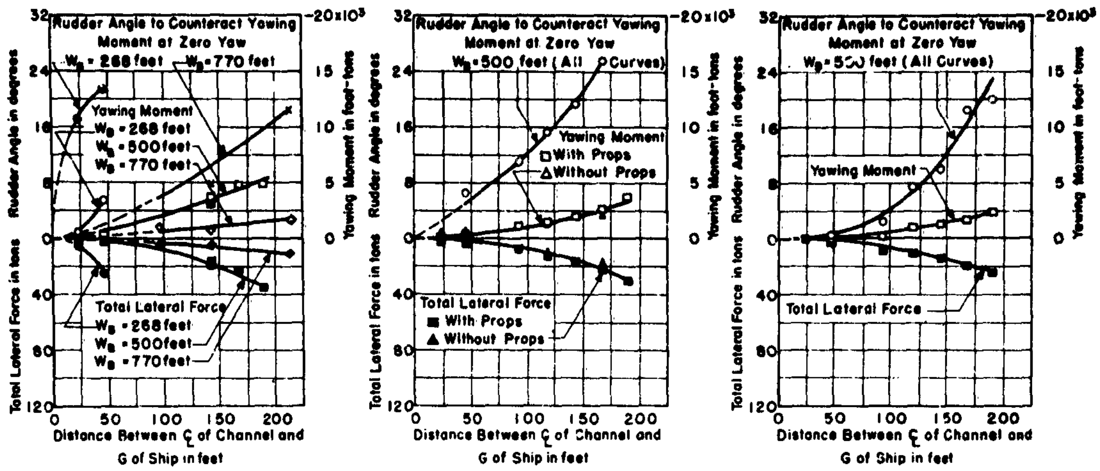


a - Channel Depth 45 Feet   b - Channel Depth 60 Feet   c - Channel Depth 80 Feet

Figure 4.39 - Rudder Angle, Yawing Moment, and Total Lateral Force as Functions of the Distance between the Centerline of the Channel and the Center of Gravity of the Ship for a Ship Speed of 7.5 Knots

Yawing moment and total lateral force are measured with the self-propelled model at zero angle of yaw unless otherwise stated. For these measurements the rudder was set at zero degrees.

Location of tests: Circulating-water channel
Model data: Model 3859, λ - 35
Channel dimensions: Side slope - vertical

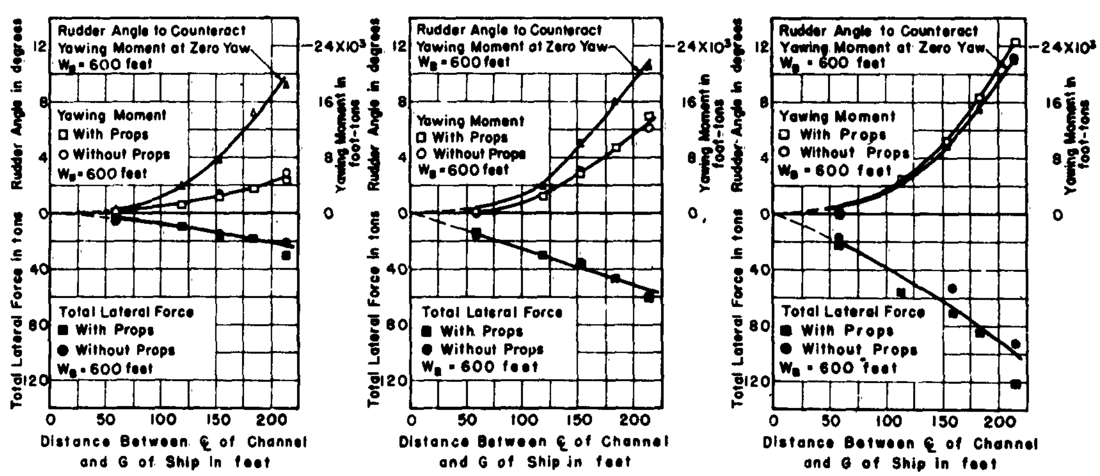


a - Channel Depth 45 Feet
b - Channel Depth 60 Feet
c - Channel Depth 80 Feet

Figure 4.40 - Rudder Angle, Yawing Moment, and Total Lateral Force as Functions of the Distance between the Centerline of the Channel and the Center of Gravity of the Ship for a Ship Speed of 4.56 Knots

Yawing moment and total lateral force are measured with the self-propelled model at zero angle of yaw unless otherwise stated. For these measurements the rudder was set at zero degrees.

Location of tests: Circulating-water channel
Model data: Model 3859, λ - 35
Channel dimensions: Side slope - vertical

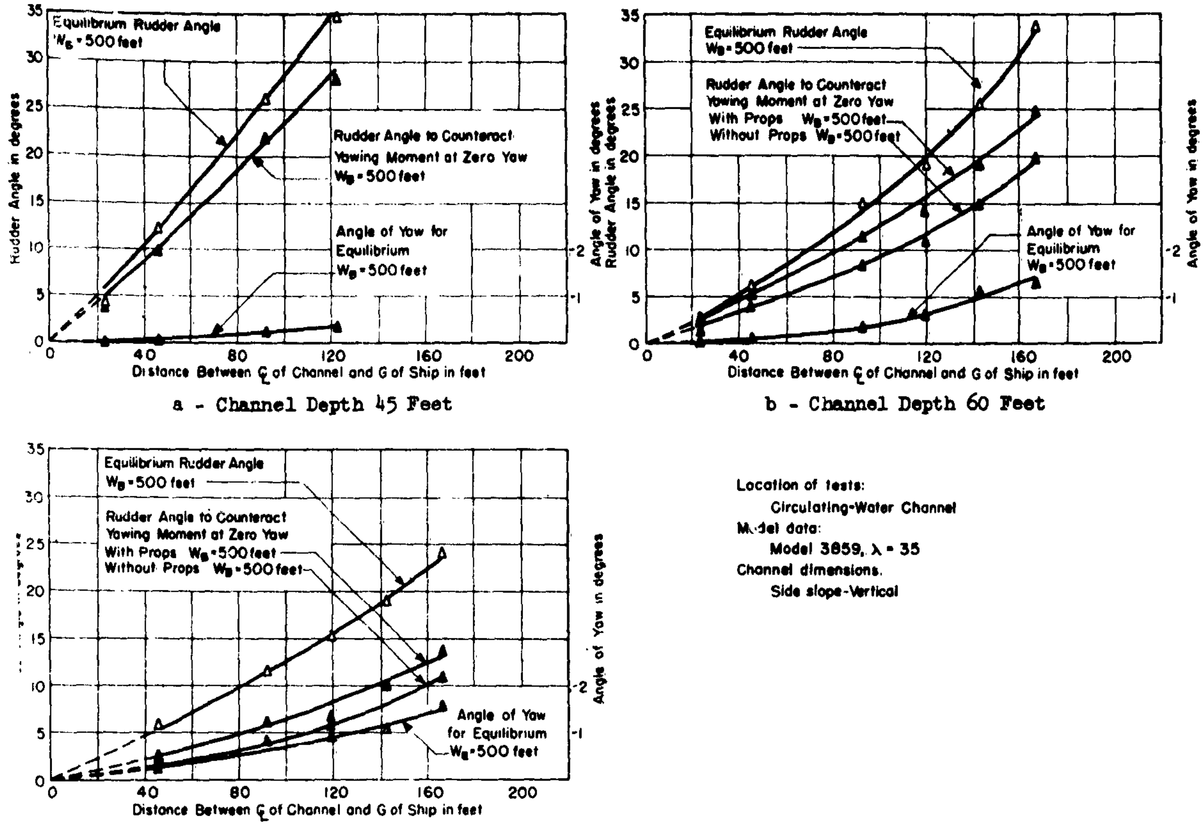


a - Ship Speed 4.5 Knots
b - Ship Speed 7.5 Knots
c - Ship Speed 10 Knots

Figure 4.41 - Rudder Angle, Yawing Moment, and Total Lateral Force as Functions of the Distance between the Centerline of the Channel and the Center of Gravity of the Ship for Model 3769

Yawing moment and total lateral force are measured with the model at zero angle of yaw. For these measurements the rudder was set at zero degrees.

Location of tests: Circulating-water channel
Model data: Model 3769, λ - 45
Channel dimensions: Side slope - vertical



a - Channel Depth 45 Feet

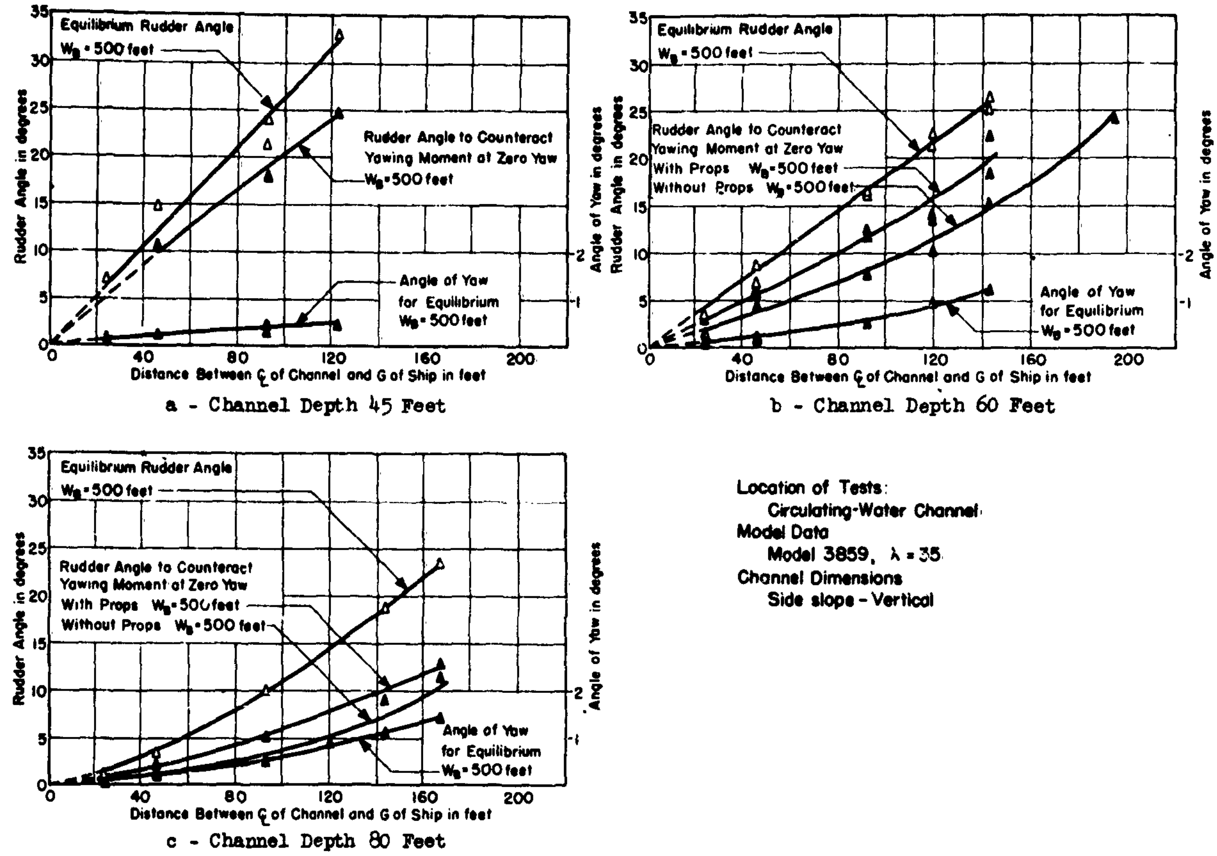
b - Channel Depth 60 Feet

c - Channel Depth 80 Feet

Figure 4.42 - Rudder Angle for Equilibrium and Rudder Angle for Zero Moment at Zero Angle of Yaw as Functions of the Distance between the Centerline of the Channel and the Center of Gravity of the Ship for a Ship Speed of 10 Knots

Rudder angle to counteract yawing moment at zero angle of yaw is measured with propellers unless otherwise stated.

conclusions: The yawing moment acting on the ship due to bank suction is not materially affected by the action of the propellers; however, the action of the propellers does materially affect the counteracting moment produced by the rudder. In the case of Model 3769, the propeller action apparently increases the moment produced by the rudder, whereas with Model 3859 the opposite is apparently true.



Location of Tests:
Circulating-Water Channel
Model Data
Model 3859, $\lambda = 35$
Channel Dimensions
Side slope - Vertical

Figure 4.43 - Rudder Angle for Equilibrium and Rudder Angle for Zero Moment at Zero Angle of Yaw as Functions of the Distance between the Centerline of the Channel and the Center of Gravity of the Ship for a Ship Speed of 7.5 Knots

Rudder angle to counteract yawing moment is measured at zero angle of yaw with propellers unless otherwise stated.

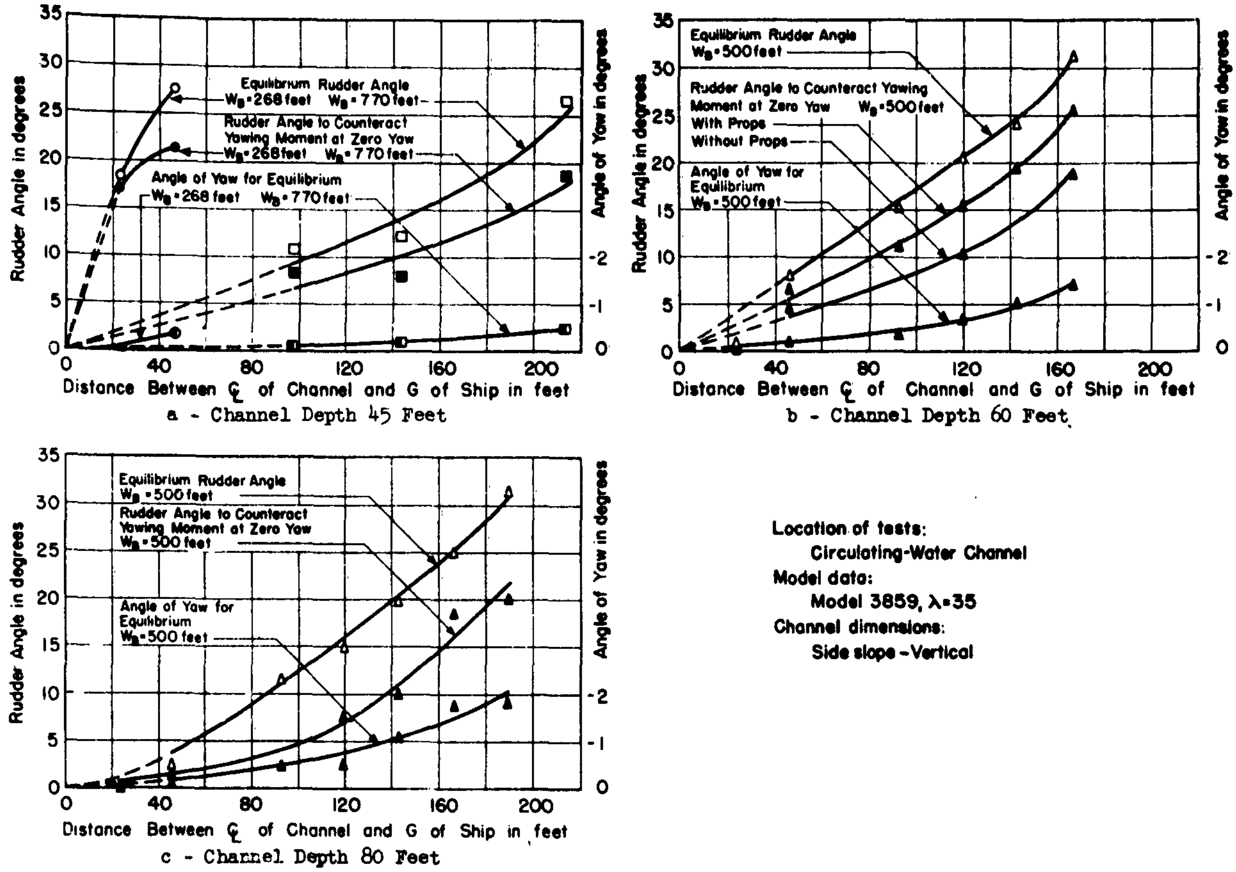


Figure 4.44 - Rudder Angle for Equilibrium and Rudder Angle for Zero Moment at Zero Angle of Yaw as Functions of the Distance between the Centerline of the Channel and the Center of Gravity of the Ship for a Ship Speed of 4.56 Knots

Rudder angle to counteract yawing moment is measured at zero angle of yaw with propellers unless otherwise stated.

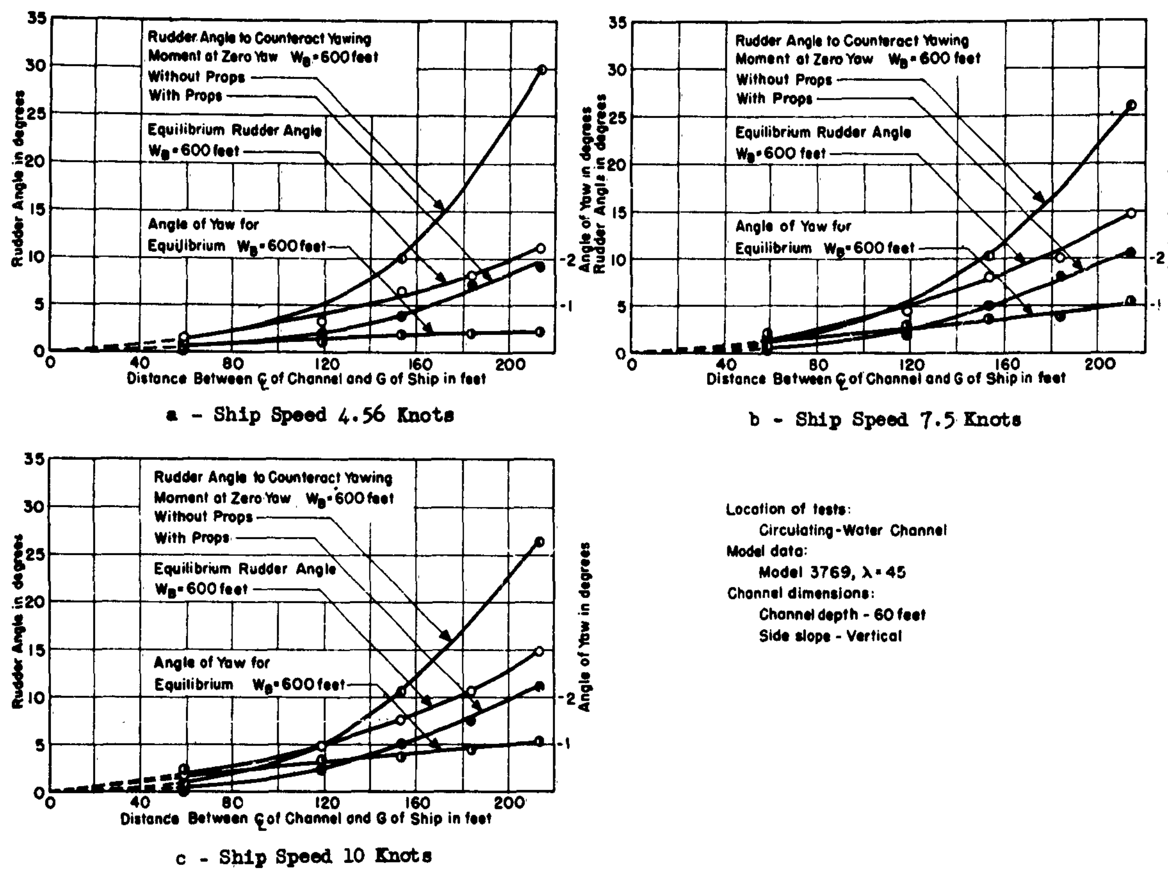


Figure 4.45 - Rudder Angle for Equilibrium and Rudder Angle for Zero Moment at Zero Angle of Yaw as Functions of the Distance between the Centerline of the Channel and the Center of Gravity of the Ship for Model 3769

TABLE 4.1

Equilibrium-Rudder-Angle Data Obtained from Shallow-Water-Basin Tests

Date Tests Were Made	Model	λ	Channel Width in feet	Channel Depth in feet	Side Slope degrees	V_s* knots	V_w** knots	Y† feet	Rudder Angle for Equilibrium degrees
14-27 Nov 46	3769	45	300	45	45	5	0	22.5	6.5
						6			7.5
						7			8.5
						8			9.5
						9			10.5
14-27 Nov 46	3769	45	300	45	45	5	0	45	14
						6			14
						7			18
						8			20
						9			21
14-27 Nov'46	3769	45	300	45	45	5		67.5	23
17 Dec 46	3769	45	300	60	45	5	0	22.5	3
						6			3.5
						8			4
18 Dec 46	3769	45	300	60	45	10	0	22.5	4
						12			5
						13			5
19 Dec 46	3769	45	300	60	45	5	0	45	6.5
						6			6
23 Dec 46	3769	45	300	60	45	8	0	45	7.5
						10			8
						12			9
						13			10
30 Dec 46	3769	45	300	60	45	5	0	67.5	11
						7			12
						9			13
						10			13.5
8 Jan 47	3769	45	300	80	45	5	0	22.5	1
						7			2
						9			2.5
						10			2.5
						12			3
						14			3.5
						15			3.0
16 Jan 47	3769	45	300	80	45	5	0	45	3.5
						7			3.5
						9			5
						10			4.5
						12			5.0
						14			5.5
						15			5.5
10 and 13 Jan 47	3769	45	300	80	45	5	0	45	4.5
						7			5
						9			4.5
						10			4.5
						12			4.5
						14			5
						15			5
13 Jan 47	3769	45	300	80	45	5	0	67.5	7
						7			7.5
						9			7.5
						10			8
						12			8.5
						14			9
						15			8.5

* V_s is the ship speed with respect to the water.

** V_w is the water speed (+ indicates a following current, - indicates an ahead current).

† Y is the distance between centerline of the channel and center of gravity of the ship.

TABLE 4.1 (Continued)

Date Tests Were Made	Model	λ	Channel Width in feet	Channel Depth in feet	Side Slope degrees	V_s knots	V_w knots	Y feet	Rudder Angle for Equilibrium degrees
16 Jan 47	3769	45	300	80	45	5	0	90	8.5
						7			8
						9			8
27 Jan 47	3769	45	500	45	45	5.45	0	45	2.5
						7.25			4
						9			5.4
						10			6.2
						11			6.75
						11.9			7.8
28 Jan 47	3769	45	500	45	45	5	0	90	7.5
						6.1			8.5
						7			9
						7.98			10
						8.75			10.6
						9.8			11.5
						11			14
						11.75			16.5
6 Feb 47	3769	45	500	45	45	4.8	0	135	13.75
						5			15.5
						5.8			13.5
						6.8			17.5
						7			16
						7.9			18
						8.8			19.75
						9.8			21.5
29 Jan 47	3769	45	500	60	45	5	0	90	5.5
						7			6.0
						9			6.5
						10			6
						12			6.5
						14			8
10 Feb 47	3769	45	500	60	45	5	0	90	5.25
						7			5.8
						9			6.5
						11			6.9
11 Feb 47	3769	45	500	60	45	4.1	0	135	8.2
						5			9
						7			9
						9			9
						11			9.4
						11.5			9.5
						13			12.4
11 Feb 47	3769	45	500	60	45	5.25	0	135	8.8
						6			9.3
						8.1			9
						10.1			9
						12			11
14 Feb 47	3769	45	500	60	45	5	0	167.5	15
						7			16
						8			16
						9			16
						10			16
						12			21
21 Feb 47	3769	45	500	80	45	5	0	45	1
						7			0.7
						9			1.5
						11			1.7
						13			2

TABLE 4.1 (Continued)

Date Tests Were Made	Model	i_λ°	Channel Width in feet	Channel Depth in feet	Side Slope degrees	V_s knots	V_w knots	Y feet	Rudder Angle for Equilibrium degrees
21 Feb 47	3769	45	500	80	45	15	0	45	2.2
21 Feb 47	3769	45	500	80	45	5	0	90	2.5
						7			3
						9			3.7
						11			4
						13			4.2
						15			4.7
21 Feb 47	3769	45	500	80	45	5	0	135	5.5
						7			5.2
						9			6
						11			6
						13			6.7
						15			8
21 Feb 47	3769	45	500	80	45	5	0	167.5	6.5
						7			7.5
						9			7.5
						10			7.5
						12			7.5
						14			7.5
						16			9.5
3 Mar 47	3769	45	700	45	45	5.2	0	90	2.7
						7			3
						9			3.2
						11.1			4
						13			7
4 Mar 47	3769	45	700	45	45	5	0	180	8.5
						7			9.5
						9			10.5
						10			11.5
						11			13
						12			16
5 Mar 47	3769	45	700	45	45	5.33	0	267.5	21.2
						6			23
						7.26			24
						8			27
						8.65			28
						9			29
6 Mar 47	3769	45	700	60	45	5	0	90	1.7
						7			1.5
						9			2
						10			2
						12			2
						14			2
						16			3
7 Mar 47	3769	45	700	60	45	5	0	180	5.5
						10			6.5
						13			6.3
						14			6
						16			11
7 Mar 47	3769	45	700	60	45	5	0	267.5	11.5
						7			14.5
						9			14
						10			17
						11			17.5
10 Mar 47	3769	45	700	80	45	5	0	180	3.5
						10			4.25
						12			4.7
						13			5
						14			5.5
						15			6.5
						16			6.7

TABLE 4.1 (Continued)

Date Tests Were Made	Model	λ	Channel Width in feet	Channel Depth in feet	Side Slope degrees	V_s knots	V_w knots	Y feet	Rudder Angle for Equilibrium degrees
11 Mar 47	3769	45	700	80	45	5	0	225	6
						8			6.5
						10			7.5
						12			8.5
						13			8.75
						14			8.8
						15			9
						16			9.7
10 Mar 47	3769	45	700	80	45	5	0	267.5	7
						6			8
						7			8.5
						9			9
						11			9.5
						13			10
						14			10.5
						15			11.5
						16			12
12 Jun 47	3748-4	45	500	60	45	5	0	90	1
						7.5			1
13 Jun 47	3748-4	45	500	60	45	5	0	135	2
						7.5			2
						10			2
19 Jun 47	3748-4	45	500	60	45	5	0	200	5
						7.5			8
						10			10
27 Jun 47	3748-4	45	500	60	45	5	+5	135	3
						7.5			4
						9			4
						10			4
30 Jun 47	3748-4	45	500	60	45	5	+5	200	5
						7.5			10
						8.5			10
						10			10
1 Jul 47	3748-4	45	500	60	45	2	+5	200	6
						3			6
						4			6
						5			6
						6			10
						7.5			10
						8.5			12
						9			12
						10			12
20 Jun 47	3748-4	45	500	60	45	7.5	-5	135	4
						10			3
24 Jun 47	3748-4	45	500	60	45	5	-5	200	2
						7.5			4
						10			9
3 Jul 47	4018	45	500	60	45	10	0	45	6.25
								90	15.5
								135	22.5
3 Jul 47	4018	45	500	60	45	10	+5	45	5
								90	13
								135	26

TABLE 4.2

Data Obtained from Force-Measurement Tests in the Circulating-Water Channel

Date Tests Were Made	Model	λ	Channel Width feet	Channel Depth feet	Side Slope degrees	V, † knots	Y †† feet	Equilibrium Rudder Angle in degrees	Angle of Yaw for Equilibrium in degrees	Rudder Angle* for Zero Yaw in degrees (with Props.)	Rudder Angle* for Zero Yaw in degrees (without Props.)	Yawing Moment** for Zero Yaw in ft-tons (with Props.)	Total Lateral** Force for Zero Yaw in tons (with Props.)	Yawing Moment** for Zero Yaw in ft-tons (without Props.)	Total Lateral** Force for Zero Yaw in tons (without Props.)
22-31 Oct 46	3859	35	268	45	Vertical	4.56	23.2	18.3	-0.1	17		-562	4.9		
2-18 Oct 46	3859	35	268	45	Vertical	4.56	46.6	27.5	-0.3	21.3		-3,495	25.7		
5-7 Mar 47	3859	35	500	45	Vertical	4.56	23.3	6	-0.1			-413	1.3		
							45.8	11.8	-0.1			-413	3.0		
								12	-0.1						
								12	-0.2						
							92.4	22	-0.4						
							92.4	23	-0.3						
							142.8					-3,902	18		
												-3,845	16.1		
												-3,264	16.3		
												-3,208	19.9		
							166.2					-4,783	23.4		
							189.4					-4,990	36.0		
22 Mar 47	3859	35	500	45	Vertical	7.5	23.3	7	-0.2	21.3		-188	10.3		
							45.8	14.8	-0.2	10.5					
							45.8					-2,138	10.7		
21 Mar 47	3859	35	500	45	Vertical	7.5	92.4	21.3	-0.3	17.8		-5,622	26.2		
26 Mar 47	3859	35	500	45	Vertical	7.5	92.4	23.8	-0.4	18.5		-5,121	26.8		
							92.4					-5,220	25.7		
							119.5					-8,415	41.4		
25 Mar 47	3859	35	500	45	Vertical	7.5	122.5	33.0	-0.5	24.6					
22 Mar 47	3859	35	500	45	Vertical	7.5	166.3	33.0	-0.5	24.6		-13,970	79.2		
31 Mar 47	3859	35	500	45	Vertical	10.0	23.3	4.4	0	3.8		-1,261	7.1		
29 Mar 47	3859	35	500	45	Vertical	10.0	45.8	12.2	-0.1	9.8		-4,374	22.9		
							92.4	26.0	-0.2	22.0		-11,052	45.7		
							119.5					-17,482	63.0		
29 Mar 47	3859	35	500	45	Vertical	10.0	122.5	34.6	-0.4	28.0					

† V, ship speed relative to undisturbed water.
†† Y is the distance between centerline of channel and center of gravity of ship.

* Rudder angle to counteract yawing moment at zero yaw.
** These measurements were taken with the rudder set amidship.

TABLE 4.2 (Continued)

Date Tests Were Made	Model	λ	Channel Width feet	Channel Depth feet	Side Slope degrees	V, knots	Y feet	Equilibrium Rudder Angle in degrees	Angle of Yaw for Equilibrium in degrees	Rudder Angle for Zero Yaw in degrees (with Props.)	Rudder Angle for Zero Yaw in degrees (without Props.)	Yawing Moment for Zero Yaw in ft-tons (with Props.)	Total Lateral Force for Zero Yaw in tons (with Props.)	Yawing Moment for Zero Yaw in ft-tons (without Props.)	Total Lateral Force for Zero Yaw in tons (without Props.)
29 Apr 47	3859	35	500	60	Vertical	4.56	23.3	0.6	0	0.5					
							23.3					-195	0.9		
30 Apr 47	3859	35	500	60	Vertical	4.56	45.8	8.0	-0.2	6.5	4.5	-435	3.6	-502	1.5
							45.8					502	1.5		
							92.4	15.2	-0.3	11.0		-1,073	7.9		
							119.4	20.5	-0.7	15.4	10.2	-1,500	2.9	-1,200	10.7
							142.8	24.0	-1.0	19.3		-2,054	6.3		
							166.3	31.5	-1.4	25.5	18.8	-2,700	22.3	-2,054	18.0
							189.4					-3,510	31.5		
15 Apr 47	3859	35	500	60	Vertical	7.5	23.3	2.7	-0.2	0.5	1.4	-128	7.1		
							45.8	6.7	-0.2	6.6	4.3	-1,185	8.8		
16 Apr 47	3859	35	500	60	Vertical	7.5	92.4	6.7	-0.5	11.5	7.8	-2,895	21.4		
							92.4	16.6	-0.5	11.6		-2,872	20.0		
							119.4	22.5	-0.9	13.3	10.2	-3,248	31.1		
17 Apr 47	3859	35	500	60	Vertical	7.5	142.8	26.2	-1.2	20.2	15.3	-5,310	38.8		
							166.3					-7,179	55.6		
26 Apr 47	3859	35	500	60	Vertical	7.5	189.4				24.2	-7,645	80.2		
					Rerun of above tests		23.3	3.5	-0.1	2.1					
							45.8	8.5	-0.2	5.8					
							92.4	16.0	-0.5	11.5					
							119.3	21.2	-0.9	14.0					
							142.8	25.0	-1.2	18.2					
24 Apr 47	3859	35	500	60	Vertical	10.0	23.3	2.2	-0.0	1.6	1.2	-997	10.1	-810	7.9
							45.8	6.1	-0.1	5.1	3.8	-2,511	9.9	-1,979	17.2
							92.4	14.9	-0.3	11.2	8.4	-5,510	37.3	-4,310	40.8
							119.4	19.0	-0.6	14.1	10.9	-7,070	50.8	-5,615	52.8
25 Apr 47	3859	35	500	60	Vertical	10.0	142.8	25.3	-1.1	19.0	14.8	-10,370	75.8	-7,810	65.0
							166.2	33.9	-1.3	24.8	19.8	-13,850	105.8	-10,670	86.8
12 May 47	3859	35	500	80	Vertical	4.56	23.3	0	0	0		0	0		
							45.8	2.5	-0.2	0.5		-75	2.1		
							92.4	11.5	-0.5	2.5		-360	8.4		
							119.4	15.0	-0.5	7.5		-998	10.1		
							142.8	19.8	-1.1	10.0		-1,447	13.5		
							166.2	25.0	-1.8	18.5		-1,687	19.3		
							189.4	31.5	-1.8	20.0		-2,383	24.2		

TABLE 4.2 (Continued)

Date Tests Were Made	Model	λ	Channel Width feet	Channel Depth feet	Side Slope degrees	V, knots	Y feet	Equilibrium Rudder Angle in degrees	Angle of Yaw for Equilibrium in degrees	Rudder Angle for Zero Yaw in degrees (with Props.)	Rudder Angle for Zero Yaw in degrees (without Props.)	Yawing Moment for Zero Yaw in ft-tons (with Props.)	Total Lateral Force for Zero Yaw in tons (with Props.)	Yawing Moment for Zero Yaw in ft-tons (without Props.)	Total Lateral Force for Zero Yaw in tons (without Props.)
1 May 47	3859	35	500	80	Vertical	7.5	23.3	1.2	-0.0	0.8		-127	2.2		
												0	1.3		
												-375	4.3		
							45.8	3.4	-0.2	2.0	1.2	-622	7.1	-322	7.1
							92.4	10.0	-0.5	5.0		-1,500	15.9		
							119.4				4.3			-1065	20.8
							142.8	18.8	-1.1	9.0		-3,000	30.0		
												-2,781	28.7		
							166.3	23.1	-1.4	12.9	11.2	-4,071	35.0	-3450	32.2
9 May 47	3859	35	500	80	Vertical	10.0	45.8	6.0	-0.4	2.5	1.0	-825	15.0	-375	11.6
7 May 47	3859	35	500	80	Vertical	10.0	92.4	11.6	-0.8	5.8		-2,378	30.2		
							119.4	15.2	-0.9	6.8		-2,685	46.5	-2678	42.2
												-3,000	35.6		
							142.8	19.0	-1.1	10.0		-4,635	58.6		
							166.3	24.0	-1.6	13.8	10.9	-7,875	73.0	-6000	64.3
14 Nov 46	3859	35	770	45	Vertical	4.56	97.3	10.7	-0.1	8.2		-900	4.3		
6 Dec 46	3859	35	770	45	Vertical	4.56	143.5	12.1	-0.2	7.8		-825	4.9		
10-13 Dec 46	3859	35	770	45	Vertical	4.56	213.5	26.5	-0.5	18.6		-1,650	10.5		
23 Jan 47	3859	35	770	45	Vertical	7.5	46.6	8.2	-0.1			-1,000	6.5		
22 & 23 Jan 47	3859	35	770	45	Vertical	7.5	167.0	21.2	-0.1			-4,700	16.5		
21 Jan 47	3859	35	770	45	Vertical	7.5	213.6	27.5	-0.2			-7,050	27.0		
							260.0					-10,000	39.5		
27 & 31 Dec 46	3859	35	770	45	Vertical	10.0	143.5	18.5	-0.2			-5,739	41.6		
2, 3, 6 Jan 47	3859	35	770	45	Vertical	10.0	213.6	29.0	-0.8			-13,870	55.8		
							59.0	1.5	-0.1	0.3	1.0				
16 May 47	3769	45	600	60	Vertical	4.56						-164	4.1	62	5.9
							118.8	3.2	-0.2	2.0		-1,332	9.1		
							153.4	6.5	-0.4	3.8	10.0	-2,214	16.9	-2726	15.0
							183.6	8.2	-0.4	7.2		-3,792	18.2		

TABLE 4.2 (Continued)

Date Tests Were Made	Model	λ	Channel Width feet	Channel Depth feet	Side Slope degrees	V, knots	Y feet	Equilibrium Rudder Angle in degrees	Angle of Yaw for Equilibrium in degrees	Rudder Angle for Zero Yaw in degrees (with Props.)	Rudder Angle for Zero Yaw in degrees (without Props.)	Yawing Moment for Zero Yaw in ft-tons (with Props.)	Total Lateral Force for Zero Yaw in tons (with Props.)	Yawing Moment for Zero Yaw in ft-tons (without Props.)	Total Lateral Force for Zero Yaw in tons (without Props.)
19 May 47	3769	45	600	60	Vertical	4.56	213.8	11.1	-0.4	9.2	30.0	-4,776	30.5	-5,842	21.0
20 May 47	3769	45	600	60	Vertical	7.5									
							59.0	1.8	-0.4	0.2	0.5	-205	13.7	-102	16.4
							118.8	4.5	-0.6	2.0		-2,419	30.5		
							153.4	8.0	-0.7	5.0	10.2	-5,842	36.4	-5,842	36.4
							183.6	10.0	-0.8	8.0		-9,430	47.4		
							213.8	14.8	-1.1	10.5	26.0	-14,042	61.0	-12,198	59.2
21 May 47	3769	45	600	60	Vertical	10.0									
							59.0	1.8	-0.5	0	-0.8	-144	22.3	-205	16.4
							118.8	4.8	-0.6	2.2		-4,982	56.0		
							153.4	7.5	-0.7	5.0	10.5	-10,455	71.1	-10,455	52.8
22 May 47	3769	45	600	60	Vertical	10.0	183.6	10.5	-0.9	7.5		-16,708	84.7		
21 May 47	3769	45	600	60	Vertical	10.0	213.8	14.8	-1.0	11.[illegible]	26.2	-24,662	121.6	-22,386	92.5
4 Feb 47	3673-A	44.5	979	60	Vertical	5	59.2	1.4	-0.12			-1,373	0.9		
							212.3	4.9	0			-3,334	8.8		
							212.3	5.1	-0.03			-3,334	9.7		
							271.4	7.2	-0.14			-4,471	9.2		
30 Jan 47						7.5	59.2	1.9	-0.17			-1,255	9.2		
							212.3	5.9	-0.13			-5,981	25.6		
							271.4	7.9	-0.15			-10,531	30.4		
						10.0	59.2	2.0	0			-4,902	13.2		
							212.3	4.2	0			-13,727	33.0		
							271.4	8.1	0			-19,512	48.5		

SECTION 5

CONTROLLABILITY OF SHIPS IN TWO-WAY TRAFFIC IN STRAIGHT CHANNELS

ABSTRACT

The model tests described in this section were undertaken to obtain information as to the effect of channel dimensions on the controllability of specified ships under specified conditions of operation in two-way traffic in straight channels. Particular note was made of the interaction between ships and of the controllability of ships during the meeting maneuver. The majority of these tests represented a channel of 500-foot width and 60-foot depth constructed at a linear ratio of 45. The two models used throughout these tests represented a large naval vessel and a modified Liberty ship and were run at speeds of 5, 7.5, and 10 knots. Tests were made in still water and in ahead and following currents of 3 and 5 knots. The results indicated that no serious maneuvering difficulties would be experienced under these conditions with the two ships meeting at normal clearance distances.

INTRODUCTION

The two-way-traffic studies are part of the restricted-channel model tests made at the David Taylor Model Basin and sponsored by the Panama Canal under the authority of Public Law 280, Seventy-Ninth Congress. The studies were made to determine the effect of varying the cross-sectional dimensions of the channel and to observe the effect of current on the handling characteristics of specified ships meeting in a restricted channel. When two ships meet in a restricted channel their movements and controllability are not the same as they are in open water. This is due to the bank suction between the ship and the channel boundaries and to the interaction between ships meeting in the canal. The tests were made in model channels erected in the shallow water basin. A general view of a restricted-channel setup is shown in Figure 4.1. The studies were made with two models; Model 3769, representing a large naval vessel and Model 3748-4 representing a modified Liberty ship. These ship types were chosen because this combination of a large naval vessel and a Liberty ship was considered as an example of one of the extreme conditions for two-way traffic in a modernized Panama Canal. Ship speeds were 5, 7.5, and 10 knots, with respect to the undisturbed water. Ten knots was considered the top normal operational speed for ships meeting under these conditions. Tests were also made with ahead and following currents of 3 and 5 knots as this covered the maximum expected current in case a sea-level canal is constructed at Panama and in event the tide-control structures become inoperative. All of these tests were made with Panama Canal pilots giving the necessary rudder orders to maneuver the self-propelled models.

The results of these tests were judged primarily on visual observation. Additional conclusions have been made from a study of the photographs, the engineer's test notes, and from the pilot's comments.

GENERAL CONSIDERATIONS

A linear ratio of 45 between model and full scale was chosen as being the most suitable for these tests. The basis for the selection of this linear ratio is described in detail in Section 2. Model 3769, the large naval vessel, was 20 feet in length and Model 3748-4, the Liberty ship, was 10 feet in length.

The investigations in this section were conducted with Froude's law as the basis for relating model and full-scale dimensions and phenomena. With this law as a basis the following relationship must be maintained:

a. Time rates for the model should equal the time rates for the full-scale ship multiplied by the square root of the linear ratio. These time rates include rate of rudder movement, propeller RPM, and also the number of rudder orders given per unit of time.

b. Velocity for the model and for the current should equal the full-scale value divided by the square root of the linear ratio.

The general situation which exists when two ships meet in a restricted channel is as follows. Each ship interferes with the lines of flow about the other vessel with the result that an asymmetrical pressure distribution develops on the two sides of each vessel which tends to divert the ships from their original path. Throughout the meeting maneuver, the turning moment caused by these pressures changes direction several times. At first, when the bows of the two vessels come abreast of each other, there is a tendency of the two vessels to yaw away from each other due to the water surface building up between them. As the bow of one vessel approaches the stern of the other ship, the bow tends to move towards the low water in the vicinity of the stern of the other ship. As the sterns of the ships come opposite each other, the low water surface between them tends to bring the two sterns towards each other. Superimposed upon this interaction between the two ships is the effect caused by bank suction. In general, bank suction tends to cause the vessel to yaw away from the near bank. Model tests appeared to be a practical means of studying the effects of these phenomena on the controllability of the ships.

Normal ship clearance was considered to be 100 feet or the beam of the larger vessel, whichever is the greater. This distance was agreed upon in a conference attended by members of the Special Engineering Division of the Panama Canal, Panama Canal Pilots, and members of the DTMB staff.

TEST APPARATUS

The two-way-traffic studies were made with a series of scale models of restricted channels erected in the shallow water basin at the David Taylor Model Basin. The test procedure and equipment was quite similar to that used on the one-way-traffic studies previously conducted and reported in Section 4. The water in the test section could be controlled as regards depth and current speed. A detailed description of this equipment, its control, and calibration is given in Section 3.

The first series of tests were made in 700-foot and 500-foot channels with still water. The meeting conditions for the 700-foot channel are shown in Figure 5.1. The observational tests described in Section 4 indicate that the normal width of the ship lane is approximately 170 per cent of the beam of the ship and this is the basis for the ship lanes shown in Figures 5.1 and 5.2.

In the first series of tests the modified Liberty ship was towed on an endless cable while the large naval vessel was self-propelled, free to maneuver, and controlled from the towing carriage which followed it down the channel. The control of the model was effected by means of a small cable which carried the electrical leads necessary for operation of the propellers and rudder gear. It was attempted to keep this power cable slack and directly over the model so as not to influence the movement of the model. In this series of tests the original rudder-control apparatus was used. This apparatus did not give quite as good control as the electronic rudder-control gear which

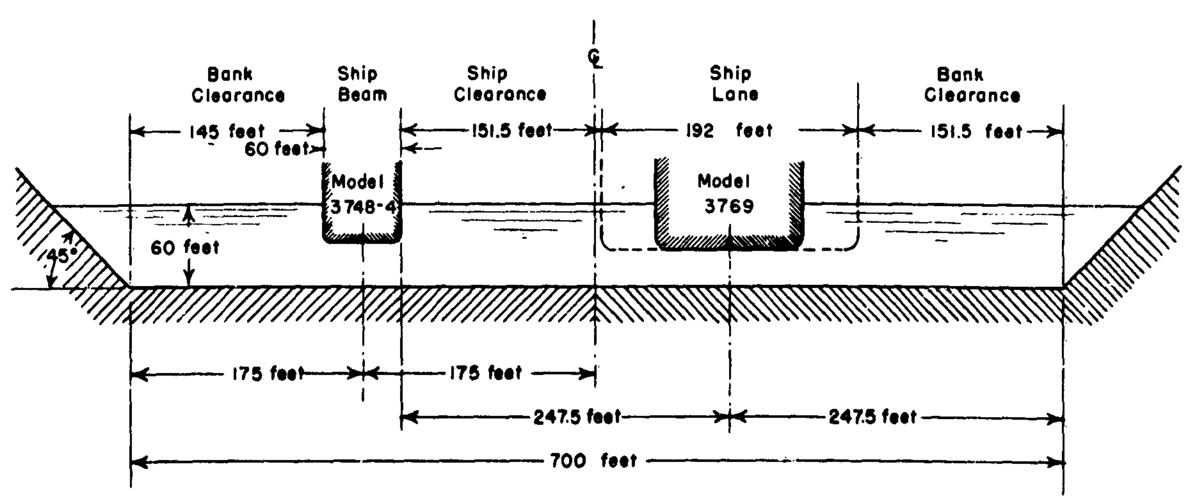


Figure 5.1 - Test Conditions in a 700-Foot Channel

Model 3748-4 was towed by cable at the indicated position whereas Model 3769 was self-propelled and maneuvered by Panama Canal pilots. Model 3769 was started on the channel centerline and then was maneuvered past Model 3748-4 at approximately the center of the available channel after which it was maneuvered back to the channel centerline.

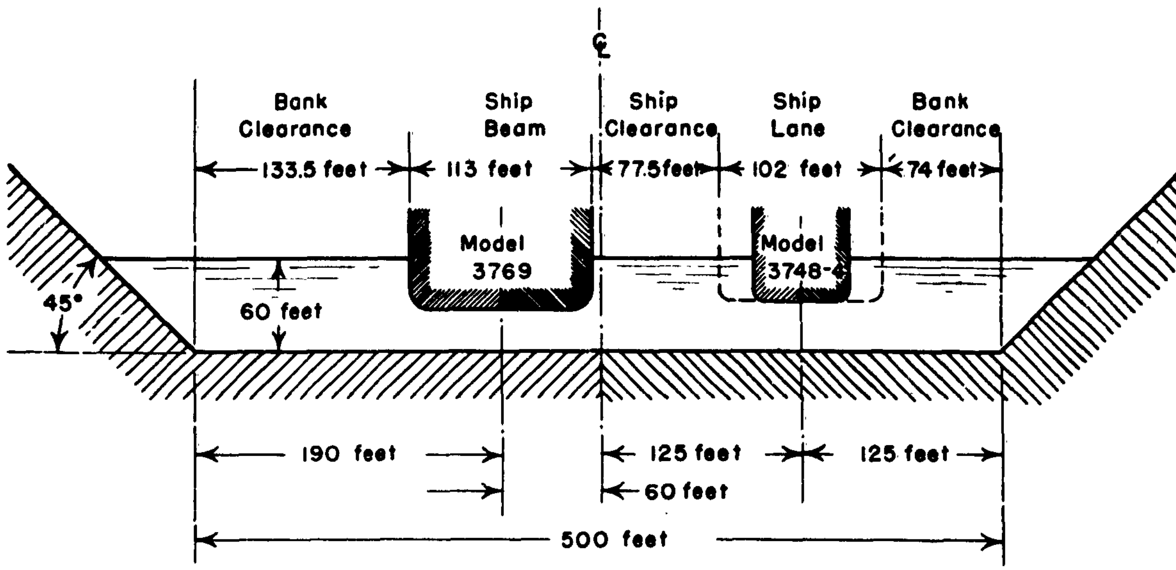


Figure 5.2 - Test Conditions in a 500-Foot Channel

Model 3769 was towed by cable at the indicated position whereas Model 3748-4 was self-propelled and maneuvered by Panama Canal pilots. Model 3748-4 was started on the channel centerline and then was maneuvered past Model 3769 at approximately the quarter point of the channel, after which it was maneuvered back to the channel centerline.

was developed later. In addition to the visual observations some photographic records (Addendum VI) were taken of these tests. The second series of tests, which were conducted with the large naval vessel being towed and the modified Liberty ship being maneuvered, were made with the improved electronic rudder-control apparatus. These tests were all made in a 500-foot by 60-foot channel. In these tests, an overhead camera mounted on the carriage framework was synchronized with another camera which recorded time and rudder angles, shown on the rudder-control box. Records of these photographs are given in Addendum V.

TEST METHODS AND PROCEDURE

In the two-way-traffic studies one model was towed by the endless cable while the other model was maneuvered by Panama Canal pilots. A typical channel arrangement is shown in Figure 5.3. All tests were run with Panama Canal pilots as they were familiar with the handling of full-scale ships. In general, the pilots agreed that models duplicated the handling qualities of the full-scale ships reasonably well. It was attempted to have each pilot make several runs for the same condition and to have at least two different pilots for each condition. Observation of meeting reactions was necessarily limited to the self-propelled model as the towed model was restrained laterally by the cable.

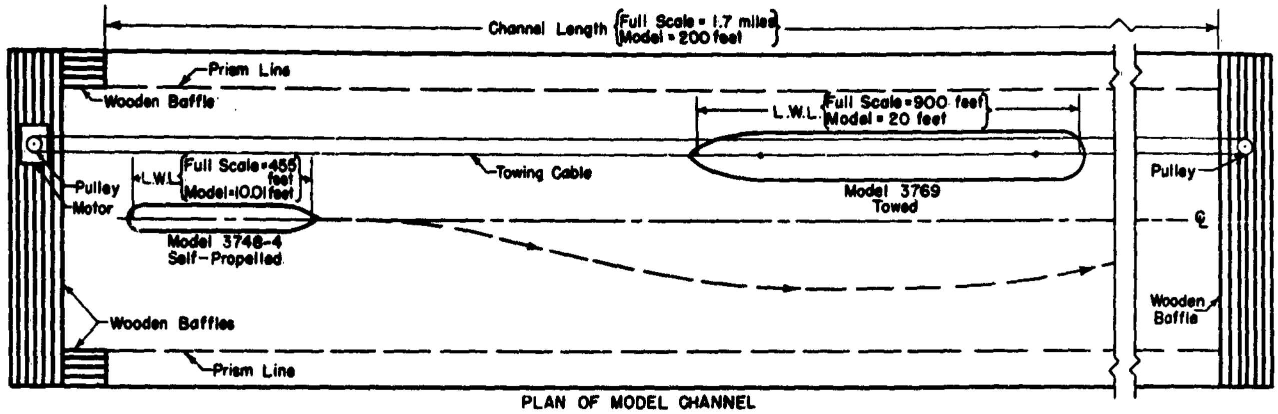


Figure 5.3 - Model and Full-Scale Dimensions of the Channel in Which Models 3769 and 3748-4 Were Tested for Two-Way-Traffic Conditions

The two-way-traffic studies were made in still water and in ahead and following currents of 3 and 5 knots. Tests were run at ship speeds of 5, 7.5 and 10 knots. The speeds of the two ships for the majority of tests were kept equal so that at a ship speed of 5 knots in a 5-knot current, one ship would be stationary while the other would be moving at 10 knots with respect to the ground. Model 3769, when towed, was run at distances of 150 or 190 feet from the prism line. In tests where Model 3748-4 was towed, it was run at the quarter point of the channel width. The procedure was to start both models so that they would meet at approximately the midpoint of the channel. The self-propelled model was released from the towing carriage on the centerline of the channel and then maneuvered past the oncoming towed model and then brought back to the centerline of the channel. The self-propelled model was then secured to the towing carriage and returned to its starting position while in the meantime the towed model had been returned to its starting position.

It was attempted to produce a uniform velocity distribution for the current at the upstream end of the channel. However, a velocity variation within plus or minus 10 per cent of the nominal current over the middle three-fourths of the channel was obtained. In a full-scale channel, the normal distribution tends to be parabolic except in the bends or where the channel sides are very irregular. Current distribution and current control are discussed in Section 3.

TEST RESULTS

Test results as given in the following paragraphs are based mostly on observation of the test runs. This appeared to be the most practical method of evaluating the difficulties experienced in two-way traffic in restricted channels. The terms "ahead current" and "following current" refer to the self-propelled model, rather than the towed model. The conditions under which the tests were run are given in Table 5.1. For simplification, the test results are divided into two groups, dependent upon which model was being maneuvered.

TESTS WITH THE LARGE NAVAL VESSEL (MODEL 3769) BEING MANEUVERED

The two-way-traffic studies for the 700-foot channels were made in still water and in depths of 80, 60, and 45 feet. The large naval vessel was self-propelled and maneuvered by control from the carriage while the modified Liberty ship was towed on a fixed path by an endless cable. Figure 5.1 shows a cross-sectional view of this condition. The large naval vessel was run at speeds ranging from 5 to 15 knots while the Liberty ship was run at speeds of

TABLE 5.1

Test Conditions for Two-Way-Traffic Tests

Width of Channel feet	Depth of Channel feet	Velocity of Current* knots	Maneuvered Model	Towed Model	Distance Z** feet	Speed of Towed Model knots	Speed† of Maneuvered Model knots
700	80	0	3769	3748-4	175	5, 7	5 to 15
700	60	0	3769	3748-4	175	5, 10	5 to 15
700	45	0	3769	3748-4	175	5, 7, 10	5 to 13
500	45	0	3769	3748-4	125	5, 7	5 to 15
500	60	0	3748-4	3769	150	5, 7.5, 10	5, 7.5, 10
500	60	-3	3748-4	3769	150	5, 7.5, 10	5, 7.5, 10
500	60	-5	3748-4	3769	150	5, 7.5, 10	5, 7.5, 10
500	60	0	3748-4	3769	190	5, 7.5, 10	5, 7.5, 10
500	60	-3	3748-4	3769	190	5, 7.5, 10	5, 7.5, 10
500	60	-5	3748-4	3769	190	5, 7.5, 10	5, 7.5, 10
500	60	+3	3748-4	3769	190	5, 7.5, 10	5, 7.5, 10
500	60	+5	3748-4	3769	190	5, 7.5, 10	5, 7.5, 10

* Ahead currents are denoted by (-) and following currents by (+).

** Distance Z is the distance between the centerline of the towed model and the near prism line.

† In the tests for the 500- by 60-foot channel the speeds of the two models were always kept equal in a given run.

5, 7, or 10 knots. The procedure used in these tests was to start the naval vessel on the centerline of the channel and then maneuver past the Liberty ship at approximately the quarter point of the channel and then return to the centerline. No serious difficulty was had in maneuvering the large naval vessel at speeds up to 10 knots regardless of the depth of water although it was indicated that the maneuvering became more difficult as the depth was reduced. With the 80-foot depth of water the effect of the towed Liberty ship was not noticeable on the large naval vessel. Therefore, some special tests were made to observe the interaction between the two vessels by meeting at reduced ship clearance. In these tests it was attempted to keep the large naval vessel on a steady course down the centerline of the channel. In this position the ship clearance distance was about 90 feet. It was attempted to have the naval vessel at zero angle of yaw with the rudder midship at the time the effects of interaction between the two ships first developed. If possible the rudder remained midship till after the effects of interaction ended. These tests indicated that the interaction on the large naval vessel increased as its speed was increased, as would be expected. The naval vessel tended to sheer to starboard as the two bows approached each other. With the models abeam, this sheer to starboard was reversed and the model sheered to port. As the two sterns passed, this port sheer was diminished, nullified, or reversed. The largest of these interaction effects appeared to be that which took place while the vessels were abreast of each other, resulting in a final port sheer usually. It should be noted that the maneuvered ship was usually nearest to the bank when the two ships were abreast and thus bank suction may be an important factor in the port sheer which developes when the two ships are abreast.

Tests were next made for a 500- by 45-foot channel with still water. The large naval vessel was self-propelled as before while the Liberty ship was towed at a distance of 125 feet from the near prism line. In these tests the ship clearance and bank clearance distances were greatly reduced from those of the 700-foot channel. Maneuvering was more difficult in this channel but no definite conclusions could be made owing to the limited number of test runs. Only one day was available for these tests as the two-way-traffic studies were interrupted in order to begin the bend studies.

TESTS WITH THE LIBERTY SHIP (MODEL 3748-4) BEING MANEUVERED

From the results of the previous two-way-traffic tests and from data obtained by one-way-traffic studies, a 500-foot by 60-foot channel was agreed upon as being the logical channel to be tested upon resumption of the two-way-traffic studies. In these tests, the relative positions of the two vessels were reversed from those used in the previous tests, i.e., the Liberty ship was maneuvered while the large naval vessel was towed on the endless cable. This arrangement is similar to that shown in Figure 5.2 except that the naval vessel was run at a distance of 150 feet from the prism line. Tests were made at ship speeds of 5, 7.5, and 10 knots and for each condition tested the speed of both vessels was kept equal. Tests were made in still water and in ahead currents of 3 and 5 knots. In these tests, the ship clearance distance was 117 feet when the Liberty ship was exactly in the center of the available free channel. This distance is practically normal clearance distance as the beam of the large naval vessel is 113 feet. The passing maneuver in all of these tests was made without any unusual difficulty regardless of the ship speed or current speed.

The next series of tests were made with the naval vessel moved to a distance of 190 feet from the near prism line. In this condition, as shown by Figure 5.2, the port side of the naval vessel is practically on the centerline of the channel. This series of tests were complete as tests were made for still water and for both ahead and following currents. Ship speeds were 5, 7.5, and 10 knots and current speeds were 3 and 5 knots. Slightly more difficulty was had in these tests than in the preceding tests where the naval vessel was towed at a distance of 150 feet from the prism line. A special condition occurred when the ship speeds were 5 knots in a 5-knot ahead current. Under these conditions the large naval vessel was moving at 10 knots in respect to the ground while the Liberty ship was stationary. Nevertheless, the Liberty ship handled very well and no difficulty was had in maneuvering so as to stay clear of the oncoming naval vessel. With the exception of the condition of 10 knots ship speed in following currents, the test results for all conditions were very similar. The increased difficulty at 10 knots speed in following currents may be partly due to the high ground speed of the maneuvered model having a psychological effect on the pilots

DISCUSSION OF RESULTS

The two-way-traffic studies in restricted channels were conducted as observational tests owing to the difficulty of otherwise judging the complex factors involved. The conclusions drawn from these tests are based on the combined judgment of the Panama Canal pilots and the test engineers. Only a sufficient number of runs were made for each condition to verify general trends.

The model tests were not made under exactly the same conditions as would exist for full-scale ships.

The pilot could not be located on the deck of the model and thus could not get the feel of the ship. It is believed that this difference between model and prototype conditions did not materially affect the test result because the parabolic reflector and light source located on the model projected a beam of light on a screen at the end of the channel and this enabled the pilot to detect changes in sheer easily and quickly. No attempt was made to simulate either weather conditions or the irregularities which normally occur in full-scale canals. The time scale in these tests required that the pilot and the quartermaster think and act about seven times faster than full-scale operations require, in order to simulate full-scale conditions. The time scale tends to make the test results conservative whereas the other two differences have the opposite effect. It is not believed that these differences materially affect the value of the tests. The Panama Canal pilots concluded that, from the overall standpoint, the tests produced results quite similar to full-scale, but slightly on the conservative side.

CONCLUSIONS

The two-way-traffic tests indicate that for the ship speeds and channel currents tested, a channel 500 feet by 60 feet is large enough so that interaction between ships of these types will not seriously affect the controllability of the ships except possibly at 10 knots ship speed in a 5-knot following current.

In this connection, however, Figure 5.2 shows a clearance distance of 77.5 feet between the two vessels. This is somewhat less than the normal ship clearance, i.e., the beam of the naval vessel. Also, if the naval vessel had been maneuvered at the same off-center position at which it was towed, it is seen that, on the basis of the normal ship lane, the clearance distance might have been reduced to 37 feet. This would be a very dangerous condition because of the greatly increased interaction between the two ships and also because of the danger of the ships' colliding. The earlier series of test in the same channel, with the large naval vessel towed in a position 40 feet closer to the prism line provided 40 feet more of ship clearance and thus would be safer from the standpoint of interaction between the two ships. However, the reduced bank clearance for the naval vessel increased the hazard due to bank suction acting on it. The ideal lateral position for the vessels during the meeting maneuver should be a compromise such as to make the combination of bank suction and interaction between the ships the least dangerous to navigation. On this basis the tests with the naval vessel towed at a fixed position 150 feet from the prism line would probably represent conditions closer to the ideal passing position for these two vessels in this channel than would Figure 5.2.

In general the variation in ship speed had little effect on the controllability of the ships. The effect of interaction between two ships meeting in a restricted channel is such that it apparently assists the pilot in making the necessary maneuvers. The controllability appeared to be approximately the same for ahead and following current and for still water except that at 10 knots ship speed in a 5-knot following current the controllability of the Liberty ship was relatively poor.

The controllability was noticeably poorer at the 45-foot channel depth than at the 60-foot channel depth. This would indicate that the present practice of having the channel depth only a few feet greater than the maximum draft should not be followed in the design of any new canal.

SECTION 6

CONTROLLABILITY OF SHIPS IN CHANNEL BENDS

ABSTRACT

The shallow water basin of the David Taylor Model Basin was adapted for use in laying out and comparing various types of bends as shown in Figure 6.1. The purpose of these tests was to assist in the selection of the best bend for the proposed Panama Canal. The first series of bends were tested at a linear ratio of 86, followed by tests of two bends at a linear ratio of 45. Photographs were taken which synchronized the path of the vessel with rudder angles used. By means of these tests four different types of bends were compared. The magnitude of the scale effect and therefore the reliability of model results in forecasting full-scale performance for the bends of linear ratio 45 was investigated. This was done by running tests in a 45-linear-ratio replica of the La Pita Bend of the Panama Canal. In addition, since the 26-degree parallel bend was tested at both a 45 and an 86 linear ratio, the magnitude of the scale effect for the latter bends could also be estimated. The effect of ship speed and current speed and direction on maneuverability in the bends was studied by tests. Another factor investigated was the risk involved in a large vessel meeting and passing another vessel in the bend. The test results were compared with the comments of the Panama Canal pilots who performed the maneuvers.

INTRODUCTION

A study of the literature on the subject shows that the theoretical study of bend designs is very limited due to the complexity of the variables affecting the hydrodynamic forces on a ship in a bend. A discussion of the change in appearance of the water surface and velocity distribution when water moves around a bend appears in Woodward and Posey (71). No reference was found which developed a theoretical method for determining the proper channel bend.

Since information concerning the best design of bends was so meager, this series of tests was initiated. The primary purpose of the bend tests was to assist in the selection of the best bend for the proposed Panama Canal. This was done by investigating the comparative difficulty encountered in maneuvering a specified ship around variously designed bends. It was also desired to study the effect of ship speed and current speed and direction on the handling characteristics of a specified ship. A ship speed of 10 knots was considered the maximum desirable speed. In the event a sea-level canal were selected, a maximum current speed of 5 knots would result if a tidal lock either were not installed or were destroyed. The feasibility of one vessel passing another transiting in the opposite direction while in the bend was also considered. Several factors such as the effect of side slope and bend irregularities were not considered in these tests. The significance of these factors in bend design should be investigated.

GENERAL CONSIDERATIONS

A theoretical method of determining the proper cross section and design of a bend is virtually impossible. The analysis of the magnitude and effect of hydrodynamic forces on a vessel in a straight channel is exceedingly difficult and there are additional effects on a ship in a bend. Even in still water, with a vessel going into a turn, a moment and a side force are developed, which because of the transient condition cannot be accurately determined. The presence of currents introduces additional hydrodynamic forces. The centrifugal motion of the water results in a change of the slope of the water surface, tending to make it higher at the outer bank and lower toward the inner bank. This difference in level would cause a side force on the vessel and also a moment when entering or leaving the bend. The velocity distribution is no longer uniform. All this makes the problem too difficult at present to be handled successfully by analytic methods.

The only recourse, then, was to study the results obtained by testing different bends under a variety of conditions. If a proper criterion to indicate the maneuverability of a ship could be determined, different bends and conditions could be compared. Possibly the best way of comparing bends would be by running a tremendous number of tests for each condition and then determining which type of bend resulted in the smallest percentage of accidents due to maneuvering difficulties. A test of this nature would be costly and time-consuming. Therefore, a substitute method was used, in which two variables were measured, i.e., the path of the ship and the rudder angles used in the test. The question was considered whether they were pertinent factors in indicating the risk involved in the maneuver. For a given channel bend the further off the centerline, the greater are the hydrodynamic forces on the ship. Consequently the more difficult and hazardous is the maneuver. Also since the rudder angle is a measure of the forces on the ship, the greater the rudder angle necessary to perform a maneuver, the greater the risk. Therefore it would seem that both path and rudder angle are important in considering the controllability of a ship.

TEST METHODS AND PROCEDURE

The first series of bend tests were made at a linear ratio of 86. This large ratio was required because of space limitations. Model 3992, whose characteristics are given in Figure 2.1, was used since, although it has good handling characteristics, it represents a very large vessel and therefore would be difficult to maneuver in a restricted channel. Four different types of bends were tested at the 86 linear ratio. Streak photographs were taken and used to obtain the path of the ship and synchronized film shots to obtain the rudder angles used. The techniques of obtaining the streak photographs and film shots are described in Section 3 and a sample streak photograph is reproduced in Figure 3.20. A section of straight channel was constructed ahead of the bend to permit accelerating the model to the required speed before it reached the bend. The model was attached to the towing carriage while it was being accelerated, after which it was released from the carriage and maneuvered around the bend by remote control, the only connection being an overhead cable. Sufficient slack was maintained in the cable by means of an overhead boom to minimize the introduction of extraneous forces on the model. Veteran Panama Canal pilots issued the helm and engine orders during each run. Since the propeller shafts could not be individually controlled, engine orders were limited to reducing speed and backing up in emergencies. The voltage-control panel, parallel light beam, electronic rudder-control gear, and other features were similar to those used previously and described in Section 3.

The bends tested at the 86 linear ratio are shown in Figure 6.1. These, in the order tested, are as follows:

a. 40-degree widened bend,

b. 26-degree parallel widened bend,

c. double 13-degree bend,

d. 26-degree parallel bend.

The tests were conducted at ship speeds relative to the undisturbed water of 5, 7.5, and 10 knots* and with both ahead and following currents of zero, 3, and 5 knots. When the bend studies were initiated it was planned to investigate arbitrary bend angles of 20 and 40 degrees and to use a straight channel section with a width of 600 feet and a depth of 60 feet at the entrance to and from the bend. However, at the conclusion of the first

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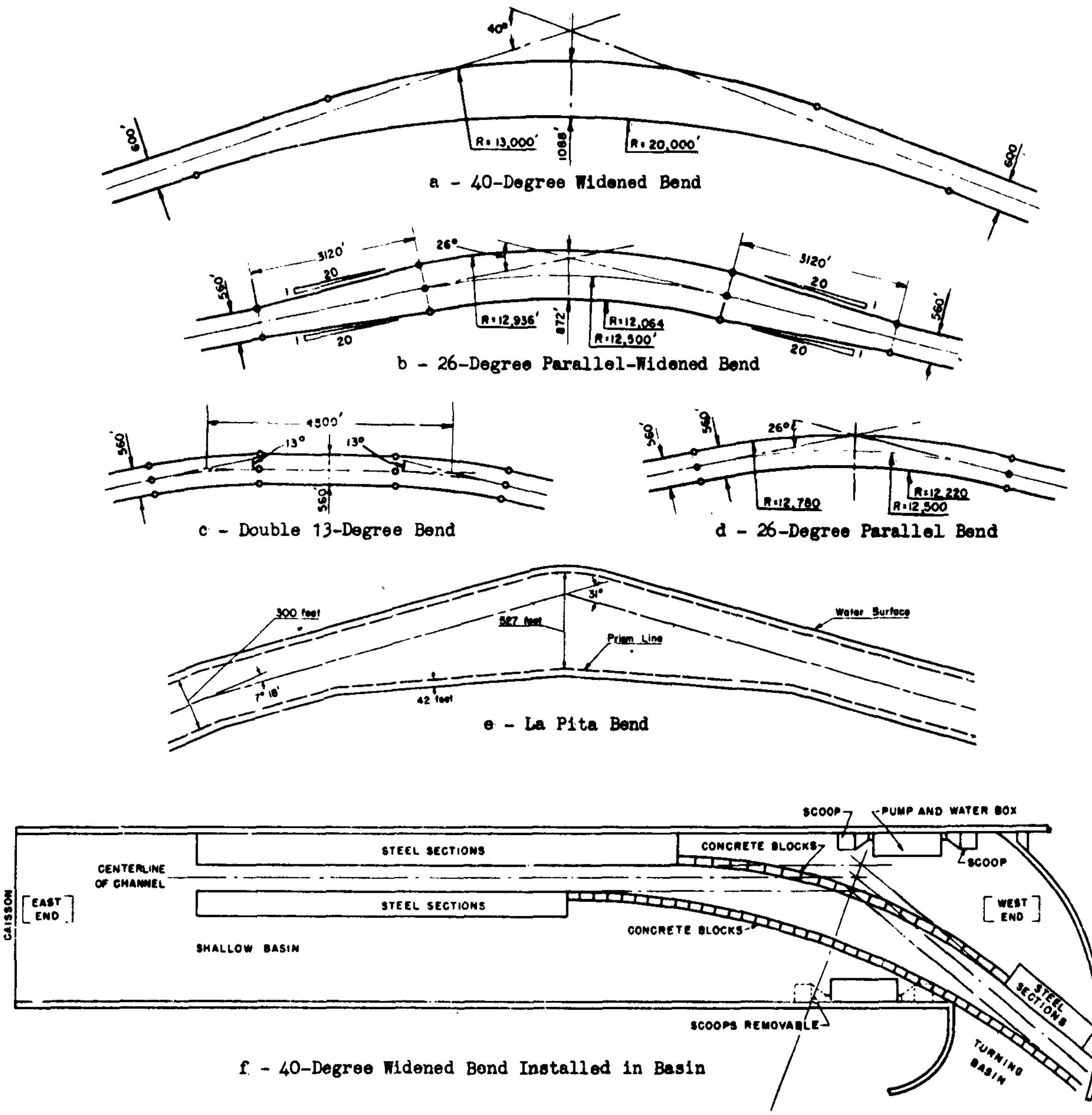
* In the discussion, although tests were model tests, all dimensions and speeds refer to the full-scale equivalent. All ship speeds are with respect to the water.



BEND DATA (DIMENSIONS GIVEN IN FULL SCALE FEET)											
NAME OF BEND	REFER TO	LINEAR RATIO	STRAIGHT SECTION EAST	STRAIGHT SECTION WEST	OUTER RADIUS	INNER RADIUS	CENTER-LINE RADIUS	PRISM WIDTH	OTHER STRAIGHT SECTION	GREATEST PRISM WIDTH	WATER DEPTH
26° PARALLEL	d	45	5400	45	12780	12220	12500	560	NONE	560	60
LA PITA	e	45	6300	1350				300	NONE	535	42
26° PARALLEL	d	86	12000	2580	12780	12220	12500	560	NONE	560	60
DOUBLE 13°	c	86	12000	3440	CURVED CHANNELS ARE SPIRALS APPROXIMATING 8800 ft. RADIUS			560	2500 MID-SECT.	560	60
26° PARALLEL WIDENED	b	86	9480	86	12064	12936	12500	560	NONE	872	60
40° WIDENED	a	86	9480	NONE	13000	20000		600	NONE	1088	60

Figure 6.1 - Channel Bend Layouts

40-degree bend test, available information indicated that a channel width of 560 feet (600 feet wide at the 40-foot depth). a depth of 60 feet, and a maximum bend angle of 26 degrees would be of primary interest. All bends tested had a side slope of 45 degrees. To test the possibility of passing oncoming vessels in the bend, the model was maneuvered at the centerline and at the quarter point on either side of the centerline for all conditions of ship speed and current which were not too hazardous. The reduction in cross section and the smaller angle required enabled the construction of two bends at a 45 linear ratio. The two bends tested were:

a. 26-degree parallel bend as shown in Figure 6.1,

b. a model of the La Pita bend, Panama Canal, as shown in Figure 6.1.

Models 3769, 4018, and 3748-4 were tested in the two bends. Their characteristics are shown in Figure 2.1. Model 3769 has handling characteristics, ship lines, and dimensions similar to Model 3992. Therefore, results for the two models were deemed comparable. Model 4018 was tested because it was considered as the possible ultimate that the channel would have to handle as regards a combination of size and poor handling characteristics. It is considerably larger than any existing ship of that type. Model 3748-4 was used because it represents the usual type of ship that transits the Panama Canal and was therefore one that the Panama Canal Pilots were familiar with.

The reasons for the 45-linear-ratio tests were as follows·

a. By comparison of results of tests of the model of the La Pita bend with full-scale results some idea of the reliability of the 45-linear-ratio tests can be obtained.

b. By comparison of the 26-degree parallel bend at the 45 linear ratio with the same bend at a linear ratio of 86 some idea as to the magnitude of the scale effect for the 86-linear-ratio bend tests can be determined.

One problem involved was the difference in technique of the various pilots. Some pilots tended to use rather large rudder angles for short periods of time while others tended to use relatively small angles for longer periods. In order to reduce the human variable, an attempt was made to have sufficient runs so that each of the pilots could run at least one test for each condition.

In addition to the streak photographs and film, the test engineer took notes on each run giving test conditions, rudder angle commands, pilot's comments, and any other pertinent information.

As part of the test program, it was decided to investigate the behavior of a vessel under emergency conditions. A brief series of "planned breakdown tests" was therefore made to simulate conditions that might exist in the event of rudder or engine failure.

TEST RESULTS

The rudder-angle film and the streak photographs giving the paths of the vessels are in Addendums I and II. Some of the film giving the rudder angles failed to print due to mechanical failure or other difficulties. For these tests, the test engineer's records were used. For study purposes, the path and rudder-angle data can be combined in a single figure, as illustrated by Figures 6.2 through 6.4.

The test conditions and resultant paths for the "breakdown" tests appear in Addendum I, Volume IVb.

DISCUSSION OF RESULTS

For all the bends tested, a substantial number of runs were made with the vessel maneuvered at the quarterpoint on either side of the centerline. This was an attempt to investigate the possibility of passing oncoming ships in the bend. The results indicated that such a maneuver might be dangerous where one vessel was large. However, little difficulty was forseen for Liberty-type ships. Therefore, the condition of a large vessel meeting and passing another vessel in the bend was eliminated as one of the requirements for the bend design at the present time. Further study at some future date would be useful if it is desired to have a bend capable of permitting this maneuver. Only centerline runs were used for comparing different bends.

FACTORS USED IN COMPARISON OF BENDS

The problem of comparing bends by study of the path of the ship and the rudder angles used in making the maneuver is extremely difficult. The maximum rudder angle required for a particular run and the maximum distance from the desired path, or maximum deviation,* would be indicative of the controllability of the vessel since the extreme conditions are of more concern than the average for a particular run.

Deviation does not take into account differences in channel cross-section. A widened bend provides more room for maneuvering than a uniform width of channel. Therefore a better criterion than maximum deviation would be defined by the ratio of the actual maximum deviation to the theoretical

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* Deviation is defined here as the departure of the forward or after perpendicular, whichever is greater, from the intended path of the center of gravity of the vessel.

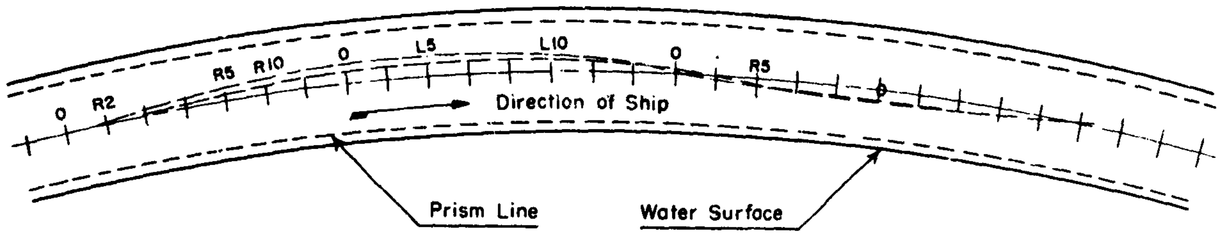


Figure 6.2 - Maneuvering Test in a 26-Degree Parallel Bend with No Current

This is Run H_4-62 as listed in Appendix 6.1.

Location of Test: Shallow Water Basin	Test Conditions:
Bend: 26-Degree Parallel Bend, λ - 45	V_s - 7.5 knots
Model Data: Model 3769, λ - 45	V_w - 0 knot

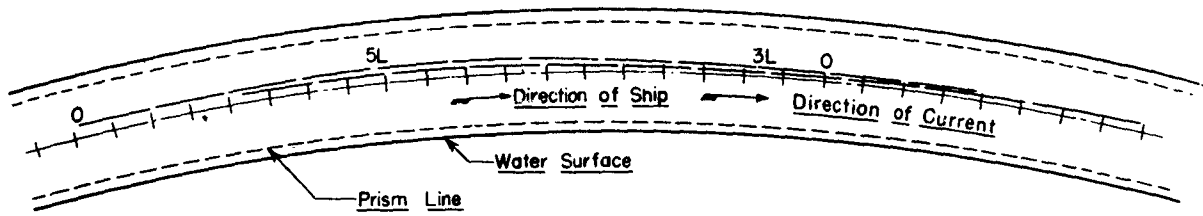


Figure 6.3 - Maneuvering Test in 26-Degree Parallel Bend with a Following Current

This is Run H_4-99 as listed in Appendix 6.1.

Location of Test: Shallow Water Basin	Test Conditions:
Bend: 26-Degree Parallel Bend, λ - 45	V_s - 7.5 knots
Model Data: Model 3769, λ - 45	V_w - +3 knots (following current)

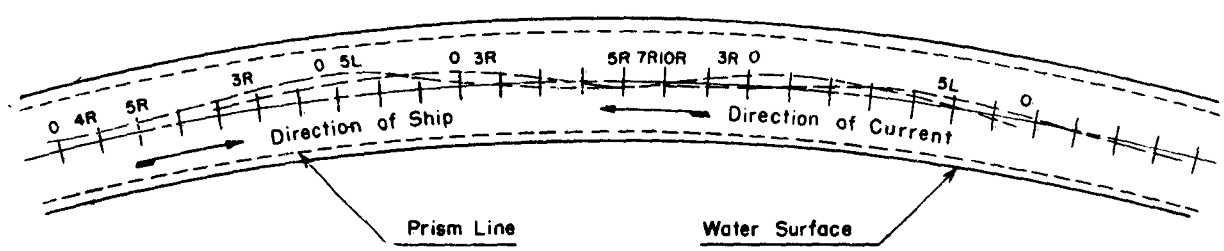


Figure 6.4 - Maneuvering Test in a 26-Degree Parallel Bend with an Ahead Current

This is Run H_4-153 as listed in Appendix 6.1.

Location of Test: Shallow Water Basin	Test Conditions:
Bend: 26-Degree Parallel Bend, λ - 45	V_s - 7.5 knots
Model Data: Model 3769, λ - 45	V_w - -3 knots (ahead current)

maximum deviation. The theoretical maximum·deviation is very nearly equal to the distance from the centerline of the channel to the prism line for a centerline run. The ratio of maximum deviation to one-half channel bottom width will be referred to as maximum deviation ratio.

In comparing two bends, the maximum deviation ratio may be the same but the vessel might be wandering over both sides of the course for one of the bends. This would indicate greater difficulty in maneuvering and yet would not show in the value of the maximum deviation ratio. This could be taken care of by adding the maximum deviation to port and the maximum deviation to starboard. To take differences in channel width into account the result was divided by the channel bottom width. The resultant ratio is called the path ratio and is equal to one-half the sum of the maximum port and starboard deviation ratios.

In compiling Table 6.1, the maximum rudder angle, the maximum deviation ratio, and the path ratio were obtained for each run and in order to get an overall picture of the extremes to be expected for each condition, the results for all runs for one condition were averaged together.

In obtaining the average maximum rudder angle and average maximum deviation, no concern was given to the direction, whether left or right rudder, or port or starboard deviation. The results are shown in the form of a bar graph in Figure 6.5. Some difficulty was encountered in the selection and evaluation of runs. Using the average maximum rudder angle and deviation indicates the difficulty of performing the maneuver on the average but perhaps it might be better to use the number and nature of the poor runs only, since they might be more indicative of the hazard. This was decided against because of the limited number of poor runs. In some cases, there might be several good runs and only one poor run. It is possible that a few of the poor runs were not entirely the fault of the bend but were caused by friction in the rudder mechanism, the effect of the cable, or a mistake by the helmsman which was not noticed. In interpreting Figure 6.5 it must be realized that due to failure of the photographic equipment and lack of time, only one or two runs were obtained for some conditions. The scatter obtained from the tests would raise doubt as to the validity of using the results of such few runs in establishing an average.

The number of runs is given in Table 6.1 and should be considered in weighting the results.

The results of all the centerline runs with Models 3992 and 3769 are tabulated in Appendix 6.1.

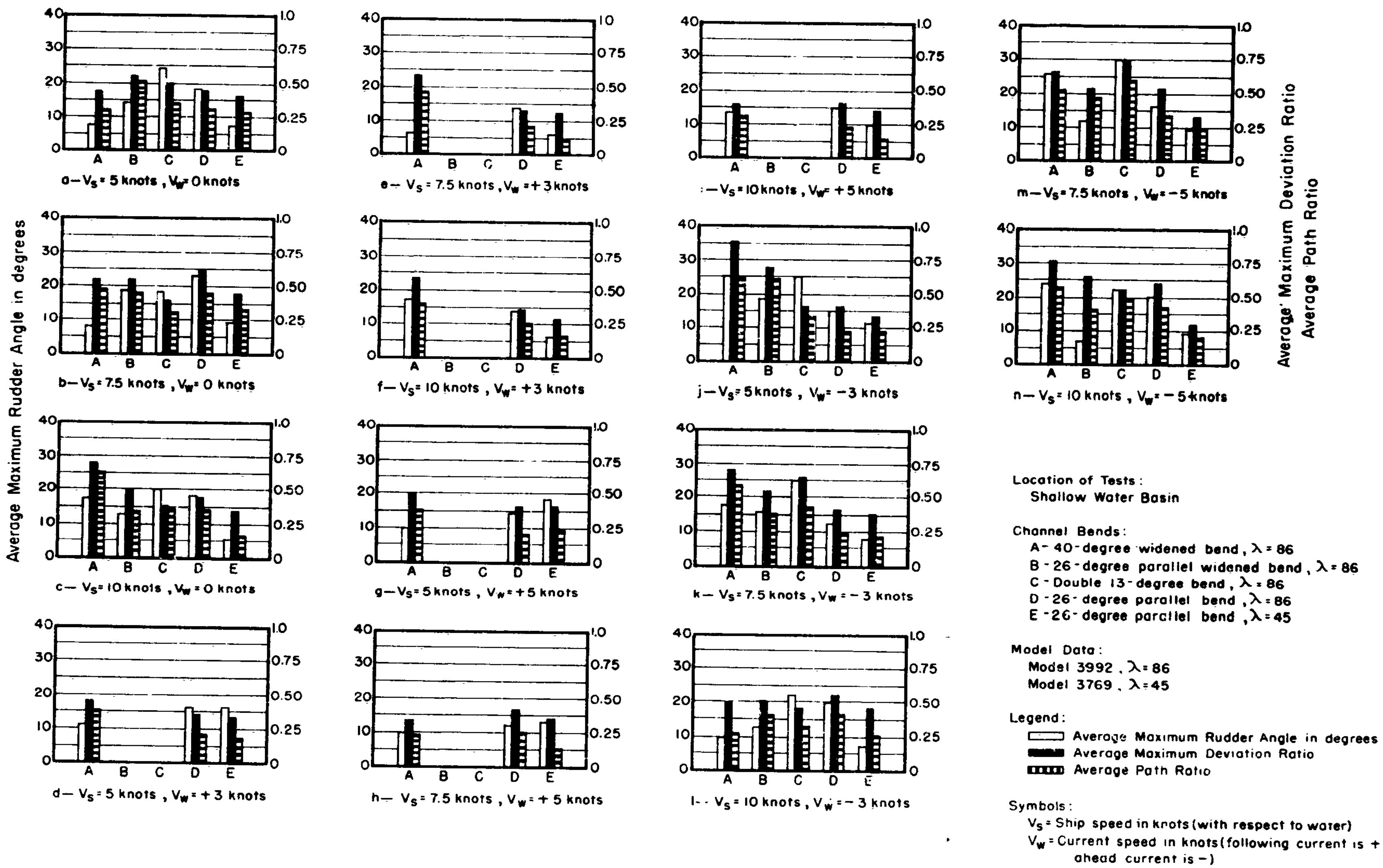


Figure 6.5 - Graphical Comparison of Ship Performance in Various Types of Bends

COMPARISON OF THE 86-LINEAR-RATIO BENDS

In Figure 6.5, A, B, C, and D represent bends tested at an 86 linear ratio. The 26-degree parallel widened bend and the double 13-degree bend were tested in still water and with a head current only, since at the completion of these tests it was realized that these bends were not the best designs.

In the still-water tests, there was not a great deal of difference between bends but in moving water the 26-degree parallel bend was superior to any of the others tested. This bend shows a great consistency of results for all conditions tested. The average maximum rudder angle was usually below 20 degrees and never exceeded 24 degrees while the path was consistently confined within the quarter points. Where currents are likely to exist, the 26-degree parallel bend seems the best.

The poorness of the double 13-degree bend can be attributed to the comparatively short radius required. This results in greater curvature of the flow and consequently a greater variation of the hydroynamic forces acting on the ship. Also a greater rudder angle is required to make the shorter-radius bend. At first thought, a widened bend would seem safer since it provides more room for maneuvering than a uniform width of channel in the bend. However, the data show that where currents exist the maneuvering was more difficult, the path of the vessel more erratic, and the accidents more numerous. This is principally due to the continuous variation in the hydrodynamic forces as a vessel transits a gradually widening bend. This continually changing force makes it more difficult for the pilot to judge the proper rudder angle for equilibrium and therefore makes it more difficult to maintain a fixed path. In still water, the additional width may compensate for this, but in moving water the resultant changing velocity distribution due to widening makes transiting the bend more difficult than in a parallel bend. The 26-degree parallel widened bend has discontinuities at the beginning of the enlargement and also where the inner bank curve meets the straight section. These discontinuities cause abrupt changes in the flow pattern and resultant changes in the hydrodynamic forces.

COMPARISON OF 26-DEGREE PARALLEL BEND AT 86 AND 45 LINEAR RATIO

For most conditions, tests conducted at a 45 linear ratio required smaller rudder angles and had smaller deviations from the centerline path than the 86-linear-ratio bend as shown in Figure 6.5. These differences were not very great in most instances and could be laid to several factors. For proper correlation between 86- and 45-linear-ratio tests, the time rate* for

* See Section 2 for a discussion of Froude's relationships.

the 86-linear-ratio tests must be 1.4 times that for the 45 scale ratio. With the high time rates required in model studies this would be very difficult to achieve. The inability to maintain Froude's relationship for time rate is equivalent to too slow a rudder action and a resultant poorer run.

Another result of the reduction in linear ratio is scale effect. Even if the Froude number is the same for 86- and 45-linear-ratio models, there are other forces on the ship beside gravity forces and these cannot be correlated. In small models these forces may become significant and cause noticeable differences in comparing model and prototype.

The presence of extraneous forces which have the same magnitude for both 86- and 45-linear-ratio tests will have a bigger effect on the 86-linear-ratio tests. The most likely of these forces were due to the presence of the cable necessary to supply power to the model. Every effort was made to eliminate the effect of the cable, such as attaching the cable at the center of gravity of the ship. Still, for some runs, incorrect handling of the cable resulted in a noticeable heel of the vessel. When this was observed the run was discarded. Some runs included in the results may have been affected by the cable and resulted in poorer runs. At a 45 scale ratio, the cable did not exert sufficient force to noticeably affect the model. All models tested were able to maneuver successfully around the 45-linear-ratio bend for all conditions. The tanker Model 4018 did not handle well while the Liberty ship handled very well.

COMPARISON OF FULL-SCALE TESTS WITH 45-LINEAR-RATIO TESTS FOR LA PITA BEND

The 45-linear-ratio tests were all in still water. The main basis of comparison for these tests were the comments of the pilots. In addition, photographs were taken of the path and rudder angles and the results were compared with full-scale data. Figure 6.6 shows the results obtained for Model 3769 as compared with the USS WISCONSIN transiting the bend at a speed of 5 knots. The sample runs shown are fairly representative of full-scale- and model-test results. The path of the model is quite similar to that of the battleship although slightly more erratic. The reduction in size from full-scale ship to model would probably introduce scale effect but with the linear ratio used it should not be significant. More important, in order to have the proper Froude number for the model, the time rate must be almost seven times as great as for the full-scale vessel. Although the rudder rate could be increased accordingly, the reaction rate of the pilot and helmsman could not possibly be increased so much. Therefore, poorer runs would result. Another factor was that the scale ratio used made it impossible to provide room for the pilot in the model and thus let him "feel" the action of the vessel as it deviated from its heading. A pilot on a full-scale vessel normally "feels" or anticipates the motion of the vessel well in advance of an observer not on the vessel. This factor was minimized by the light system which accentuated small motions.

Tests on Model 4018 indicated that a ship of that type would have extreme difficulty in maneuvering around the La Pita bend. Full rudder was required for many of the runs. Model 3748-4 behaved similarly to a full-scale Liberty ship and had no difficulty performing the maneuver even at 7 knots.

EFFECT OF SHIP SPEED AND CURRENTS ON MANEUVERABILITY

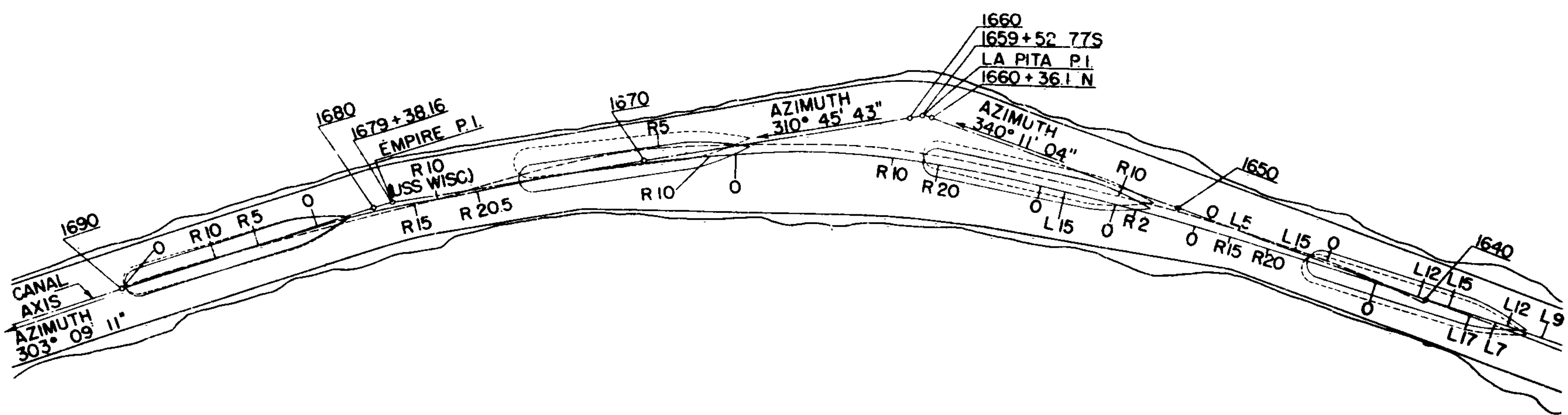
Since the 45-linear-ratio tests come closer to full-scale results, these were used as a means of comparison. In Figure 6.4, Column E shows the results for Model 3769 in a 26-degree parallel bend at a 45 linear ratio.

For the conditions tested, variation in ship speed or current had very little effect upon the maneuverability of the vessel. A ship speed of 5 knots relative to the water resulted in comparatively poorer rudder power and therefore required slightly greater rudder angles. As far as path and rudder angles are concerned, there is very little difference because of current, the variations being rather random. There seems to be a slight trend indicating that an ahead current results in a slightly more erratic path. This could be easily explained on a time basis, since for the same speed relative to the water the ship spends more time in the bend moving against an ahead current. Therefore there is more opportunity for deviating from the path.

Figures 6.2, 6.3, and 6.4 show transits made in the 26-degree parallel bend at a 45 linear ratio with a ship speed (V_s) of 7.5 knots and a water speed (V_w) of 0, 3, and -3 knots respectively. No special attempt was made to select an average run but these runs are fairly typical for the conditions tested. The path and maximum rudder angles required improve as the time the ship spends in the bend decreases. Another noticeable difference is that the number of rudder-angle commands is decreased in a following current. However, it must be remembered that less time is spent in the bend. The actual time rate for issuing rudder-angle commands remains about the same for all current conditions with the same ship speed relative to the water.

DISCUSSION OF "BREAKDOWN" TESTS

The results of "breakdown" tests did not indicate any particular pattern of behavior that might be expected. Their value in estimating the performance of the full-scale vessel is open to question. The full-scale



Notes

The bend shown is copied from the Annual Survey Chart, July 1, 1945, published by: The Panama Canal, Department of Operation and Maintenance, Dredging Division, Gamboa, Canal Zone.

Panama Canal pilots endeavored to steer the self-propelled, remote cotrolled model on the most desirable course.

Legend

Dashed curve represents path of Model 3769 (run H4-11)

Solid curve represents path of USS WISCONSIN

	Ship Data	
	Model 3769	USS WISCONSIN
Type	Large Naval Vessel	Battle Ship
Length	900 feet	887 feet
Beam	113 feet	108 feet
Draft	32.25 feet	36.5 feet
Displacment	55000 tons	57000 tons
Number of propellers	4	4
Number of rudders	2	2
Observation point aft of foward perpendicular	410 feet	404 feet
Speed	5 knots	5 knots
λ	45	1

Figure 6.6 - Comparative Ship Performance in Model and Full-Scale La Pita Bends

This figure shows a northbound transit of the USS WISCONSIN through La Pita Bend and the transit of a model of a large naval vessel through a 1:45-scale model of the same bend. The curves show the path of a point which is 0.455 per cent of the ship length from the forward perpendicular and is on the centerline of the vessel.

ship frequently has available more and better methods of corrective action than were available in the model tests. The ship models were not equipped for a careful study of performance under "breakdown" circumstances. Therefore it was concluded that the improvised tests made thus far could not be considered as accurate or complete indications of the effects of mistakes or machinery failure.

COMMENT OF PILOTS

As pointed out previously, the Panama Canal Pilots' comments were of invaluable assistance in comparing model tests to similar full-scale maneuvers. A composite of their comments includes the following:

a. The model tests simulated full-scale tests very well. The chief reasons for differences for the 45-linear-ratio tests were the greatly increased time rate and the fact that the pilot was not located in the vessel. The 86-linear-ratio tests were also satisfactory but the effect of the cable was significant and may have resulted in poorer runs.

b. The 26-degree parallel bend was the best of the bends tested and was satisfactory for all conditions.

c. Although currents could be handled satisfactorily, they constituted an additional risk especially at a ship speed relative to the water of 5 knots. In this connection, it should be mentioned that the pilots at first felt that a following current would be more dangerous because of their greater land speed and consequently they had less time to adjust their course. In the actual tests it was found that the number of rudder orders required per unit time was approximately the same for all conditions where the ship speed with respect to the water was the same. The higher ground speed due to a following current creates a mental hazard, but not an actual risk. After the tests, the opinion among the Panama Canal Pilots was divided but the majority thought that an ahead current was more likely to result in an accident than still water or a following current. The Cape Cod Pilots who have considerable experience with currents felt that they provide very little additional hazard.

CONCLUSIONS

The tests performed on different channel bends indicate the following:

a. Model tests can be used to simulate full-scale conditions. The differences at a 45 linear ratio are small and are probably due to scale effect, high time rates required for rudder action, and the unfavorable location of the pilot. Considerable differences occur between model and full-scale results using a linear ratio of 86, but still there is sufficient similarity to permit the comparison of different bends all at an 86 linear ratio. Model tests are conservative.

b. Where currents exist, the 26-degree parallel bend seems best for the conditions tested.

c. The widened bends as designed made transit more difficult where currents are present and do not even improve the maneuverability of the vessel in still water.

d. Tests at a 45 linear ratio on a 26-degree parallel bend with a bottom width of 560 feet, a depth of 60 feet, and a side slope of 45 degrees show that it is satisfactory for the conditions tested as long as the ship makes a centerline transit. For ship speeds up to 10 knots and current speeds up to 5 knots, ship speed and current speed had very little effect upon the maneuverability of the models tested. It seems best to use a ship speed exceeding 5 knots while it was also observed that ahead currents gave slightly worse results at the same ship speed. This might be explained on the basis that the ship spends more time in a bend with an ahead current.

e. The meeting and passing of two large vessels or one large vessel and one Liberty ship would be hazardous in bends with the dimensions tested.

APPENDIX 6.1

Since the streak photographs, rudder-angle film, and the test engineers' records could not be incorporated into the general report, a tabulation of the centerline runs for Models 3992 and 3769 are presented. The tables contain the basic data obtained plus information necessary to compile Table 6.1. This required the inclusion of the maximum deviation ratio for the widened bends, otherwise the path would have to be known. For the parallel bends, the maximum deviation ratio can be obtained by dividing the maximum deviation by one-half the channel prism-line width (280 feet). The maximum path ratio is one-half the sum of the maximum deviation ratios, port and starboard. Where a minus sign appears in the column for maximum starboard deviation, the ship has transited the bend on the port side always. In the tabulation, V_s is the ship speed in knots with respect to the water and V_w is the current speed. A plus sign indicates a following current and a minus sign an ahead current.

(Text continued on page 6.20.)

TABLE 6.1

Tabular Comparison of Ship Performance in Various Types of Channel Bends

Panama Canal pilots endeavored to steer the self-propelled, remote-controlled models along the channel centerline.

Bend layouts are shown in Figure 6.1.

Bend	V_w = 0 knot					V_w = +3 knots					V_w = +5 knots	
	Rudder Angle Data		Path Data			Rudder Angle Data		Path Data			Rudder Angle Data	
	Number of Runs	Av. Max. Rudder Angle in degrees	Number of Runs	Average Maximum Deviation Ratio	Average Maximum Path Ratio	Number of Runs	Av. Max. Rudder Angle in degrees	Number of Runs	Average Maximum Deviation Ratio	Average Maximum Path Ratio	Number of Runs	Av. Max. Rudder Angle in degrees
V_s = 5												
40° Widened λ = 86	2	7.5	2	0.45	0.30	4	11.2	4	0.46	0.38	2	10.0
26° Parallel Widened, λ = 86	7	14	6	0.61	0.51							
Double 13° λ = 86	7	24.3	7	0.50	0.35							
26° Parallel λ = 86	7	18.6	7	0.45	0.32	4	16.2	4	0.35	0.22	9	14.4
26° Parallel λ = 45	4	7.5	4	0.41	0.29	4	16.2	4	0.33	0.19	6	18.3
V_s = 7.5												
40° Widened λ = 86	4	8.0	4	0.55	0.48	3	6.7	2	0.59	0.47	3	10.0
26° Parallel Widened, λ = 86	7	19	7	0.55	0.46							
Double 13° λ = 86	8	18.8	6	0.40	0.31							
26° Parallel λ = 86	8	23.1	8	0.62	0.46	4	13.8	4	0.33	0.22	5	12.0
26° Parallel λ = 45	4	9.2	4	0.45	0.33	4	7.5	4	0.32	0.12	6	13.3
V_s = 10												
40° Widened λ = 86	2	17.5	2	0.69	0.63	4	17.5	4	0.59	0.41	3	13.3
26° Parallel Widened, λ = 86	4	13.0	4	0.50	0.35							
Double 13° λ = 86	4	20.0	2	0.39	0.36							
26° Parallel λ = 86	7	18.6	7	0.45	0.36	4	13.8	4	0.36	0.26	5	15.0
26° Parallel λ = 45	4	5.8	4	0.36	0.17	4	6.2	4	0.29	0.17	6	10.0

Location of tests:
Shallow water basin
Bends:
As indicated
Model data:
Model 3992 for λ = 86
Model 3769 for λ = 45

Symbols:
V_s = velocity of ship in knots (with respect to water)
V_w = current speed in knots (following current is +, ahead current is -)

Table 6.1 (Continued)

V_w = +5 knots			V_w = -3 knots					V_w = -5 knots				
Path Data			Rudder Angle Data		Path Data			Rudder Angle Data		Path Data		
Number of Runs	Average Maximum Deviation Ratio	Average Maximum Path Ratio	Number of Runs	Av. Max. Rudder Angle in degrees	Number of Runs	Average Maximum Deviation Ratio	Average Maximum Path Ratio	Number of Runs	Av. Max. Rudder Angle in degrees	Number of Runs	Average Maximum Deviation Ratio	Average Maximum Path Ratio
2	0.49	0.38	3	25.0	2	0.90	0.62					
			3	19.0	2	0.70	0.62					
			3	25.0	3	0.42	0.34					
9	0.41	0.28	3	15.0	3	0.41	0.23					
6	0.42	0.24	6	11.6	5	0.37	0.23					
3	0.34	0.24	5	18.0	5	0.72	0.59	9	26.1	7	0.66	0.53
			7	16.0	7	0.54	0.38	4	12.0	4	0.54	0.47
			4	25.0	2	0.65	0.44	4	30.0	4	0.75	0.60
5	0.42	0.26	9	12.8	9	0.41	0.24	7	16.3	7	0.54	0.34
6	0.35	0.14	8	8.0	7	0.38	0.22	5	9.4	5	0.33	0.25
3	0.39	0.32	6	10.0	1	0.51	0.28	5	24.0	3	0.77	0.58
			6	13.0	6	0.52	0.42	4	7.0	4	0.65	0.42
			2	22.5	2	0.46	0.33	4	22.5	4	0.57	0.50
5	0.42	0.24	4	20.0	5	0.56	0.42	7	20.7	7	0.61	0.43
6	0.36	0.15	5	7.6	5	0.47	0.27	6	9.8	6	0.30	0.21

TABLE 6.2

Tabulation of Data from Centerline Runs for Model 3992 in the 40-Degree Widened Bend, $\lambda = 86$

Run Number	V_s	V_w	Maximum Rudder Angle in degrees		Maximum Deviation		Maximum Deviation Ratio	
			Left	Right	Port	Starboard	Port	Starboard
1E 6	5	0	5	3	81	114	0.21	0.29
8			10	5	37	272	0.07	0.61
16	7.5	0	5	3	187	260	0.50	0.65
17			15	15	215	337	0.62	0.79
18			7	5	69	171	0.09	0.45
22			5	5	146	187	0.30	0.40
24	10	0	20	20	544	402	0.95	0.95
25			10	15	130	154	0.20	0.42
1F 30	5	+3	10	0	130	138	0.20	0.30
31			10	10	195	309	0.30	0.65
36			10	0	228	195	0.36	0.40
38			15	5	219	211	0.35	0.50
40	7.5	+3	5	0	252	284	0.40	0.50
41			10	10	175	317	0.30	0.68
39			5	0				
48	10	+3	10	5	183	73	0.30	0.1
49			10	0	211	142	0.32	0.38
52			15	2	402	81	0.70	0.16
58			35	15	321	98	0.99	0.30
1	5	+5	15	5	179	195	0.30	0.48
2			5	0	162	195	0.25	0.50
8	7.5	+5	5	2	53	162	0.1	0.38
13			5	20	130	211	0.25	0.39
16			5	2	98	49	0.25	0.08
20	10	+5	10	10	154	146	0.28	0.3
23			15	10	158	130	0.50	0.28
27			15	20	126	81	0.25	0.30
84	5	-3	17	20	447	325	0.81	0.60

TABLE 6.2 (Continued)

Run Number	V_s	V_w	Maximum Rudder Angle in degrees		Maximum Deviation		Maximum Deviation Ratio	
			Left	Right	Port	Starboard	Port	Starboard
1F 86	5	-3	15	30				
85*			30	5	488	48	0.05	1.0
87*			20	10				
88	7.5	-3	10	10	305	93	0.60	0.20
89			15	7	228	138	0.52	0.35
90			20	30	438	337	0.99	0.81
91			14	20	455	219	0.80	0.70
93			15	10	386	77	0.70	0.20
97	10	-3	7	10	244	49	0.51	0.05
101			5	10				
104			5	10				
105			5	10				
106			5	10				
107			10	10				
61	7.5	-5	20	35				
62*			20	30				
63			10	30	389	228	0.69	0.42
64			10	20	146	179	0.30	0.32
65			5	15	268	260	0.54	0.50
66			10	25	366	183	0.60	0.39
67			10	30	358	292	0.60	0.80
80			20	20	455	130	0.78	0.28
81			20	30	374	158	0.90	0.30
68	10	-5	10	35				
70			20	20				
74			10	20	268	228	0.70	0.50
82			15	15	390	154	0.99	0.38
83			5	30	73	268	0.30	0.61

* Indicates accident.

In the runs listed, an attempt was made to eliminate all those where the quality of the run was influenced by rudder failure, the pull of the cable, or incorrect response of the helmsman to rudder commands. The run numbers correspond to those used in compiling the addenda.

In reading the streak photographs, the camera was located sufficiently high above the bend so that it would be assumed that the photograph was a plan view without distortion. Since the full-scale dimensions were known, it was easy to determine the scale. Once this was established, the maximum deviation could be read off the photograph and multipled by the scale to obtain the full-scale equivalent.

TABLE 6.3

Tabulation of Data from Centerline Runs for Model 3992 in the 26-Degree Parallel Widened Bend, $\lambda = 86$

Run Number	V_s in knots	V_w in knots	Maximum Rudder Angle in degrees		Maximum Deviation in feet		Maximum Deviation Ratio	
			Left	Right	Port	Starboard	Port	Starboard
H_1- 1	5	0	15	10				
2			10	10	183	127	0.40	0.38
7			10	2	131	97	0.29	0.30
8			20	20	265	280	0.78	0.68
117*			5	20				
118			8	4	127	179	0.30	0.92
121			10	15	277	179	0.76	0.48
122			10	10	172	187	0.38	0.48
14	7.5	0	20	15	235	146	0.60	0.43
15			20	30	430	153	0.98	0.50
28			15	5	164	150	0.40	0.40
29			15	10	187	75	0.40	0.25
34			15	20	191	150	0.40	0.42
35			20	20	168	123	0.30	0.58
123			10	2	135	90	0.30	0.50
22	10	0	10	30	202	239	0.50	0.60
23			5	5	150	90	0.40	0.30
43			10	10	164	56	0.40	0.20
44			7	5	179	0	0.40	0
58	5	-3	5	20				
59			30	30	348	269	0.70	0.68
62			5	8	284	161	0.70	0.42
83	7.5	-3	10	15	168	232	0.32	0.61
67			30	20	329	206	0.99	0.40
68			15	10	82	123	0.25	0.40
69			5	10	60	135	0.20	0.28
74			10	15	120	101	0.30	0.21
75			7	10	135	71	0.31	0.20
82			10	15	224	135	0.55	0.38
89	10	-3	5	10	168	153	0.42	0.30
90			10	10	187	161	0.50	0.40
95			20	30	258	86	0.80	0.29
96			10	15	142	112	0.41	0.50
105			10	10	172	131	0.50	0.50
106			5	2	164	30	0.39	0.04
126	7.5	-5	10	10	75	135	0.30	0.40
127			5	10	101	135	0.32	0.35
132			16	15	269	142	0.69	0.50
133			10	4	295	138	0.70	0.48
138	10	-5	5	3	239	52	0.66	0.18
139			7	5	411	30	0.98	0.10
146			5	8				
147			5	8	116	90	0.29	0.30

*Indicates accident.

TABLE 6.4

Tabulation of Data from Centerline Runs for Model 3992 in the Double 13-Degree Bend, $\lambda = 86$

Run Number	V_s in knots	V_w in knots	Maximum Rudder Angle in degrees		Maximum Deviation in feet	
			Left	Right	Port	Starboard
H_1-165	5	0	25	20	162	15
166			15	25	166	74
167			20	20	92	15
172			15	20	133	59
173			15	30	88	52
238			20	20	199	103
239			20	30	147	70
185	7.5	0	20	20	111	133
186			15	30	96	103
187			15	10	118	44
188			5	10	88	0
195			15	15		
196			15	15		
242			15	20	158	66
243			10	25	96	33
202	10	0	10	10		
203			20	30	114	88
207			10	20	103	92
208			10	20		
215	5	-3	15	20	114	166
216			20	30	88	81
217			10	25	96	18
212	7.5	-3	15	30		
213			20	30	184	85
214			10	20		
221			15	20	177	52
223	10	-3	15	25	122	66
224			10	20	136	44
225	7.5	-5	30	30	140	170
226			30	30	155	99
229			30	30	265	188
230			30	30	251	81
231	10	-5	30	30	284	210
232*			15	20		
234			20	25	118	96
235			15	15	74	63

*Indicates accident.

TABLE 6.5

Tabulation of Data from Centerline Runs for Model 3992 in the 26-Degree Parallel Bend, $\lambda = 86$

Run Number	V_s in knots	V_w in knots	Maximum Rudder Angle in degrees		Maximum Deviation in feet	
			Left	Right	Port	Starboard
H_1-250	5	0	15	7	155	64
251			10	7	91	8
255			5	15	91	8
256			15	15	106	30
258			20	25	129	61
261			20	30	182	125
262			20	20	129	99
268	7.5	0	30	30	102	117
269			30	20	95	4
272			20	30	159	121
278*			25	20	344	132
279			10	20	250	178
280			20	20	208	117
281			15	20	121	45
282			10	10	95	4
287	10	0	20	15	102	0
288			15	15	113	19
293			10	15	68	38
355			15	30	204	159
356			20	15	155	148
357			20	20	125	98
364			10	10	113	61
468	5	+3	15	15	98	26
469			10	10	87	45
487			20	5	106	0

* Indicates accident.

TABLE 6.5 (Continued)

Run Number	V_s in knots	V_w in knots	Maximum Rudder Angle in degrees		Maximum Deviation in feet	
			Left	Right	Port	Starboard
H_1-488	5	+3	20	10	106	15
474	7.5	+3	10	10	91	34
475			5	5	87	-19
494			15	30	132	110
495			10	10	11	61
481	10	+3	10	10	121	76
482			5	10	95	45
501			10	15	61	49
502			20	15	132	0
404	5	+5	15	5	113	45
405			10	5	98	38
406			20	10	197	35
411			15	15	91	106
412			10	15	72	166
413			20	15	129	53
414			15	15	110	72
420			10	10	49	0
421			15	10	64	0
426	7.5	+5	10	10	91	45
427			15	10	140	30
432			10	5	102	49
433			10	5	95	91
464			15	0	106	-15
441	10	+5	15	5	125	19
442			15	10	95	23
443			15	15	125	30
449			5	10	68	0
450			20	20	129	45
331	5	-3	15	15	79	0
373			10	15	121	0

TABLE 6.5 (Continued)

Run Number	V_s in knots	V_w in knots	Maximum Rudder Angle in degrees		Maximum Deviation in feet	
			Left	Right	Port	Starboard
H_1-389	5	-3	10	15	144	42
324	7.5	-3	10	20	151	26
325			10	15	87	72
336			7	15	132	0
337			10	10	148	15
342			5	10	113	61
376			10	10	132	4
377			7	15	136	49
383			10	10	155	-30
384			10	10	98	26
335*	10	-3	30	30	344	227
393			5	15	91	0
394			15	15	144	30
402			10	20	151	91
403					57	30
294	7.5	-5	10	15	121	76
295			5	15	98	11
308			5	20	174	38
309			10	20	182	45
312			15	15	64	83
350			10	10	136	15
351			20	20	257	23
300*	10	-5	30	30	322	65
301			20	15	170	83
302			10	15	185	57
313			20	30	166	76
316			10	20	102	68
321			15	15	68	189
322			15	10	102	38

* Indicates accident.

TABLE 6.6

Tabulation of Data from Centerline Runs for Model 3769 in the 26-Degree Parallel Bend, $\lambda = 45$

Run Number	V_s in knots	V_w in knots	Maximum Rudder Angle in degrees		Maximum Deviation in feet	
			Left	Right	Port	Starboard
H_4 - 50	5	0	3	5	107	16
51			10	10	118	87
56			10	10	142	43
57			5	5	59	87
62	7.5	0	10	10	110	63
63			10	5	95	0
68			7	5	122	89
69			10	7	174	116
74	10	0	3	5	75	16
75			10	10	130	-14
76			3	3	79	-16
81			5	2	114	0
86	5	+3	20	20	126	51
87			20	5	87	18
92			15	5	79	-14
93			10	5	79	-12
98	7.5	+3	5	5	99	-12
99			5	0	87	-24
104			10	5	107	-28
105			10	5	71	-20
110	10	+3	5	5	71	-8
111			10	5	110	0
116			5	5	71	-32
117			5	5	67	-24
123	5	+5	15	10	130	0
124			30	15	134	-8
125			20	5	134	59
126			15	5	87	0
139			15	10	126	36
140			15	5	99	-8
127	7.5	+5	10	5	87	-55
130			10	0	103	-41
131			15	5	87	-24
132			10	10	83	-2

TABLE 6.6 (Continued)

Run Number	V_s in knots	V_w in knots	Maximum Rudder Angle in degrees		Maximum Deviation in feet	
			Left	Right	Port	Starboard
H_4-135	7.5	+5	15	10	103	0
136			20	0	134	-16
128	10	+5	10	10	112	-20
129			5	0	114	-2
133			10	5	87	-16
134			10	5	63	12
137			10	5	107	-24
138			15	5	126	-51
141	5	-3	3	5		
142			3	10	128	24
147			10	10	134	0
148			7	10	87	24
155			10	20	103	59
156			5	15	63	32
143	7.5	-3	3	5		
144			3	5	120	32
-149	7.5	-3	7	7	118	12
150			10	7	103	0
153			5	10	118	24
154			3	7	16	32
158			5	10	181	8
159			7	10	79	12
145	10	-3	3	3	114	-8
146			10	10	174	81
151			10	5	138	-16
152			3	5	71	-34
157			5	10	158	77
160	7.5	-5	5	10	103	79
161			5	10	101	81
164			7	10	124	14
165			5	10	87	45
169			3	7	45	43
162	10	-5	10	20	116	53
163			5	10	53	28
166			5	7	95	0
167			5	10	87	39
168			5	7	89	63
170			0	5	71	12

NOTATION FOR SECTION 7

A Water area at midship section, square feet

A_c Water area at midship section when transiting at critical speed, square feet

A_n Normal cross-section area of channel, square feet

B Beam of ship, feet

C_L Lift coefficient

D Channel depth at midship section when ship is moving, feet

D_c Channel depth at midship section when ship is moving at critical speed, feet

D_a Average water depth at midship section and at critical speed, feet = $\frac{A}{W_c}$

D_0 Channel depth in undisturbed section of channel, feet

H Draft of vessel at midship section when ship is underway, feet

H_0 Draft of vessel at midship section when ship is stationary with respect to water, feet

ΔH Change of level of ship, feet

L Length of ship between perpendiculars, feet

L_0 Lift, pounds

V Average speed of reverse flow past midship section and relative to ship, knots

V_c Critical ship speed, knots

V_s Ship speed relative to undisturbed water, knots

V_t Speed of translatory wave relative to the water in the reverse flow, knots

W_B Channel bottom width, feet,

W_c Channel top width at critical depth, feet,

W_0 Channel top width at depth D_0, feet

Y Distance from center of gravity of ship to centerline of channel, feet

Z Distance from center of gravity of ship to prism line, feet

g Acceleration due to gravity = 32.2 feet per second square

λ Linear ratio of full-size ship to model

$\boxtimes$ Midship section area, square feet

m Midship coefficient = $\boxtimes / BH_0$

ρ Density, slugs per cubic foot

Note 1 - Capital letters refer to full-scale ship and channel; lower case letters to model data.

Note 2 - Where primes are used, speeds are in feet per second.

SECTION 7

CHANGE OF LEVEL IN RESTRICTED CHANNELS

ABSTRACT

A series of tests were run in the shallow water basin in order to determine the importance of change of level in fixing the proper dimensions and allowable ship speeds for a restricted channel. Tests were run to observe the effect of channel dimensions, ship speed, and transverse location of a ship on its change of level. All tests were confined to speeds up to the critical speed and the data obtained from the model tests were converted to full-scale results by use of Froude's relationships.

A method for predicting the magnitude of the change of level for a vessel in any channel cross section at speeds below the critical speed is developed from fundamental hydraulic formulas. The results compared very favorably with the sinkage data obtained from model tests. This method was extended in order to predict the critical speed and depth.

Sinkage data on several full-scale vessels were obtained and compared with the theoretical values. This indicated the applicability of the theoretical method for different hulls and the magnitude of the scale effect.

The importance of change of level as a factor in determining channel dimensions is discussed.

INTRODUCTION

When a vessel is underway in still water, the water ahead of the vessel moves forward, outward, and downward. At a comparatively short distance aft of the bow the forward motion ceases, but the water still moves outward and downward to make way for the body of the vessel. Near this point the water starts to flow aft. This reverse flow continues to within a short distance aft of the stern where the water closing in and upwards behind a vessel has a forward motion. Wherever changes in velocity occur there is a change in the elevation of the water surface. In shallow water or restricted canals the region of disturbed water about the ship is confined to a much smaller area than in water of unlimited width and depth. Therefore in a restricted channel, the reverse flow relative to the vessel has a greater magnitude than in open water for the same ship speed. The change in the water surface level due to the reverse flow results in a much greater sinkage of the ship in a restricted channel than that caused by similar hydrodynamic phenomena both in open and shallow water. The change of level or sinkage (ΔH) at any section of a vessel is defined as the change in elevation of a point in the section when the ship is moving with respect to the water as compared to its position when the vessel is stationary (reduction in elevation results in positive sinkage). This is illustrated in Figure 7.1.

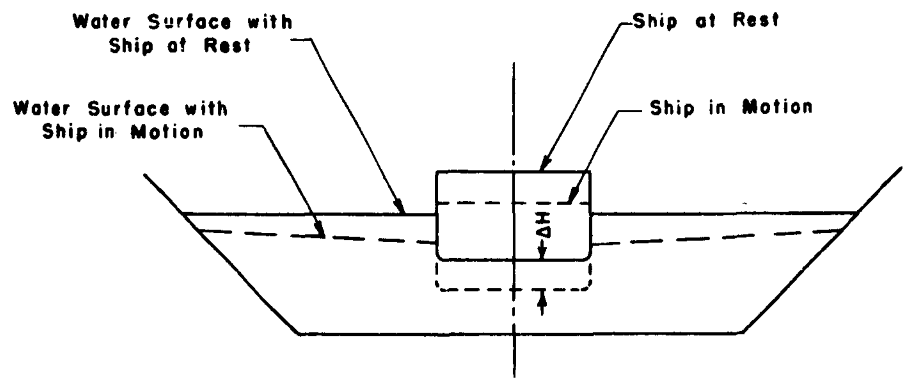


Figure 7.1 - Sketch Showing Change of Level of Ship Moving in Restricted Channel

In a restricted channel, the large change of level due to high speeds may result in the vessel scraping bottom. In addition, the change of level is an indication of the size of the surface waves and their speed past the banks. The speed will affect the rate of bank deterioration.

In the past, considerable study has been devoted to the variation in the resistance of ships in shallow water and in restricted channels, but very little work has been done on the change of level of ships under these same conditions. Some of the studies of ship resistance in shallow water and restricted channels is described in References (64), (65) and (66). In 1904, Henry N. Babcock, in Reference (39), made a series of full-scale measurements of change of level of ships in shallow waters. Some additional information on the change of level of model or full-scale vessels underway in shallow water or canals may be found in References (16), (67) and (68). In References (67) and (68), data are presented for selected ships underway in restricted channels at a range of speeds extending well above the critical speed. However, no analysis of the results had been attempted. Therefore the present studies were initiated as part of the TMB Panama Canal studies, the purpose of which was to assist in selecting the proper cross section for a new canal. For the purpose of the present investigation, it was thought that data above the critical speed would be of minor importance.

After a theory for predicting sinkage had been developed, a foreign-language Reference (69) was discovered which presented a method for determining the change of level of a ship by using the same fundamental relationship described in this report. The data were very meager, however, and the form of the results did not lend itself to an easy evaluation of the sinkage under varying conditions. The study was confined to a centerline condition and no thought was given to the significance of critical speed and depth.

TEST SETUP AND PROCEDURE

The experimental work was conducted mainly in the shallow water basin. The apparatus is described in Section 3 and shown in Figure 3.21.

For the self-propulsion tests a calibration curve was first obtained in order to determine the necessary voltage for self-propulsion at any specified speed as described in Section 3.

After the necessary voltage had been determined for the full range of speeds, cables were attached between the tow pins and tow brackets. The cables allowed the model to trim freely but prevented too much fore-and-aft motion which would result in an error in the sinkage reading. Then the change-of-level cords were attached and the dials set at zero while the model was stationary. The carriage was accelerated to the proper speed while the voltage was brought up to the proper value to make the model self-propelled. Once equilibrium was established, the sinkage dials were read. The dials magnified the change-in-level readings so that they could be read to the nearest hundredth of a foot. These readings gave the sinkage at the two points where the cords were attached to the model. Simple geometric relationships were used to determine the change of level of the model at the forward and after perpendiculars.

The readings Δ_1 and Δ_2 of the dials A and B, Figure 7.2, indicate the change of level at points 1 and 2. Then from geometry of figure:

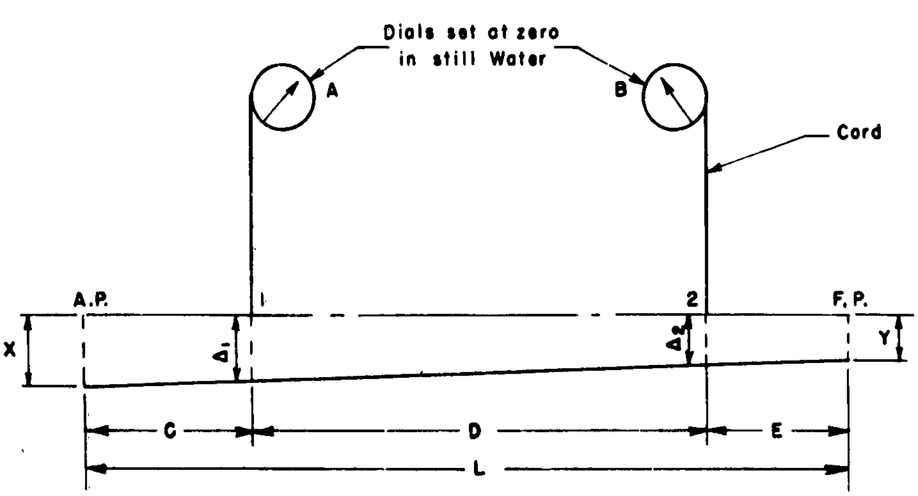


Figure 7.2 - Sketch Showing Sinkage Apparatus

Sinkage at stern* $= X = \frac{C}{D}(\Delta_1 - \Delta_2) + \Delta_1$

Sinkage at bow $= Y = \Delta_2 - \frac{E}{D}(\Delta_1 - \Delta_2)$

Sinkage at midship section $= \frac{1}{2}\left[\left(\frac{D + C - E}{D}\right)\Delta_1 + \left(\frac{D + E - C}{D}\right)\Delta_2\right]$

If the vessel trims forward then $\Delta_1 < \Delta_2$ and $\Delta_1 - \Delta_2$ is negative but the same equations are still applicable. Table 7.1 gives values of the constants C, D, and E for the models tested.

TABLE 7.1

Table of Values of Constants Used in Calculating Sinkage at Midship Section and Forward and Aft Perpendiculars

Dimensions are in inches.

Model Number	C	D	E
3769	32.5	110.5	97
3992	53	110.5	76.5
3859	21.5	60	38.5

For tests where the model was towed, no voltage calibration was necessary. The propellers were removed and replaced by hubs, the cables and cords were attached, and the dials were set at zero. The carriage was then brought to the proper speed and the sinkage was determined.

The range of speeds was from about 3 knots full scale up to the critical speed. Three knots was about the slowest speed which would give a noticeable sinkage, whereas the critical speed is the ship speed that causes a hydraulic jump to form aft of the midship section. This speed is later shown to coincide with the one on the speed-sinkage curve which makes the tangent vertical. This phenomenon is accompanied by greatly increased power requirements, excessive sinkage, and other operating difficulties so that often the critical speed could not be reached.

Several tests were run in the circulating-water channel. The purpose of this was to determine the water surface profile around the hull and whether change of level of a ship in a restricted channel was due mainly to changes in hydrostatic pressure resulting from the lowering of the water surface or to changes in the hydrodynamic lift forces on the vessel and consequently a change in the draft of the vessel.

The model was held in position by means of the dynamometer arms and the RPM's were increased until the model was self-propelled. The technique

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* Whenever reference is made to sinkage at bow or stern, the sinkage is at the forward and after perpendiculars, respectively.

and apparatus are described in Section 3. The change in the water surface was then measured by noting its height below a fixed datum and subtracting the height of the water surface in still water.

The following models were tested:

Model 3769, Model 3992, and Model 3859.

Data on these vessels are supplied in Figure 2.1.

TEST RESULTS

Figure 7.3 is a sketch illustrating the general profile of the water surface in the vicinity of a ship underway on the centerline of a restricted channel. Figure 7.4 is a plot of some actual measurements taken and shows the wave profile around a tanker model on the centerline of the

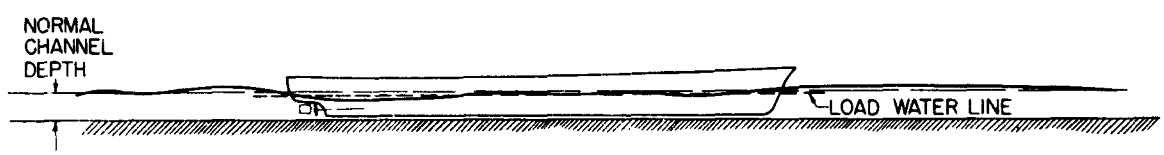


Figure 7.3 - General Contour of the Water Surface in the Vicinity of a Ship Underway in a Restricted Channel at Sub-Critical Speed

The water surface ahead and astern of the ship is slightly above the normal channel depth, while abreast of the ship it is below the normal channel depth. This is generally responsible for the change in level of the ship.

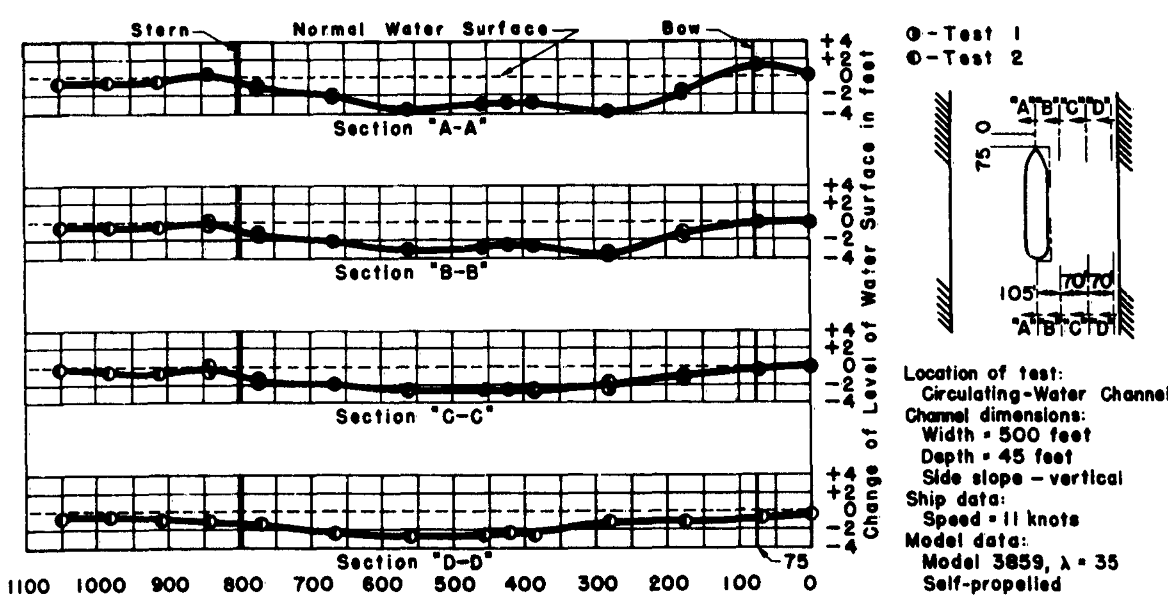


Figure 7.4 - Water Surface Profile at Various Longitudinal Sections for a Ship on Centerline of a Restricted Channel

Data are from two independent tests.

channel and moving at 11 knots.* The drop in water surface level is quite noticeable. Also, there is a distinct slope of the water surface from the walls of the channel down toward the ship.

Although accurate measurements were impossible, estimates were made of the change of water surface level and the sinkage of the ship. The change of level of the water surface in Figure 7.3 at Section A-A was about 3 feet while the sinkage of the ship was about 3.5 feet. This shows that sinkage in a restricted channel is due mainly to change in water level. At higher speed, hydrodynamic forces on the vessel may play an important part.

Figure 7.5 shows the wave profile for the same set of conditions as before except that the model is 142.75 feet off the centerline of the channel.

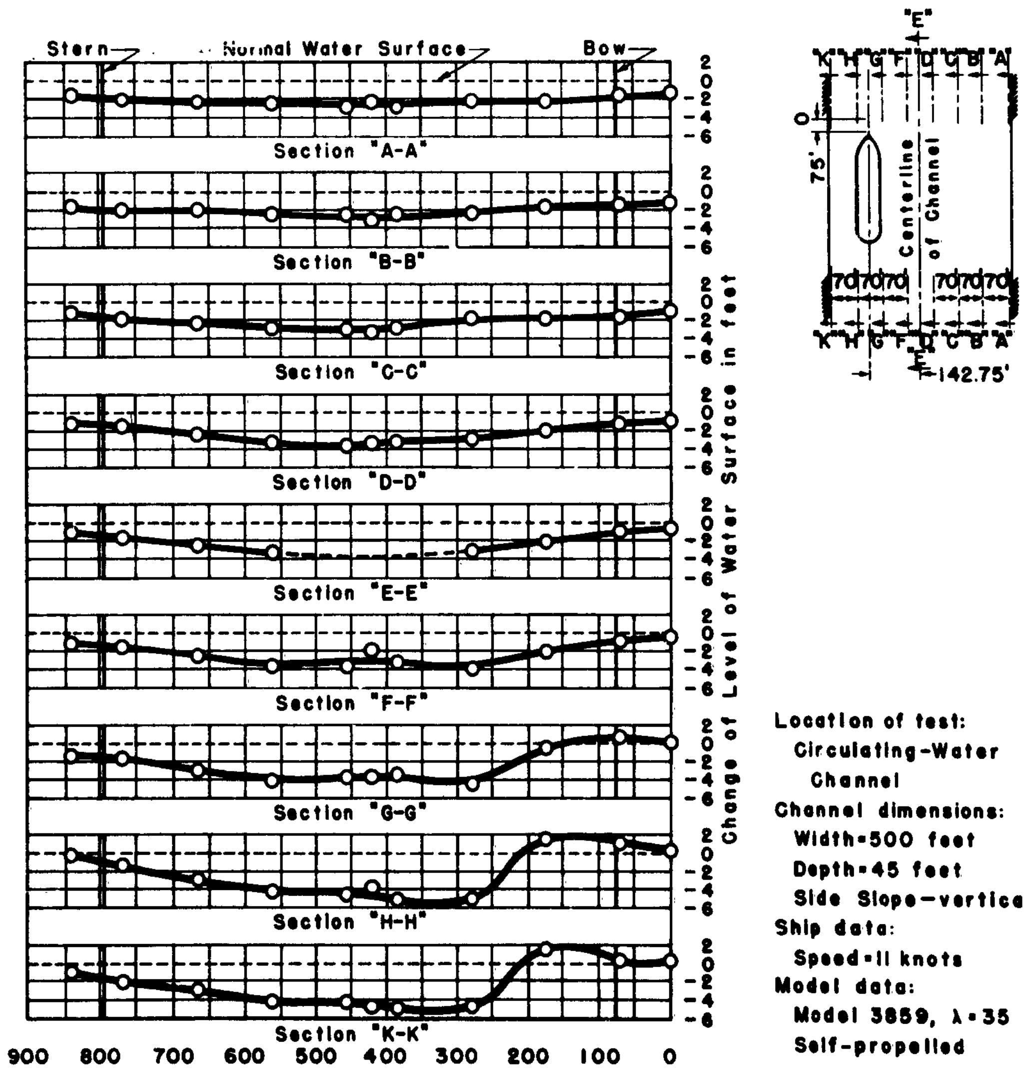


Figure 7.5 - Water Surface Profile for a Ship Located off the Centerline of a Restricted Channel

* In the discussion, although tests were model tests, all dimensions and speeds refer to the full-scale equivalent.

Although the general shape of the wave profile is the same, the difference in water surface level on either side of the model would explain the bank suction and yawing moment developed.

Tables and graphs showing the change of level of the ship plotted against ship speed for different channel dimensions for Models 3769, 3992, and 3859 are shown in Appendix 7.1, Figures 7.21 to 7.25. Channel bottom widths of 300, 500, and 700 feet, channel depths of 45, 60, and 80 feet and a 45-degree side slope were used for Model 3769, making 9 different cross-sections. Figure 7.6 shows the resultant curve for Model 3769 in a channel with a bottom width of 500 feet and a depth of 45 feet and is typical. The graph is parabolic in shape indicating that the change of level varies approximately as the square of the ship speed.

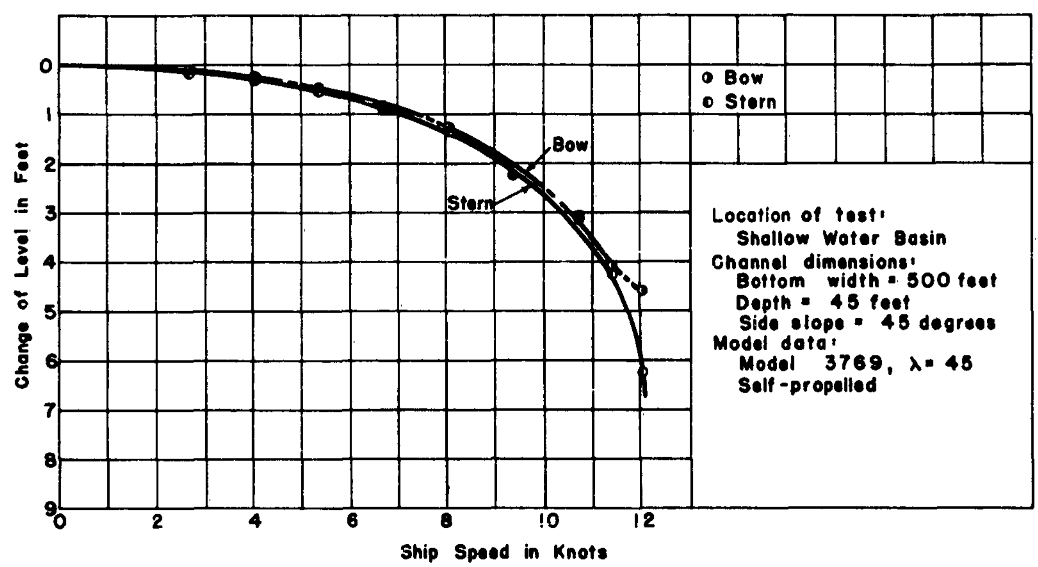


Figure 7.6 - Change of Level of Model 3769 Self-Propelled on the Centerline of a Restricted Channel

For Models 3769 and 3992, there was little change of trim right up to the critical speed, when the bow began to rise up and ride on a translatory wave being propagated along the channel. The test on Model 3859, Figure 7.7, indicated a considerable change of trim. The test could not be run up to the critical speed because the large trim forward resulted in the bow wave washing over the model.

Figure 7.8 shows the effect of varying channel depth while the bottom width is fixed. For a given speed the sinkage varies approximately inversely as the square of the channel depth. The critical speed increases with depth, and so does the sinkage of the ship at the critical speed. The

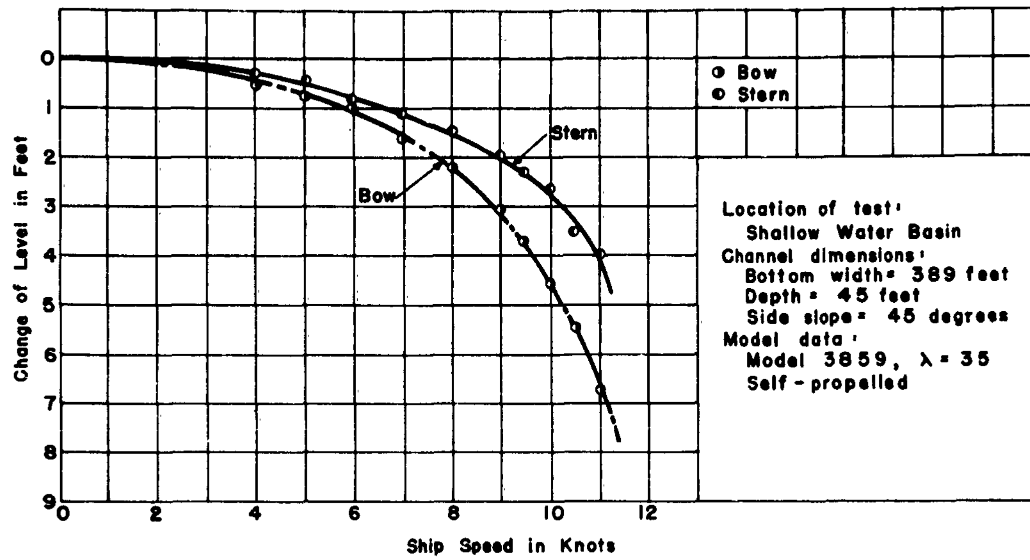
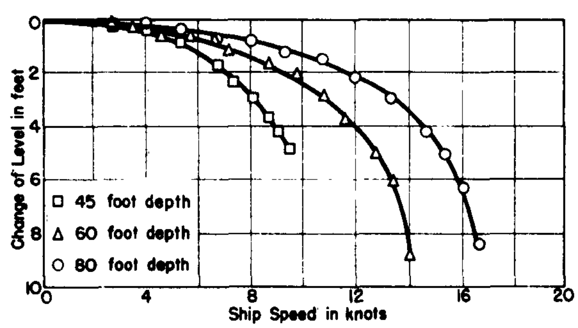
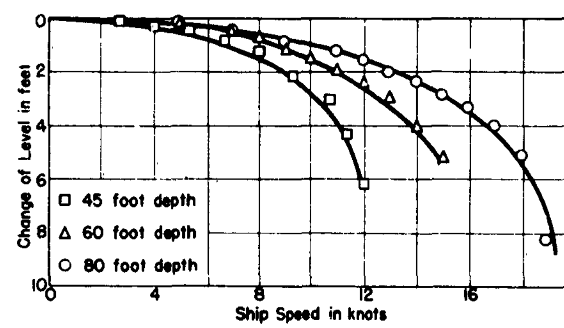


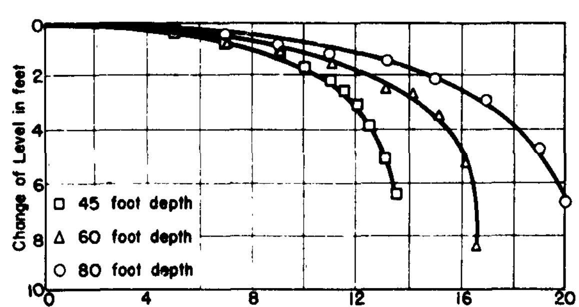
Figure 7.7 - Change of Level of a Model 3859 Self-Propelled on the Centerline of a Restricted Channel



a - Channel-Bottom Width = 300 Feet



b - Channel-Bottom Width = 500 Feet



c - Channel-Bottom Width = 700 Feet

Location of test:
Shallow Water Basin
Channel dimensions:
Side Slope = 45 degrees
Model data:
Model 3769, λ = 45
Self - propelled

Figure 7.8 Effect of Channel Depth on Change of Level of a Ship on Centerline of a Restricted Channel

The curves shown are for the stern only. The bow curves are similar.

amount of water under the hull, however, at the critical speed increases with depth. Varying the width in a given ratio has the same effect as varying the depth in the same ratio.

Figures 7.28 to 7.32 in Appendix 7.1 show the change-of-level curves for Model 3769 off the centerline in various channels, while Figures 7.33 to 7.35 compare the sinkage for Model 3769 on and off the centerline. Figure 7.9 shows comparison curves in a channel with a 500-foot bottom width and varied depths. Within the ordinary operating range of speeds, movement off centerline has practically no effect upon the sinkage curve; only when approaching

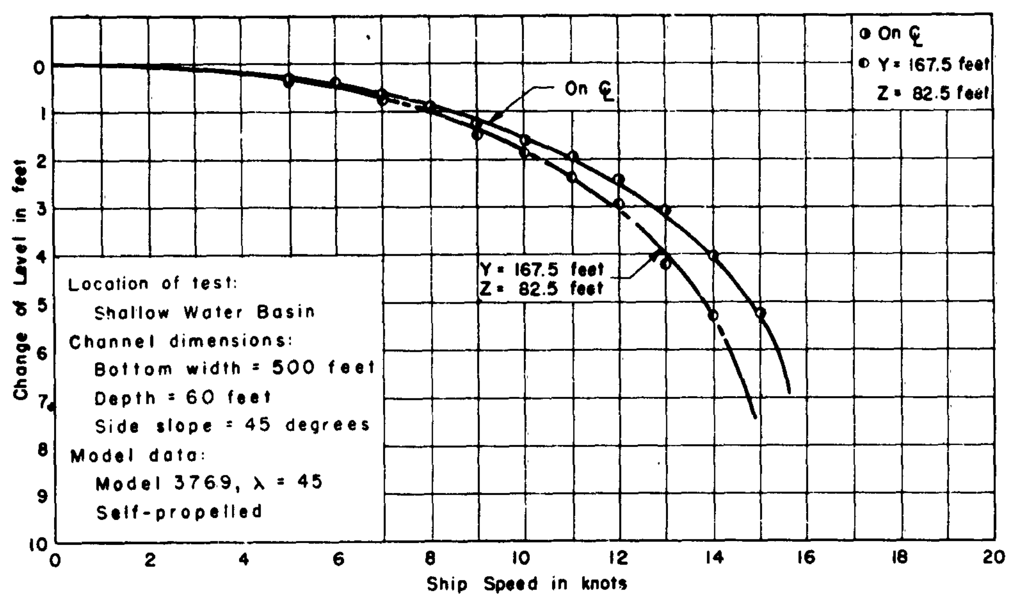


Figure 7.9 - Effect of Transverse Location on Change of Level of a Ship in a Restricted Channel

These curves are for the stern only. The bow curves are similar.

the prism line and the critical speed does the change of level increase for a given speed while the critical velocity decreases. The curves for the 700-foot width, Figure 7.35 in Appendix 7.1 indicate a considerable difference in the sinkage for the centerline and off-center conditions. However, as explained in Section 4, there are limitations as to location and ship speed due to the development of bank suction. By examining the curves of equilibrium rudder angles against distance from prism line for various speeds which are found in Section 4, Figure 4.9, the maximum ship speed for Model 3769 in a channel 700 feet wide and 45 feet deep located 82.5 feet from the prism line is found to be 5 knots. For the same conditions in a channel 60 feet deep, the maximum speed is 9 knots. The difference in sinkage between centerline and off-center positions for these two conditions is slight.

The results of a series of tests with a towed model are shown in Appendix 7.1, Figure 7.36. Comparison curves for Model 3769, self-propelled and towed, are shown in Figure 7.37. Figure 7.10 is a typical curve and indicates very little difference in the general shape of the curve and the magnitude of the critical speed. However, the pumping action of the propellers results in 10 to 15 per cent greater sinkage for the self-propelled model for most of the range of speeds.

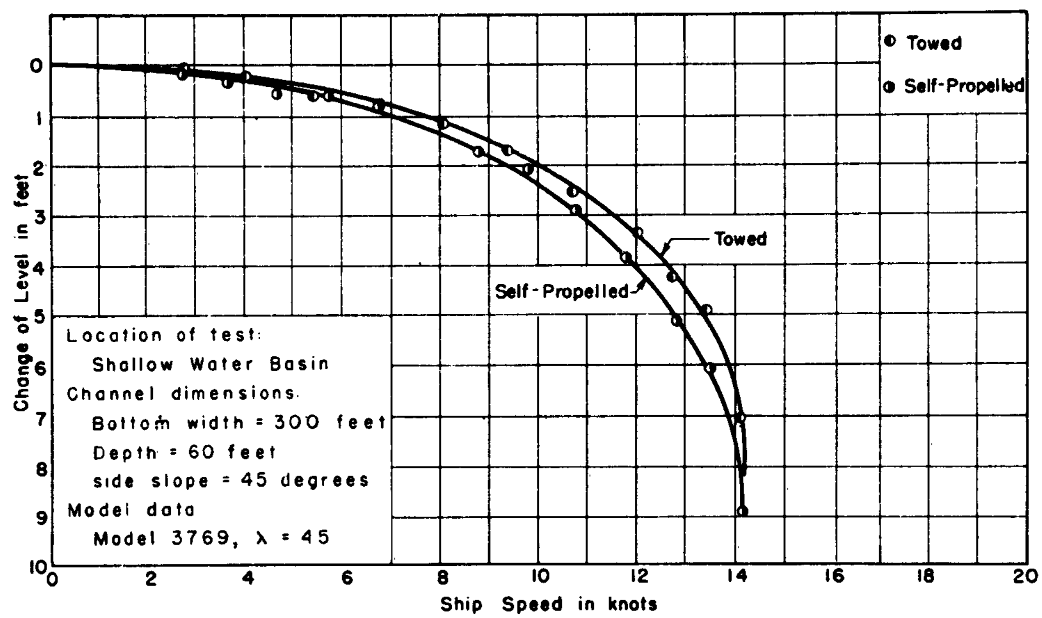


Figure 7.10 - Comparison of Change of Level for a Towed and for a Self-Propelled Ship on the Centerline of a Restricted Channel

These curves are for the stern only. The bow curves are similar.

To make sure that the use of towing brackets located off the centerline and away from the center of gravity of the vessel would not produce seriour errors in obtaining the sinkage, one test was run with a special set of towing brackets located on the centerline of the ship at the same elevation as the center of gravity. Figure 7.38 in Appendix 7.1 shows that only negligible differences result.

Figure 7.11 is a correlation curve and indicates what different combinations of channel depth and bottom width will result in the same sinkage at a given speed for Model 3769. For example, at a ship speed of 10 knots, if the allowable change of level were fixed at 2 feet, a channel with a 300-foot bottom width and a 66-foot depth or one with a 500-foot bottom width and a 52-foot depth would serve while the depth of a channel with 700 feet bottom width could be less than the 45 feet minimum depth tested.

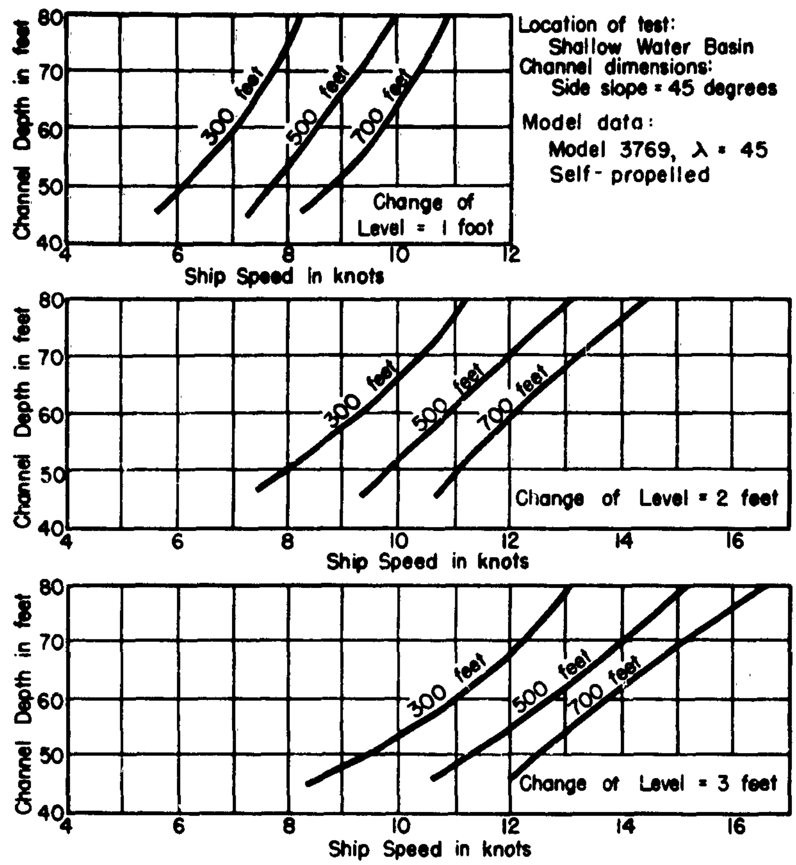


Figure 7.11 - Comparison of Channel Dimensions and Ship Speeds at Which a Change of Level of 1, 2, or 3 Feet Is Obtained

The data are plotted for the midship section so as to eliminate the effect of change in trim.

ANALYSIS AND DISCUSSION OF RESULTS

THEORETICAL DETERMINATION OF SINKAGE FOR SHIP ON CENTERLINE OF CHANNEL

Since the data obtained were limited to several ships and conditions, a theoretical method for determining the effect of the many variables involved in determining the sinkage and critical speed would be valuable. In addition, comparison of model sinkage values, theoretical sinkage, and full-scale results would be useful. Therefore the main part of this report is devoted to this purpose.

A theory based upon certain simplifying assumptions has been found to yield an equation that fits the data reasonably well. The principal assumptions are:

1. Friction losses are negligible. This permits use of Bernoulli's equation.

2. All water displaced by the motion of the vessel passes back of it to fill the void. This allows application of the continuity equation.

3. The ship can be treated as a prism with a cross-sectional area equal to the midship area of the ship.

4. For moderate speeds, wave effects and hydrodynamic lift forces on the ship itself can be neglected.

5. The channel is sufficiently narrow so that variations in the water level transversely across the channel can be neglected.

A consequence of the fourth assumption is that the theory will probably fail if the vessel comes close to the bottom of the channel, so that hydrodynamic forces on the bottom of the vessel are important. Vessels moving with little water under the keel were not adequately studied in these tests.

Another consequence of the assumptions is that the pressure acting on the vessel can be treated as hydrostatic pressure, and the displacement of the vessel therefore remains constant. Also, the sinkage is equal to the change in level of the water surface.

$$\Delta H = D_0 - D$$

For purpose of analysis the boat is assumed stationary in the horizontal plane with the water in front of the boat moving at a velocity V_s toward it as shown in Figure 7.12. Down is positive.

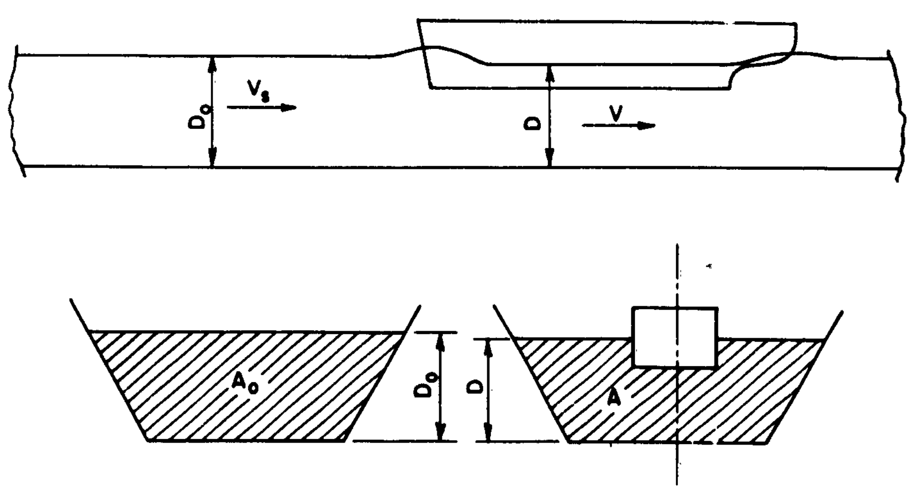


Figure 7.12 - Sketch Showing the Terms Used in the Theoretical Analysis of Change of Level for a Ship on the Centerline of a Restricted Channel

From equation of continuity

$$AV' = A_0 V_s'$$

$$V' = \frac{A_0}{A} V_s' \qquad [7.1]$$

Bernoulli's equation for a streamline on the water surface is

$$D_0 + \frac{V_s'^2}{2g} = D + \frac{V'^2}{2g}$$

$$D_0 - D = \frac{1}{2g}(V'^2 - V_s'^2) \qquad [7.2]$$

and substituting for V' from [7.1]

$$D_0 - D = \frac{1}{2g}\left[\left(\frac{A_0}{A}\right)^2 V_s'^2 - V_s'^2\right]$$

$$= \frac{V_s'^2}{2g}\left[\left(\frac{A_0}{A}\right)^2 - 1\right]$$

or

$$\frac{D_0 - D}{\frac{V_s'^2}{2g}} = \left(\frac{A_0}{A}\right)^2 - 1 \qquad [7.3]$$

and since

$$D_0 - D = \Delta H$$

$$\frac{\Delta H}{\frac{V_s'^2}{2g}} = \left(\frac{A_0}{A}\right)^2 - 1 \qquad [7.4]$$

Since Equation [7.4] is dimensionless, it is applicable to channels and ships of any size.

Ship speeds are usually given in knots; therefore Equation [7.4] will be rewritten

$$\frac{22.6\,\Delta H}{V_s^2} = \left(\frac{A_0}{A}\right)^2 - 1 \qquad [7.4a]$$

The equations developed by Lemmerman (69) by use of the same fundamental Equations [7.1] and [7.2] are

$$\frac{V' - V_s'}{V_s'} = -1 + \sqrt{1 + 2g\frac{\Delta H}{V_s'^2}} \qquad [7.5]$$

$$\frac{V' - V_s'}{V_s'} = \frac{\boxtimes + W_0\,\Delta H}{A} \qquad [7.6]$$

These equations can be combined to give [7.4] provided

$$W_0 \Delta H = A_0 - (A + \boxtimes) \qquad [7.7]$$

which is exactly true for sections with vertical walls. For walls other than vertical the error involved is insignificant.

Figure 7.13 shows the plot of Equation [7.4a] using $\frac{A_0}{A}$ and $\frac{22.6\,\Delta H}{V_s^2}$ as coordinates. In addition, values obtained from the data on Models 3769, 3859, and 3992 are shown. The midship section sinkage was used. In general, these points may differ somewhat from theoretical values because of the approximations made in developing the theory. However, if for any particular vessel these differences are a function of $\frac{A_0}{A}$, we can obtain an empirical curve for each vessel and thus be able to obtain a more precise sinkage curve for any cross section.

Examination of Figure 7.13 shows that empirical data agree quite well with theory. However, each vessel gives an empirical curve slightly different from theory and from the curves for other vessels. Therefore, the most accurate estimates of change of level in any channel and at any speed can be made if information concerning the sinkage for some one channel cross section are available.

Since the change of level is indicative of the size of the surface waves, this and possibly other resultant phenomena may set a practical limit on the allowable sinkage for a particular cross section. The allowable ship speed so as not to exceed this specified change of level can be readily obtained by use of Figure 7.13 or, it may be calculated from Equation [7.4].

Example 1

Compute the maximum speed with which a vessel corresponding to Model 3769 can transit the centerline of a channel 500 feet wide and 60 feet deep with a 45-degree side slope and not exceed a change of level of 2 feet.

$$\frac{A_0}{A} = \frac{D_0\,(W_B + D_0)}{D\,(W_B + D) - \boxtimes} = \frac{60(500 + 60)}{58(500 + 58) - 3570} = 1.166$$

From theoretical curve $22.6\,\frac{\Delta H}{V_s^2} = 0.363$

or

$$V_s = \sqrt{\frac{22.6 \times 2}{0.363}} = 11.17 \text{ knots}$$

From empirical curve $22.6\,\frac{\Delta H}{V_s^2} = 0.365$

and

$$V_s = 11.14 \text{ knots}$$

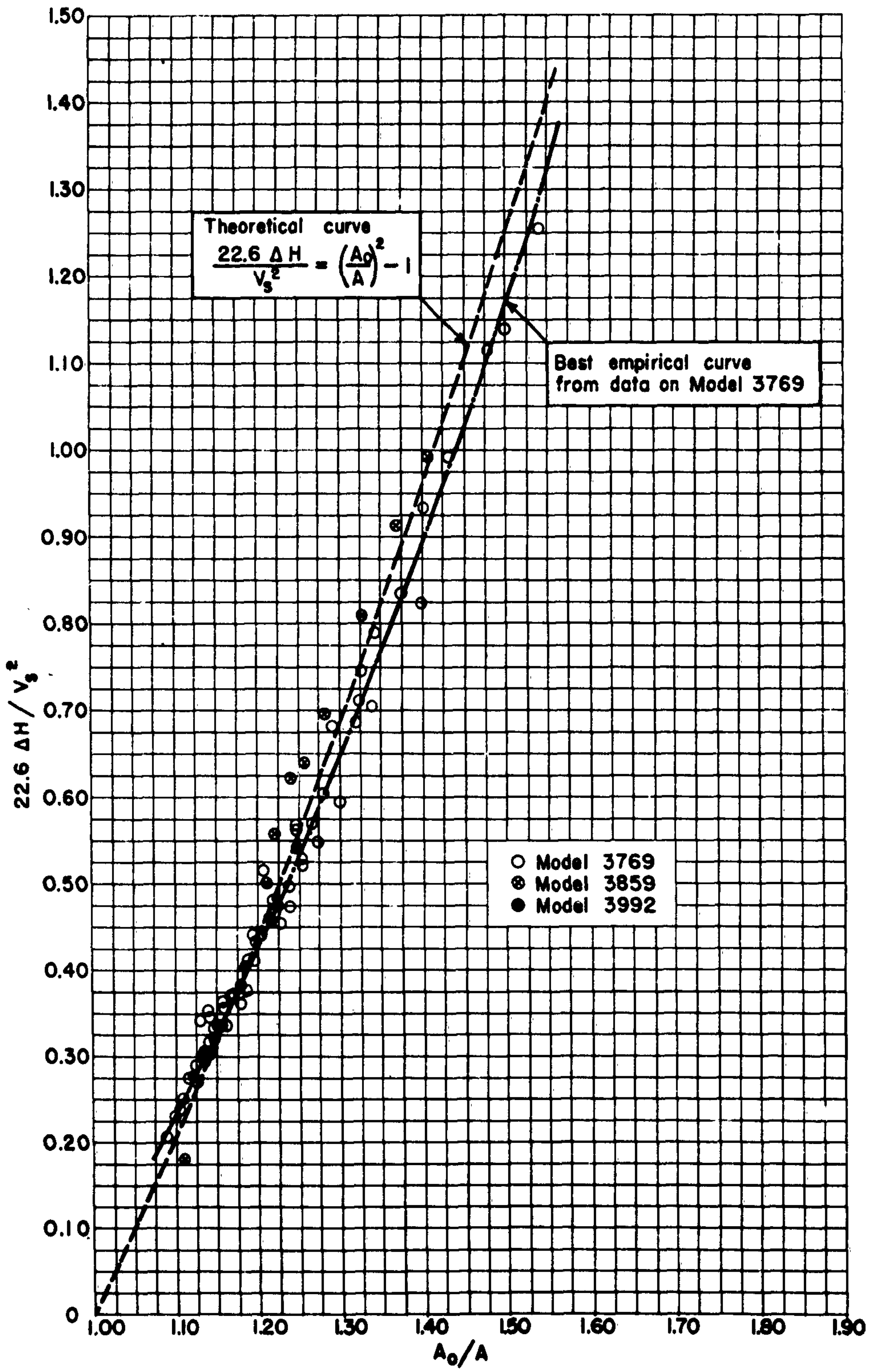


Figure 7.13 - Comparison of Theoretical Curve with Actual Values of $22.6\Delta H/V_s^2$ Plotted against A_0/A as Obtained from Model Tests

Actual V_s from tests = 10.90 knots.

It must be realized that the sinkage thus obtained is for the midship section. A knowledge of the trimming characteristics of the ship would be necessary in order to predict the sinkage at the forward and after perpendiculars. However, the change in trim is usually small and would be important only if there were danger of striking bottom.

This procedure can be applied to get complete sinkage curves by taking successive values of ΔH.

Figure 7.14 shows a comparison of the sinkage curves obtained from test results, the theoretical curve, and the empirical curve for Model 3769 in a channel whose equivalent full-scale dimensions are a width of 500 feet and a depth of 60 feet. Both theoretical and empirical curves agree quite well with actual sinkage values until speeds near the critical are reached. Here the theoretical curve gives sinkages which are greater than those actually measured.

Additional comparison curves for Models 3769 and 3992 are shown in Appendix 7.1, Figures 7.41 to 7.44. These two vessels have similar lines and cross-sections. These curves show that good approximations of the sinkage curves are obtained by use of the theoretical equation. Differences between the measured and the computed values of the sinkage may be due to

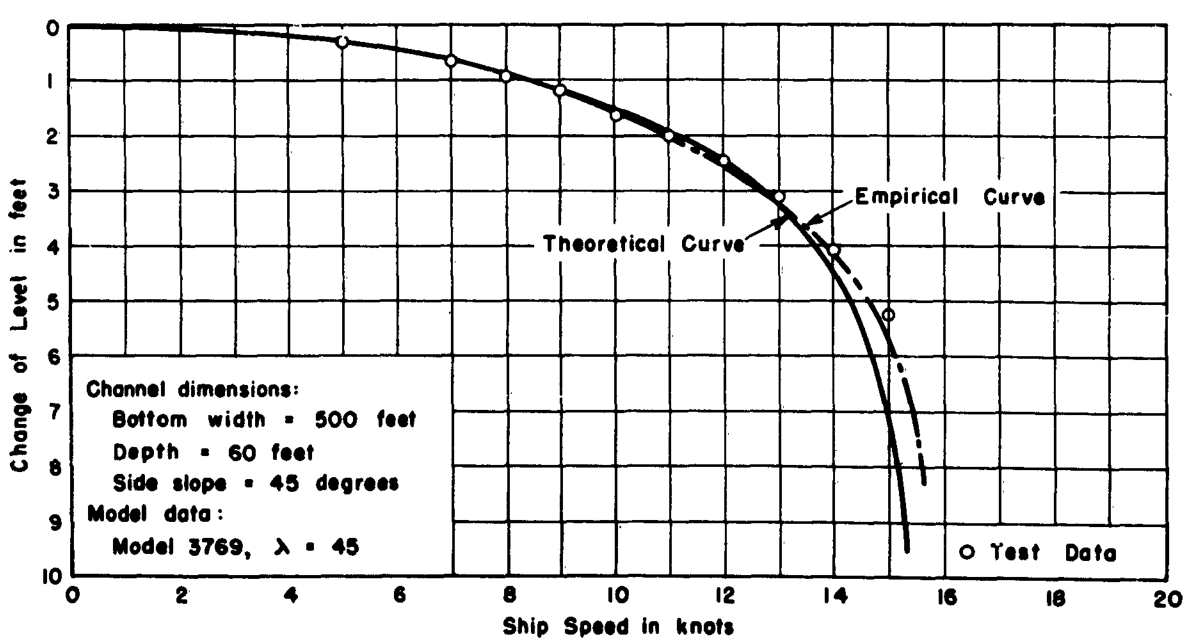


Figure 7.14 - Comparison of Theoretical and Empirical Sinkage Curves with Test Results for Model 3769

hydrodynamic lift forces which vary approximately as the square of the velocity of the water past the vessel and may be written

$$L_0 = \frac{CV^2}{g}$$

where the coefficient C for any particular ship will vary with the trim of the vessel and somewhat with channel cross section. The effect of lift is to change the displacement and the draft of the vessel. Therefore,

$$H_0 - H = KL_0^* \quad \text{and} \quad \Delta H \neq D_0 - D$$

where K is a constant of proportionality. The change in draft equals the change of level of the water surface minus the sinkage:

$$H_0 - H = D_0 - D - \Delta H$$

Combining and eliminating $H_0 - H$ we have

$$D_0 - D - \Delta H = KC \frac{V^2}{g} = C_L \frac{V^2}{g} \qquad [7.8]$$

Since C_L is a function of the trim of the vessel and the trim does vary, especially near the critical speed, we generally cannot evaluate C_L. However, test results show that for most speeds, the assumption presented in the theory that $\Delta H = D_0 - D$ results in little error.

This reasoning may explain the appearance of the curve shown in Figure 7.15 for Model 3859, a large tanker vessel. The curve compares the actual change of level at the midship section with the theoretical sinkage. Since the tanker trims forward considerably even at moderate speeds, small lift forces are developed. A forward trim usually results in a downward or positive lift which would in turn increase the draft of the vessel and result in ΔH being greater than $D_0 - D$. As the critical speed is approached, the bow starts rising and reduces the trim and therefore the lift. Hence the theoretical sinkage approaches more closely to the actual value. This graph shows that the sinkage at the midship section can be estimated satisfactorily for vessels with considerable trim. Some knowledge of the trimming tendencies of the vessel is necessary in order to estimate the sinkage at bow and stern.

Examination of Equation [7.4a] indicates that if the ship speed is given, the calculation for the change of level involves the solution of an equation of higher order which may be quite tedious. Instead, the

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* L_0 is positive downward.

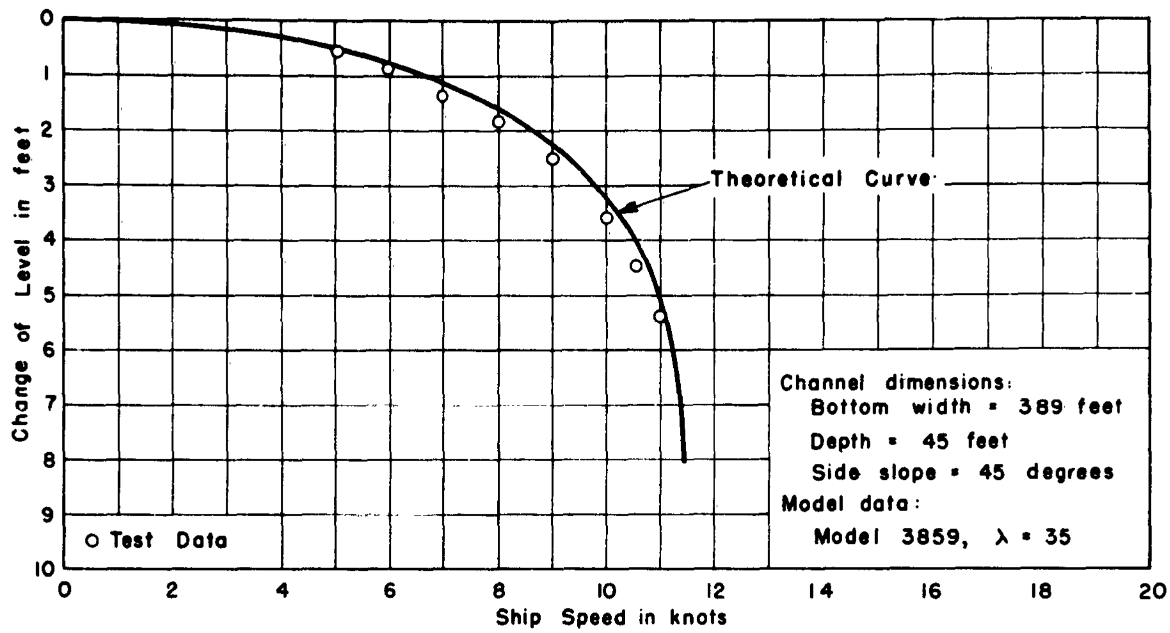


Figure 7.15 - Comparison of Theoretical Sinkage Curve with Test Results for Model 3859

approximation given by Equation [7.7] can be used to good advantage. From Equation [7.7] we obtain

$$A = A_0 - \boxtimes - W_0 \, \Delta H$$

Substituting for A in [7.4] gives

$$\frac{22.6 \, \Delta H}{V_s^2} = \left(\frac{A_0}{A_0 - \boxtimes - W_0 \, \Delta H}\right)^2 - 1$$

This is a cubic equation in ΔH which can be solved analytically. This is tedious, however, and therefore the expression was rearranged in a form to serve as a basis for a convenient plot of the solution. Rearranging and taking square roots, we have

$$\frac{A_0}{A - \boxtimes - W_0 \, \Delta H} = \sqrt{22.6 \frac{\Delta H}{V_s^2} + 1}$$

This may be rewritten as

$$\frac{1}{\sqrt{22.6 \frac{\Delta H}{V_s^2} + 1}} = \frac{A_0 - \boxtimes}{A_0} - \frac{W_0 V_s^2}{A_0} \, \frac{\Delta H}{V_s^2} \qquad [7.9]$$

This equation involves the three quantities $\frac{A_0 - \boxtimes}{A_0}$, $\frac{\Delta H}{V_s^2}$ and $\frac{W_0 V_s^2}{A_0}$ and its solution is plotted in Figure 7.16.

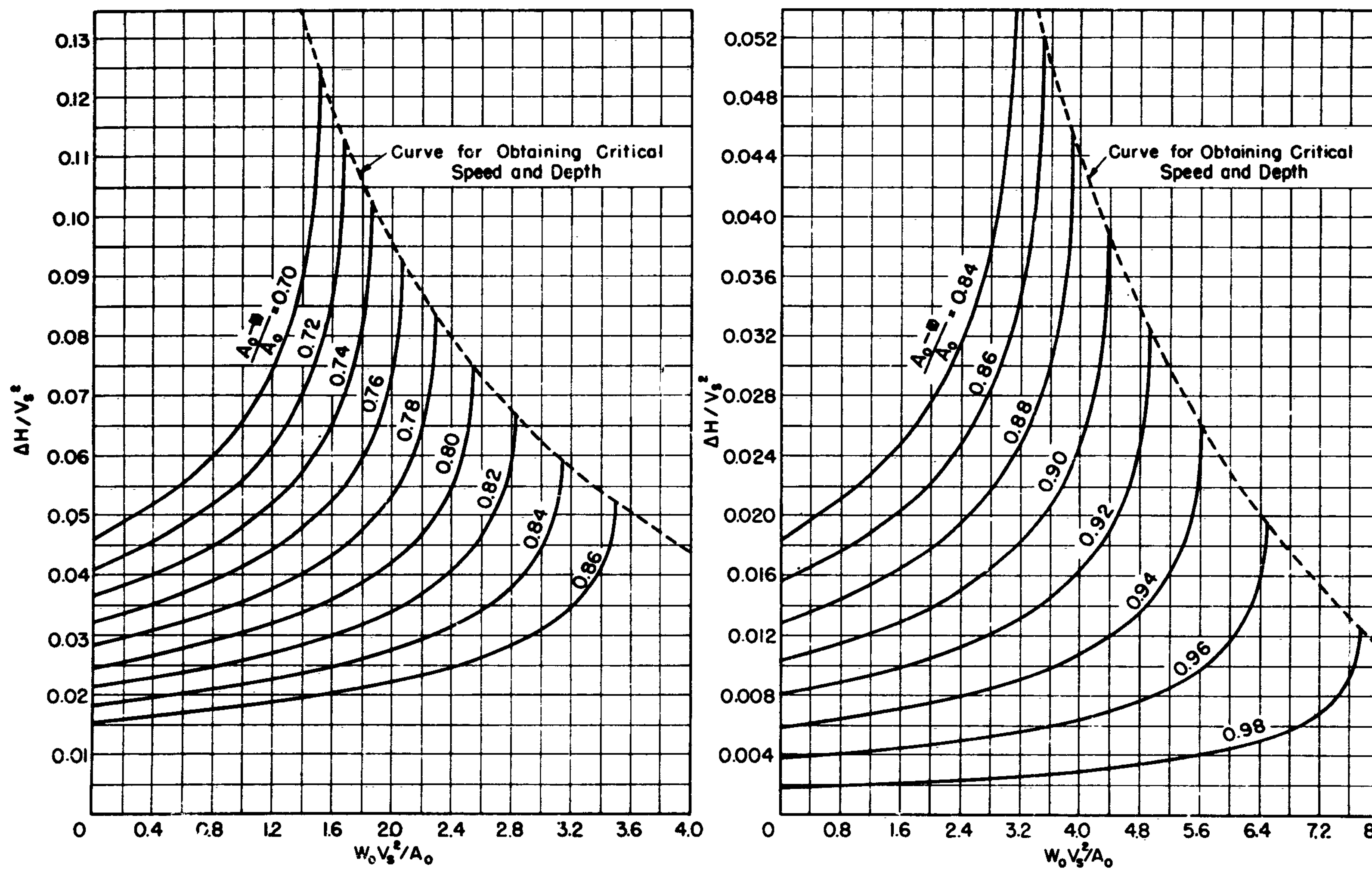


Figure 7.16 - Curves for Computing Sinkage of a Ship in a Restricted Channel

Examination of Equation [7.9] will show that for most cases there are two real values of $\Delta H/V_s^2$ which will satisfy the equation for specific values of $\frac{A_0 - \boxtimes}{A_0}$ and $\frac{W_0 V_s^2}{A_0}$. These will correspond to the two depths, one representing tranquil flow and the other rapid flow, found in open channels. The first one is the value we are interested in and is the one used in obtaining ΔH.

Example 2

Compute the change of level for a ship corresponding to Model 3769 traveling at 10 knots in a channel 500 feet wide and 60 feet deep with a 45-degree side slope. Then

$$\frac{A_0 - \boxtimes}{A_0} = \frac{560 \times 60 - 3570}{560 \times 60} = 0.894$$

and

$$\frac{W_0 V_s^2}{A_0} = \frac{620 \times 100}{33,600} = 1.845$$

From Figure 7.16, $\frac{\Delta H}{V_s^2} = 0.0146$

and $\Delta H = 1.46$ foot

This agrees closely with the measured value of ΔH, which is 1.60 foot.

Although Figure 7.16 should cover almost all possible combinations, if a case arises which does not fit the range of the curve, Equation [7.4a] can be used with little difficulty. A value of ΔH must be assumed and the equation used to determine the value of V_s which would correspond to this value of ΔH. A value very close to the true value can be obtained by making use of the relationship that the sinkage varies nearly as the square of the speed; then

$$\Delta H = \frac{V_s^2 \times \text{assumed } \Delta H}{(\text{calculated } V_s)^2}$$

If further refinement is desired, the new value of ΔH can be inserted in Equation [7.4a] and the process repeated.

Example 3

Compute the change of level for a ship corresponding to Model 3769 traveling at 10 knots in a channel 500 feet wide and 60 feet deep with a 45-degree side slope.

Assume

$$\Delta H = 2 \text{ feet}$$

Then

$$\frac{A_0}{A} = \frac{33600}{558 \times 58 - 3570} = 1.168$$

and from Figure 7.13

$$\frac{22.6\Delta H}{V_s^2} = 0.362$$

and

$$V_s = 11.17 \text{ knots}$$

therefore

$$\Delta H = \left(\frac{10}{11.17}\right)^2 \times 2 = 1.6 \text{ foot}$$

Using corrected value of ΔH,

$$\frac{A_0}{A} = \frac{33,600}{558.4 \times 584 - 3570} = 1.157$$

and

$$\frac{22.6\Delta H}{V_s^2} = 0.339$$

therefore

$$V_s = 10.33 \text{ knots}$$

and

$$\Delta H = \left(\frac{10}{10.33}\right)^2 \times 1.6 = 1.5 \text{ foot}$$

From the theoretical curve of ΔH against V_s in Figure 7.14, ΔH is 1.5 foot. By use of Figure 7.16 ΔH is 1.46 foot. All results are close and agree quite well with the actual sinkage, 1.60 foot.

APPLICATION TO OFF-CENTER POSITION

A tentative attempt was made to apply the same method to off-center positions, by means of the following additional assumptions:

1. The flow divides proportionately, that is $\frac{Q_1}{Q_2} = \frac{A_1}{A_2}$, where Q_1 and Q_2 are the rates of flow in Sections A_1 and A_2, the sections of channel on each side of the centerline of the ship.

2. Bernoulli's equation is applicable to both sections. This would necessitate no cross-flow under the hull.

3. The change in level of the ship is the average of the change in level of the two water surfaces.

We could then apply Bernoulli's equation to obtain the elevation of the two water surfaces and so obtain the sinkage of the ship.

This method led to sinkage values and differences in the water surface levels for the two sides of the vessel which were far too high, indicating that one of the assumptions is in considerable error. Figure 7.5 indicates that there must be some adjustment of the level on the two sides since the difference in level is of much smaller magnitude than anticipated.

For these investigations, further attempts to obtain an analytic solution for an off-center position were not deemed necessary since for the range involved here little difference was experienced between a vessel on or off the centerline of the channel.

CRITICAL SPEED

The critical speed can best be defined by the various phenomena occuring at this speed. The most noticeable observation is the occurence of a "hydraulic jump" aft of the midship section as shown in Figure 7.17. Other attendant phenomena are the greatly increased resistance and the sinkage and wave effects. Just below the critical speed, the sinkage increases very rapidly with a slight increase in speed. As the speed is increased above the critical, the bow begins to ride up on the bow wave and finally the whole

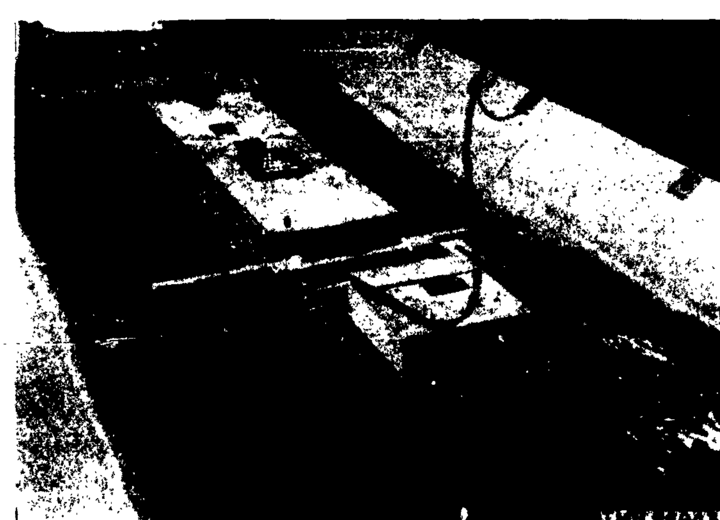


Figure 7.17 - Photograph Showing Water Surface when Vessel Is Transiting a Restricted Channel at Critical Speed

Hydraulic jump is noticeable, particularly near the sides of the channel.

vessel rises bodily, resulting in even a negative change of level and decreased resistance. At the critical speed, the bow wave becomes approximately transverse and may be regarded as a translatory wave. Since this wave keeps up with the ship, its speed must be equal to the speed of the reverse flow relative to the vessel. This is further borne out by the existence of a hydraulic jump accompanying the ship. The jump occurs at such a combination of speed and depth that $V = \sqrt{g D_s}$ (70), which is the same expression as that for the speed of translatory waves (71).

Theoretical Determination of Critical Speed

Since vessels transiting a channel at super-critical speed do not meet the problems of sinkage and high resistance encountered in the subcritical range, it might be useful in practice to transit certain channels at a super-critical speed. For this reason the value of the critical speed is of some importance in restricted-channel studies.

For theoretical purposes, the physical phenomenon that can best be utilized as a criterion of the critical speed is the observation that, as the speed approaches the critical, the sinkage increases very rapidly with a slight increase in speed, or, expressed in mathematical form,

$$\frac{d\,\Delta H}{d\,V_s} \to \infty \quad \text{as} \quad V_s \to V_c$$

This corresponds to the tangent to the curve of ΔH plotted against ship speed being vertical. The condition can also be written

$$\frac{d\,V_s}{d\,\Delta H} \to 0 \quad \text{as} \quad V_s \to V_c$$

The existence of a critical speed having the stated significance is predicted by Equation [7.9]. Its value can be found by treating ΔH as the independent variable and differentiating Equation [7.9] with respect to ΔH, but treating V_s as a constant, since at the critical speed $dV_s/d(\Delta H) = 0$. The result of such a differentiation of Equation [7.9] is

$$-\frac{11.3}{V_s^2}\left(22.6\,\frac{\Delta H}{V_s^2} + 1\right)^{-3/2} = -\frac{W_0}{A_0}$$

or

$$\frac{W_0\,V_s^2}{A_0} = \frac{11.3}{\left(22.6\,\frac{\Delta H}{V_s^2} + 1\right)^{3/2}} \qquad [7.10]$$

This equation is plotted in Figure 7.16 as a dotted line. For any value of $\frac{A_0 - ⊠}{A_0}$ we can pick off $\frac{W_0 V_c^2}{A_0}$ and then calculate V_c.

Example 4

Compute the critical velocity for a ship corresponding to Model 3769 in a channel 500 feet wide and 60 feet deep with a 45-degree side slope.

From example 2, $\frac{A_0 - ⊠}{A_0} = 0.894$, $W_0 = 620$, $A_0 = 33,600$.

Then from curve

$$\frac{W_0 V_c^2}{A_0} = 4.25$$

and therefore

$$V_c = \sqrt{\frac{33,600 \times 4.25}{620}} = 15.2 \text{ knots}$$

This is quite close to the value of V_c of 15.3 knots obtained from the theoretical sinkage curve, indicating that the approximations made in obtaining Equation [7.9] incur only a slight error.

Since theoretical curves for change of level have already been drawn, these values were used in comparing the actual and the theoretical critical speed in Table 7.2

TABLE 7.2

Comparison of Observed and Computed Values of the Critical Speed

Model Number	3769									3859	3992
Channel dimensions, feet	300 × 45	300 × 60	300 × 80	500 × 45	500 × 60	500 × 80	700 × 45	700 × 60	700 × 80	389 × 45	600 × 60
Observed V_c, knots	9.7	14.0	17.0	12.1	15.6	19.7	13.7	16.9	21.0	11.5	16.0
Computed V_c, knots	9.4	13.0	16.7	12.0	15.3	19.2	13.5	16.7	20.5	11.4	16.0

The close agreement between computed and observed values proved quite conclusively that at the critical speed, $\frac{dD}{dV_c}$ approaches infinity.

Change of level at critical speed

The change of level at the critical speed is particularly important. This is the maximum change of level, that can occur and its value indicates whether a vessel would be able to clear the bottom while increasing its speed from sub-critical to super-critical. Although hydrodynamic lift forces result in a small difference between ΔH and $D_0 - D_c$, for the first approximation we will neglect this difference. Then we can simply read ΔH off the sinkage curve at the point $V_s = V_c$. As an alternative, we can use Figure 7.16 as before. In addition to obtaining $\frac{W_0 V_s}{A_0}$, we can get $\frac{\Delta H}{V_c^2}$, thus ΔH can be obtained.

Example 5

Compute the change of level at the critical speed for a ship corresponding to Model 3769 in a channel 500 feet wide and 60 feet deep with a 45-degree side slope.

From example 4, V_c = 15.2 knots and $\frac{A_0 - ⊠}{A_0} = 0.894$
From Figure 7.16,

$$\frac{\Delta H}{V_c^2} = 0.0410$$

Therefore

$$\Delta H = 15.2^2 \times 0.0410 = 9.5 \text{ feet}$$

From theoretical curve, Figure 7.14 $D_0 - D_c$ = 9.8 feet. These both agree quite well with 8.5 feet as obtained by extrapolation of tests results in Figure 7.14. Table 7.3 compares critical change of level from the theoretical curves with fared curves obtained from test data.

TABLE 7.3

Table Comparing Computed and Measured Values of Sinkage at Critical Speed

Model Number	3769									3859	3992
Channel dimensions, feet	300 × 45	300 × 60	300 × 80	500 × 45	500 × 60	500 × 80	700 × 45	700 × 60	700 × 80	389 × 45	600 × 60
Observed ΔH, feet	7.5	8.0	9.0	6.5	8.5	10.5	7.5	9.0	10.0	8.0	10.0
Computed ΔH, feet	8.0	10.5	12.5	7.9	9.8	11.8	7.5	9.0	10.9	8.2	9.5

The agreement between computed and measured values is fairly good. Since in many tests the critical speed was not reached, experimental curves had to be extrapolated. Although this would result in very little error in V_c, since the slope is almost vertical, the error in ΔH might be quite considerable. Hence it is difficult to say whether the differences are due mainly to the approximations of the theory or to erroneous extrapolations.

Since our apparatus and setup was not sensitive enough to study separately the motion of the center of gravity of the vessel and the forward and after perpendiculars at speeds around the critical, neither the actual values of the sinkage obtained from the tests nor the theoretical values seem to be sufficiently reliable to attempt to predict the maximum sinkage for a vessel transiting a canal at a speed which will pass through the critical. For example, in a channel with a 300-foot bottom width and 45-foot depth, the change of level of the midship section at the critical speed from theory or from extrapolated test data is about 8.0 feet, leaving about 4.75 feet of water under the hull. Yet in actual tests, the propellers hit bottom. A large part of the difference may be due to the considerable trim developed at the critical speed. Although not deemed necessary for the Panama Canal studies, further investigation of the motion of a vessel at speeds around the critical seems warranted where channel depths of 50 feet or less are being studied.

Comparison of Speed of Reverse Flow with Speed of Translatory Wave at Critical Speed

From the existence of a transverse bow wave and of a hydraulic jump it was inferred that the speed of the relative reverse flow equaled that of the wave of translation at the critical speed. This may be tested by computation. As an approximation, the change in draft will be neglected in computing A and measured values of the critical speed will be used. At the critical speed, from Equation [7.1]

$$V = \frac{A_0}{A_c} V_c$$

Also $V_t = 0.5921 \sqrt{g D_e}$ where D_e is the average water depth. The average height for an area is defined as the total area divided by the length over which the area is taken, hence

$$D_e = \frac{A_c}{W_c}$$

Thus

$$V_t = 0.5921 \sqrt{g \frac{A_c}{W_c}}$$

All these quantities are known. Therefore, both V and V_t can be evaluated.

Example 6

Compare V and V_t for a vessel corresponding to Model 3769 transiting at critical speed a channel 500 feet wide and 60 feet deep with a 45-degree side slope.

From Figure 7.14 $V_c = 15.6$ knots and $D_0 - D_c = 9.8$ feet. Then

$$V = \frac{A_0}{A_c} V_c = \frac{33,600}{50.2 \times 550.2 - 3570} \times 15.6 = 21.8 \text{ knots}$$

and

$$V_t = 0.5921 \sqrt{\frac{32.2 \times 24,050}{600.4}} = 21.3 \text{ knots.}$$

Table 7.4 compares V and V_t for all conditions tested.

TABLE 7.4

Comparison of V and V_t at Critical Speed

Model Number	3769									3859	3992
Channel dimensions, feet	300 × 34	300 × 60	300 × 80	500 × 45	500 × 60	500 × 80	700 × 45	700 × 60	700 × 80	389 × 45	600 × 60
V, knots	16.9	21.8	24.1	18.1	21.8	25.8	19.1	22.2	26.2	17.9	21.9
V_t, knots	16.4	20.0	23.8	17.9	21.3	25.2	18.7	22.0	25.7	17.5	21.5

The close agreement of results shows that the velocity of the reverse flow relative to the vessel equals that of the translatory wave at the critical speed.

EFFECT OF SHIP CROSS-SECTION ON SINKAGE AND CRITICAL SPEED

The effect of varying the ship cross-section in a channel 500 feet wide and 60 feet deep with vertical side walls is shown in Figure 7.18. The curve was obtained by use of Figure 7.16.

This curve shows that, at any specified speed, increasing the cross-section of the vessel increases the sinkage, reduces the critical velocity, and increases the change of level at the critical speed. In a channel of the dimensions stated, there is no danger of damage to vessels with a midship section as large as 4800 square feet. This would correspond to a vessel of 80,000 tons displacement.

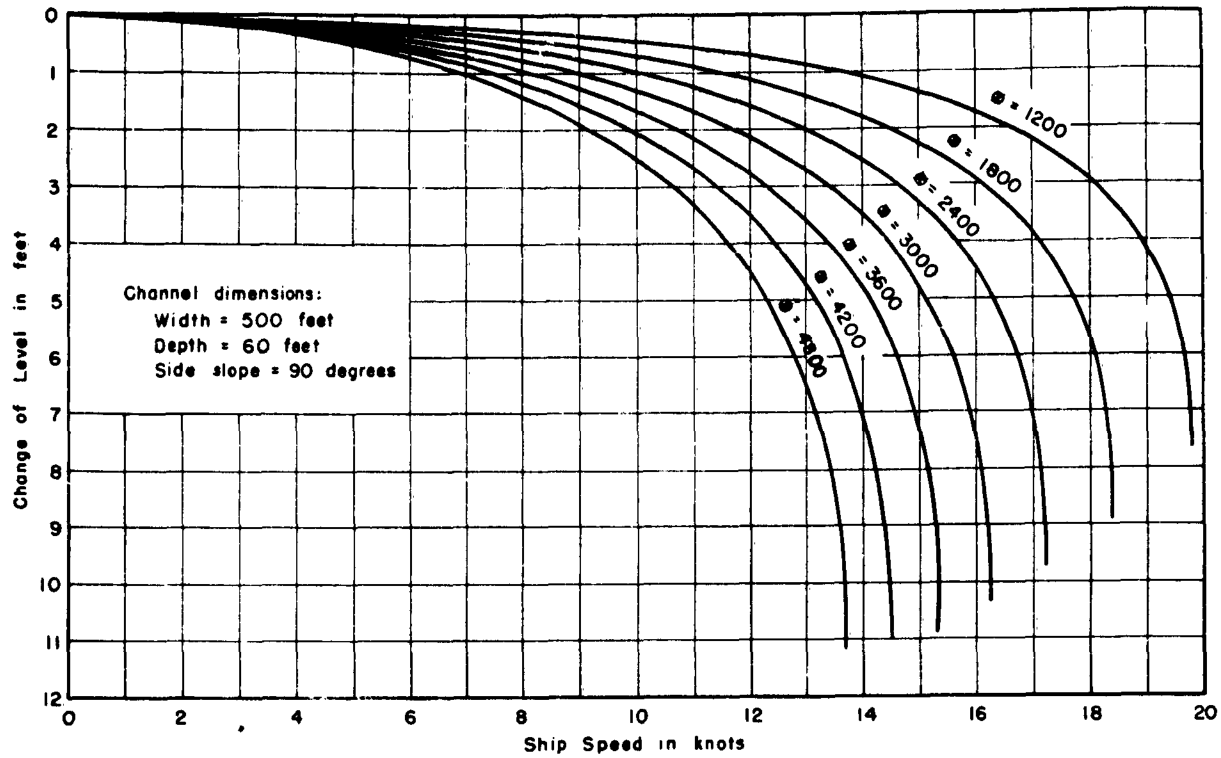


Figure 7.18 - The Effect of Ship Cross-Section on Change-of-Level Curves

EFFECT OF MOVING WATER

In deriving Equation [7.3], V_s was defined as the speed of the ship relative to the undisturbed water. Therefore, in a calculation involving moving water, V_s will be obtained by adding vectorally the current speed and the absolute speed of the ship. For example, with a vessel traveling at an absolute speed of 10 knots in an ahead current of 2 knots, V_s becomes 10 + 2 = 12 knots and the change of level would be the same as if the ship were traveling at 12 knots in still water.

COMPARISON WITH FULL-SCALE RESULTS

The validity of Froude's relationship for the conversion of model data to full-scale results has often been proved. However, comparisons of full-scale and model results are useful in ascertaining the magnitude of any scale effect that may exist, and also for testing the applicability of sinkage theory to differently shaped hulls.

For this purpose, the Special Engineering Division of the Panama Canal obtained observations upon the sinkage of several vessels in two separate sections of the Panama Canal. Station 2 was in the Bas Obispo Reach and

Station 3 in the Gamboa Reach. Values of the cross-sectional areas of the vessels at different water levels were furnished, together with all other information necessary to obtain the theoretical change of level of the midship section. These data are given in Appendix 7.1. This was compared with actual measured sinkage values.

Example 7

Find the theoretical sinkage of the SANTANDER in passing through the Bas Obispo Reach at a speed of 7.0 knots when the water level stands at 84.2 feet above the datum plane.

$$A_0 \text{ from graph} = 14{,}484 \text{ square feet}$$

$$\boxtimes = mBH_0 = 0.98 \times 62.5 \times 26.9$$

$$= 1645 \text{ square feet}$$

$$\frac{A_0 - \boxtimes}{A_0} = \frac{14{,}485 - 1645}{14{,}485} = 0.892$$

$$\frac{W_0 V_s^2}{A_0} = \frac{370 \times 49}{14{,}485} = 1.254$$

From Figure 7.16 $\frac{\Delta H}{V_s^2} = 0.01353$

$$\Delta H = 49 \times 0.01353 = 0.66 \text{ foot}$$

Since data are provided giving the sinkage at two points, the change of level at the midship section can be obtained from the data by the method described previously. The correction for difference in the water level between Pedro Miguel and Bas Obispo must be included. It is thus found that

$$\Delta H = \frac{1}{2}\left[\left(\frac{D + C - E}{D}\right)\Delta_1 + \left(\frac{D + E - C}{D}\right)\Delta_2\right] + 0.2$$

$$= \frac{1}{2}\left(\frac{365}{369} \times 0.48 - \frac{376}{369} \times 1.02\right) + 0.2$$

$$= 0.97 \text{ foot}$$

Table 7.5 shows the comparison between computed and measured sinkages for several ships.

The calculated sinkages are good approximations of the measured values; only once does the error exceed 0.3 foot. Part of the difference may be explained by observing that these vessels all trimmed considerably down by the bow, similarly to Model 3859. The positive lift would result in sinkages of about 0.1 to 0.2 foot more than theory would anticipate. In addition, the Liberty Ship R.H. ALVEY was only partly loaded, and rolled, which caused very erratic readings.

TABLE 7.5

Comparison of Computed and Measured Full-Scale Sinkage

Vessel	Channel Station	Ship Speed knots	Measured ΔH, feet	Calculated ΔH, feet
SANTANDER	2 3	7.0 10.0	0.97 0.90	0.72 0.71
MARORE (Ore Carrier)	2 3	6.1 9.9	1.29 1.90	1.03 1.32
J.C. HARPER (Liberty)	2 3	6.4 9.6	0.46 0.63	0.48 0.54
R.H. ALVEY (Liberty)	2 3	7.0 9.3	0.37 0.64	0.82 0.37

Whether other minor discrepancies are due to scale effect, differences in ship lines, or errors in the original assumptions made in the development of the theory cannot be determined. Some full-scale tests on vessels similar to Models 3769, 3859, or 3992 would be useful.

CONCLUSIONS

Based on the analysis of data from tests on models of two large naval vessels and a large tanker, a proposed method for predicting the change of level of a ship in a restricted channel at ship speeds below the critical speed has been developed and is presented in the form of graphs. Figure 7.13 gives a graphical method of determining allowable ship speed when the allowable change of level is assigned; whereas Figure 7.16 is a graph from which the change of level can be predicted for any specified ship speed.

This method was used with considerable success to predict the midship-section sinkage of several full-scale ships having different ship lines. Whether differences were due to effect of hull shapes or errors in theory could not be determined because of insufficiency of data. However, both model and full-scale results indicate that the shape and length of the hull play relatively minor-parts at speeds below the critical speed. The area of the midship section is the most important of the ship characteristics. Trim of the vessel has little effect in predicting the change of level of the midship section. It has a minor effect, inasmuch as the hydrodynamic lift forces are affected by the trim. These forces, however, are small and produce only minor errors in the estimated sinkage.

The effects of width and depth of channel and of ship speed on change of level are shown by the sinkage equation $\Delta H = \frac{V^2}{22.6}\left[\left(\frac{A_0}{A}\right)^2 - 1\right]$. Since both A_0 and A are functions of width and depth, the relationship is quite complicated. At a given speed, the sinkage varies approximately inversely as the square of the cross-sectional area. For a given cross-section, the sinkage varies approximately as the square of the ship speed.

Tests on Model 3769 show that transverse displacement of the model in the channel had little effect upon the sinkage except at speeds near the critical with the model located near the prism line, conditions which could never occur simultaneously when transiting a canal.

A method for computing the critical speed has also been developed. Figure 7.16 gives a graphical method of computing it. The critical speed which was originally defined as that ship speed which results in the "hydraulic jump" occurring in the channel was also shown to be the speed at which $\frac{d\Delta H}{dV_s}$ approached infinity. It is also the ship speed which results in the speed of the reverse flow relative to the vessel being equal to the speed of the translatory wave for the section of the channel in which the vessel is present.

Tests on a towed model indicate that the change of level of a towed ship is slightly less than that of one which is self-propelled. There is little effect of towing upon the critical speed.

Change of level plays very little part as a direct factor in determining the proper dimensions for a canal. The only direct significance would be the risk of hitting bottom, as occurred with Model 3769 in a channel 300 feet wide and 45 feet deep at a speed of 9.8 knots. Examination of Figure 7.18 indicates that even a vessel with a cross-section area of 4800 square feet which is the equivalent of an 80,000 ton vessel, would be perfectly safe from the risk of hitting bottom in a channel 500 feet wide and 60 feet deep at all speeds right up to the critical speed 13.75 knots.

APPENDIX 7.1

This appendix contains a complete tabulation of the results from the change-of-level tests carried out in the shallow water basin. In addition, a table has been provided for a graphical method to assist in the solution of Equations [7.9] and [7.10]. Equation [7.9] gives the theoretical sinkage for a specified vessel at a specified speed in a given cross-section while Equation [7.10] gives the critical speed and the change in level at the critical speed.

Since many of the curves in the body of the report represent typical curves, all curves obtained from test or theory are shown here.

TABLE 7.6

Change-of-Level Tests Performed in Shallow Water Basin with Model 3769
Self-Propelled on Centerline of Channel
λ - 45, ⊠ - 3570 square feet

Ship Speed, V_s knots	Sinkage at A.P. feet	Sinkage at F.P. feet	ΔH at Midships feet	Miscellaneous Data
2.68	0.15	0.15	0.15	
4.02	0.49	0.49	0.49	Channel dimensions:
5.36	0.90	0.90	0.90	W_B - 300 feet
6.78	1.69	1.69	1.69	D_0 - 45 feet
7.38	2.25	2.25	2.25	Side slope - 45 degrees
8.05	2.78	2.96	2.87	Date:
8.72	3.67	3.86	3.76	15 Jan 1947
9.06	4.24	4.05	4.14	
9.40	4.88	4.88	4.88	
2.68	0.15	0.08	0.12	
3.69	0.34	0.08	0.21	
4.70	0.56	0.38	0.47	
5.70	0.64	0.83	0.74	Channel dimensions:
6.71	0.79	0.71	0.75	W_B - 300 feet
7.72	1.20	1.20	1.20	D_0 - 61.4 feet
8.73	1.69	1.50	1.60	Side slope - 45 degrees
9.73	2.14	2.21	2.18	Date:
10.74	2.89	2.70	2.80	13 Dec 1946
11.75	3.83	3.45	3.64	
12.75	5.14	5.33	5.38	
13.43	6.04	7.13	6.58	
14.10	8.93	5.26		
2.68	0.11	0.19	0.15	
4.03	0.07	0.26	0.17	
5.37	0.41	0.49	0.45	
6.71	0.71	0.71	0.71	Channel dimensions
8.05	0.82	1.01	0.92	W_B - 300 feet
9.40	1.27	1.46	1.36	D_0 - 81.6 feet
10.74	1.54	1.91	1.72	Side slope - 45 degrees
12.08	2.25	2.59	2.42	Date:
13.43	3.04	3.53	3.28	8 Jan 1947
14.77	4.31	4.87	4.59	
15.44	5.10	5.36	5.23	
16.10	6.34	6.72	6.53	
16.78	8.48	6.68	7.58	

TABLE 7.6 (continued)

Ship Speed, V_s knots	Sinkage at A.P. feet	Sinkage at F.P. feet	ΔH at Midships feet	Miscellaneous Data
2.68	0.15	0.08	0.12	
4.03	0.30	0.22	0.26	
5.37	0.52	0.45	0.48	Channel dimensions:
6.70	0.90	0.83	0.86	W_B - 500 feet
8.05	1.35	1.27	1.31	D_0 - 45 feet
9.38	2.21	2.21	2.21	Side slope - 45 degrees
10.72	3.11	3.04	3.08	Date:
11.40	4.24	4.05	4.14	6 Feb 1947
12.06	6.22	4.58		
5.0	0.30	0.30	0.30	
7.0	0.64	0.64	0.64	
8.0	0.90	0.90	0.90	Channel dimensions:
9.0	1.24	1.16	1.20	W_B - 500 feet
10.0	1.61	1.61	1.61	D_0 - 60 feet
11.0	1.99	1.99	1.99	Side slope - 45 degrees
12.0	2.44	2.44	2.44	Date:
13.0	3.08	3.08	3.08	12 Feb 1947
14.0	4.05	4.05	4.05	
15.0	5.25	5.25	5.25	
5.0	0.15	0.15	0.15	
7.0	0.45	0.45	0.45	
9.0	0.83	0.83	0.83	
11.0	1.28	1.28	1.28	Channel dimensions:
12.0	1.61	1.61	1.61	W_B - 500 feet
13.0	2.03	2.03	2.03	D_0 - 81.2 feet
14.0	2.43	2.62	2.53	Side slope - 45 degrees
15.0	2.89	3.08	2.98	Date:
16.0	3.34	3.53	3.44	19 Feb 1947
17.0	4.05	4.54	4.30	
18.0	5.22	5.55	5.38	
19.0	8.26	8.26	8.26	
20.0	hydraulic jump			

TABLE 7.6 (continued)

Ship Speed, V, knots	Sinkage at A.P. feet	Sinkage at F.P. feet	ΔH at Midships feet	Miscellaneous Data
5.0	0.38	0.38	0.38	
7.0	0.75	0.75	0.75	
9.0	1.28	1.28	1.28	Channel dimensions:
10.0	1.65	1.65	1.65	W_B - 700 feet
11.0	2.21	2.21	2.21	D_0 - 45 feet
11.5	2.59	2.59	2.59	Side slope - 45 degrees
12.0	3.07	3.07	3.07	Date:
12.5	3.90	3.90	3.90	11 Mar 1947
13.0	5.10	5.10	5.10	
13.5	6.38	6.38	6.38	
5.0	0.23	0.23	0.23	
7.0	0.68	0.41	0.54	
9.0	1.09	0.75	0.92	Channel dimensions:
11.0	1.58	1.65	1.62	W_B - 700 feet
13.0	2.44	2.52	2.48	D_0 - 59.5 feet
14.0	2.74	3.00	2.87	Side slope - 45 degrees
15.0	3.53	4.43	3.98	Date:
16.0	5.25	5.25	5.25	6 Mar 1947
17.0	8.40	8.78	8.59	
18.0	hydraulic jump			
5.0	0.22	0.22	0.22	
7.0	0.45	0.38	0.42	
9.0	0.71	0.71	0.71	Channel dimensions:
11.0	1.09	1.09	1.09	W_B - 700 feet
13.0	1.50	1.69	1.60	D_0 - 79.4 feet
15.0	2.10	2.47	2.28	Side slope - 45 degrees
17.0	2.96	2.85	2.90	Date:
19.0	4.69	5.33	4.99	8 Mar 1947
20.0	6.75	6.75	6.75	
21.0	hydraulic jump			

TABLE 7.6 (continued)

Ship Speed, V_s knots	Sinkage at A.P. feet	Sinkage at F.P. feet	ΔH at Midships feet	Miscellaneous Data
5.0	0.38	0.38	0.38	
7.0	0.75	0.75	0.75	
9.0	1.28	1.28	1.28	Channel dimensions:
10.0	1.65	1.65	1.65	W_B - 700 feet
11.0	2.21	2.21	2.21	D_0 - 45 feet
11.5	2.59	2.59	2.59	Side slope - 45 degrees
12.0	3.07	3.07	3.07	Date:
12.5	3.90	3.90	3.90	11 Mar 1947
13.0	5.10	5.10	5.10	
13.5	6.38	6.38	6.38	
5.0	0.23	0.23	0.23	
7.0	0.68	0.41	0.54	
9.0	1.09	0.75	0.92	Channel dimensions:
11.0	1.58	1.65	1.62	W_B - 700 feet
13.0	2.44	2.52	2.48	D_0 - 59.5 feet
14.0	2.74	3.00	2.87	Side slope - 45 degrees
15.0	3.53	4.43	3.98	Date:
16.0	5.25	5.25	5.25	6 Mar 1947
17.0	8.40	8.78	8.59	
18.0	hydraulic jump			
5.0	0.22	0.22	0.22	
7.0	0.45	0.38	0.42	
9.0	0.71	0.71	0.71	Channel dimensions:
11.0	1.09	1.09	1.09	W_B - 700 feet
13.0	1.50	1.69	1.60	D_0 - 79.4 feet
15.0	2.10	2.47	2.28	Side slope - 45 degrees
17.0	2.96	2.85	2.90	Date:
19.0	4.69	5.33	4.99	8 Mar 1947
20.0	6.75	6.75	6.75	
21.0	hydraulic jump			

TABLE 7.7

Change-of-Level Tests Performed in Shallow Water Basin with Model 3992 Self-Propelled on Centerline of Channel

Ship Speed, V_s knots	Sinkage at A.P. feet	Sinkage at F.P. feet	ΔH at Midships feet	Miscellaneous Data
4.0	0.14	0.14	0.14	Channel dimensions:
6.0	0.29	0.29	0.29	W_B - 600 feet
8.0	0.79	0.79	0.79	D_0 - 60 feet
10.0	1.29	1.43	1.36	Side slope - 45 degrees
12.0	2.08	2.28	2.15	Ship data:
14.0	3.37	3.65	3.51	$\boxtimes$ - 3670 square feet
15.0	4.51	4.65	4.58	Model data:
15.5	5.95	5.66	5.80	Model 3992, λ - 86
*16.0	11.90	2.58	7.24	Date:
				5 April 1947

* Hydraulic jump

TABLE 7.8

Change-of-Level Test Performed in Shallow Water Basin with Model 3859 Self-Propelled on Centerline of Channel

Ship Speed, V_s knots	Sinkage at A.P. feet	Sinkage at F.P. feet	ΔH at Midships feet	Miscellaneous Data
4.02	0.26	0.51	0.38	Channel dimensions:
5.03	0.41	0.72	0.56	W_B - 389 feet
5.98	0.79	0.96	0.88	D_0 - 45 feet
6.98	1.08	1.60	1.34	Side slope - 45 degrees
8,00	1.43	2.19	1.81	Ship data:
9.00	1.93	3.06	2.50	$\boxtimes$ - 3122 square feet
9.43	2.30	3.70	3.00	Model data:
10.00	2.62	4.55	3.58	Model 3859, λ - 35
10.52	3.50	5.45	4.48	Date:
11.02	3.97	6.71	5.34	4 Feb 1947

TABLE 7.9

Change-of-Level Tests Performed in Shallow Water Basin with Model 3769 Self-Propelled in Off-Center Position

45-Foot Depth			60-Foot Depth			80-Foot Depth			Miscellaneous Data
Ship Speed, V, knots	Sinkage at A.P. feet	Sinkage at F.P. feet	Ship Speed, V_s knots	Sinkage at A.P. feet	Sinkage at F.P. feet	Ship Speed, V_s knots	Sinkage at A.P. feet	Sinkage at F.P. feet	
20 Jan 1947			26 Dec 1946			15 Jan 1947			
2.68	0.15	0.22	2.68	0.15	0.08	2.62	0.11	0.11	
4.05	0.56	0.56	4.03	0.34	0.53	4.03	0.15	0.15	
5.37	0.98	0.98	5.43	0.86	0.53	5.37	0.38	0.38	
6.71	1.58	1.50	6.78	0.86	1.05	6.71	0.64	0.64	Channel dimensions:
7.38	2.14	2.14	8.12	1.39	1.72	8.05	0.94	0.94	W_B - 300 feet
8.05	3.00	2.74	9.46	1.99	2.55	9.40	1.43	1.43	Side slope - 45 degrees
8.73	3.94	3.56	10.74	2.81	3.00	10.74	2.06	1.99	Y - 67.5 feet
9.06	4.61	4.61	11.41	3.19	3.37	12.08	2.59	2.77	Z - 82.5 feet
9.39	5.86	5.86	12.08	4.09	4.43	13.43	3.30	3.79	
			12.75	5.18	5.66	14.77	3.71	4.54	
			13.49	8.56	6.91	15.44	4.57	5.33	
						16.10	6.46	6.94	
27 Feb 1947			13 Feb 1947			25 Feb 1947			
5.0	0.34	0.71	5.0	0.38	0.38	5.0	0.19	0.38	
6.1	0.86	0.94	6.0	0.38	0.38	7.0	0.45	0.45	
7.0	1.39	1.39	7.0	0.75	0.75	9.0	0.86	1.05	
8.0	2.14	2.06	8.0	0.94	0.94	10.0	1.12	1.12	Channel dimensions:
8.5	2.40	1.91	9.0	1.50	1.50	11.0	1.35	1.57	W_B - 500 feet
9.0	2.89	2.58	10.0	1.88	1.80	12.0	1.69	1.91	Side slope - 45 degrees
9.5	3.38	3.38	11.0	2.40	2.66	13.0	1.95	2.39	Y - 167.5 feet
10.0	3.97	3.71	12.0	2.96	3.15	13.5	2.39	2.66	Z - 82.5 feet
			13.0	4.20	4.20	14.0	2.47	2.81	
			14.0	5.29	5.67	14.5	2.70	3.26	
			*15.0	9.0	9.0	15.0	3.15	3.52	
						16.0	3.75	4.42	

* Hydraulic jump

TABLE 7.10

Change-of-Level Tests Performed in Shallow Water Basin with Model 3769 Self-Propelled in Off-Center Position

Ship Speed, V_s knots	Sinkage at A.P. feet	Sinkage at F.P. feet	Ship Speed, V_s knots	Sinkage at A.P. feet	Sinkage at F.P. feet	Ship Speed, V_s knots	Sinkage at F.P. feet	Sinkage at A.P. feet	Ship Speed, V_s knots	Sinkage at A.P. feet	Sinkage at F.P. feet
20 Dec 1946			7 Feb 1947			25 March 1947			27 March 1947		
2.68	0.31	0.12	4.0	0.34	0.41	5.0	0.56	0.41	5.0	0.34	0.34
4.02	0.85	0.08	5.0	0.45	0.52	6.0	0.86	0.56	7.0	0.71	0.71
5.37	0.58	0.58	6.0	0.75	0.75	7.0	1.24	0.86	9.0	1.20	1.12
6.71	0.92	0.92	7.0	0.75	0.75	8.0	1.88	1.24	11.0	2.14	1.95
7.72	1.35	1.15	8.0	1.54	1.61	9.0	2.33	1.76	12.0	2.55	2.21
8.72	1.66	2.04	9.0	2.02	2.21	10.0	3.15	2.59	13.0	3.39	2.74
9.73	2.31	2.50	10.0	2.89	3.07	10.5	3.38	2.63	14.0	4.09	3.90
10.74	3.00	3.20	11.0	4.16	4.43	11.0	3.86	2.44	15.0	5.48	5.14
11.40	3.08	3.12	11.5	5.96	5.66	11.5	5.44	4.13	15.5	6.83	5.82
12.08	4.16	4.66									
12.75	5.32	5.97									
13.08	6.47	6.97									
13.41	8.20	7.43									
Channel dimensions: W_B - 300 feet D_0 - 60 feet Side slope - 45 degrees Y - 45 feet Z - 105 feet			Channel dimensions: W_B - 500 feet D_0 - 45 feet Side slope - 45 degrees Y - 135 feet Z - 115 feet			Channel dimensions: W_B - 700 feet D_0 - 45 feet Side slope - 45 degrees Y - 267.5 feet Z - 82.5 feet			Channel dimensions: W_B - 700 feet D_0 - 60 feet Side slope - 45 degrees Y - 267.5 feet Z - 82.5 feet		

TABLE 7.11

Change-of-Level Tests Performed in Shallow Water Basin with Model 3769 Towed on Centerline of Channel

45 foot depth			60 foot depth			80 foot depth			Miscellaneous Data
Ship Speed, V, knots	Sinkage at A.P. feet	Sinkage at F.P. feet	Ship Speed, V, knots	Sinkage at A.P. feet	Sinkage at F.P. feet	Ship Speed, V, knots	Sinkage at A.P. feet	Sinkage at F.P. feet	
20 Nov 1946			6 Jan 1947			9 Jan 1947			
2.75	0.00	0.00	2.75	0.08	0.08	2.75	0.19	0.11	
3.49	0.53	0.11	4.03	0.22	0.22	4.03	0.11	0.04	
4.09	0.68	0.49	5.44	0.56	0.56	5.37	0.45	0.45	
5.43	0.90	0.68	6.85	0.75	0.75	6.78	0.60	0.60	
6.11	1.20	1.12	8.05	1.12	1.12	8.16	0.86	0.86	
6.78	1.57	1.46	9.40	1.69	2.02	9.40	1.13	1.13	Channel dimensions:
7.45	1.87	1.87	10.74	2.51	2.32	10.74	1.73	1.73	W_B - 300 feet
8.12	2.17	2.17	12.08	3.37	3.37	12.08	2.33	2.25	Side slope - 45 degrees
8.79	2.85	2.85	12.75	4.24	4.43	13.43	2.77	3.26	
9.46	4.35	3.78	13.43	4.84	5.02	14.77	3.56	3.90	
			14.10	7.50	5.40	15.44	4.62	4.92	
						16.10	5.18	5.74	
						16.78	6.39	5.59	

TABLE 7.12

Change-of-Level Tests Performed in Shallow Water Basin with Model 3769 Towed on Centerline of Channel Using Two Different Types of Towing Brackets

Ship Speed, V, knots	Sinkage in feet Using Regular Brackets		Sinkage in feet Using Special Centerline Brackets		Miscellaneous Data
	A.P.	F.P.	A.P.	F.P.	
5.0	0.11	0.11	0.19	0.19	
7.0	0.38	0.38	0.41	0.41	
9.0	0.67	0.67	0.75	0.75	Channel dimensions:
11.0	1.09	1.28	1.09	1.20	W_B - 500 feet
13.0	1.69	1.95	1.69	1.99	D_0 - 80 feet
15.0	2.44	2.78	2.36	2.78	Side slope - 45 degrees
17.0	3.64	4.45	3.44	4.09	Date:
18.0	4.75	5.02	4.45	5.16	26 Feb 1947
19.0	6.06	6.50	6.00	6.63	

TABLE 7.13

Tabulation of Data for Plot of Sinkage Equations

$$\frac{A_0 - \boxtimes}{A_0} - (22.6\ \Delta H/V_s^2 + 1)^{-1/2} = \frac{W_0\ V_s^2}{A_0}\ \frac{\Delta H}{V_s^2}$$

$\Delta H/V_s^2$	$W_0 V_s^2/A_0$	$\Delta H/V_s^2$	$W_0 V_s^2/A_0$	$\Delta H/V_s^2$	$W_0 V_s^2/A_0$	$\Delta H/V_s^2$	$W_0 V_s^2/A_0$	$\Delta H/V_s^2$	$W_0 V_s^2/A_0$
$\frac{A_0 - \boxtimes}{A_0} = 0.70$		$\frac{A_0 - \boxtimes}{A_0} = 0.72$		$\frac{A_0 - \boxtimes}{A_0} = 0.74$		$\frac{A_0 - \boxtimes}{A_0} = 0.76$		$\frac{A_0 - \boxtimes}{A_0} = 0.78$	
0.04604	0	0.0411	0	0.03655	0	0.03235	0	0.02840	0
0.048	0.155	0.044	0.271	0.038	0.172	0.034	0.236	0.030	0.268
0.052	0.423	0.048	0.572	0.040	0.382	0.038	0.698	0.032	0.570
0.056	0.636	0.052	0.807	0.044	0.725	0.044	1.180	0.036	1.040
0.064	0.948	0.056	0.994	0.048	0.989	0.048	1.405	0.040	1.382
0.072	1.154	0.062	1.204	0.052	1.192	0.052	1.576	0.048	1.822
0.080	1.290	0.068	1.355	0.056	1.351	0.056	1.708	0.052	1.961
0.088	1.381	0.074	1.463	0.064	1.572	0.062	1.850	0.056	2.065
0.096	1.440	0.080	1.541	0.072	1.709	0.068	1.944	0.060	2.141
0.100	1.462	0.088	1.609	0.080	1.790	0.074	2.004	0.064	2.197
0.102	1.470	0.096	1.649	0.088	1.836	0.080	2.041	0.068	2.237
0.104	1.478	0.102	1.667	0.090	1.843	0.088	2.063	0.072	2.264
0.106	1.484	0.104	1.670	0.092	1.849	0.096	2.066	0.076	2.281
0.108	1.490	0.106	1.673	0.094	1.853			0.078	2.287
0.110	1.495	0.108	1.675	0.096	1.857			0.080	2.290
0.112	1.499	0.110	1.676	0.098	1.860			0.082	2.292
0.114	1.502	0.112	1.677	0.100	1.862			0.084	2.293
0.116	1.505	0.114	1.677	0.102	1.863				
0.118	1.507								
0.120	1.508								
0.130	1.508								
$\frac{A_0 - \boxtimes}{A_0} = 0.80$		$\frac{A_0 - \boxtimes}{A_0} = 0.82$		$\frac{A_0 - \boxtimes}{A_0} = 0.84$		$\frac{A_0 - \boxtimes}{A_0} = 0.86$		$\frac{A_0 - \boxtimes}{A_0} = 0.88$	
0.02489	0	0.0215	0	0.01845	0	0.01557	0	0.01288	0
0.026	0.244	0.024	0.617	0.020	0.506	0.016	0.185	0.014	0.604
0.028	0.621	0.026	1.014	0.022	1.034	0.018	0.939	0.016	1.438
0.032	1.195	0.028	1.336	0.024	1.451	0.020	1.520	0.020	2.506
0.034	1.412	0.032	1.820	0.026	1.783	0.024	2.283	0.022	2.852
0.038	1.751	0.036	2.151	0.028	2.050	0.028	2.764	0.024	3.112
0.044	2.089	0.040	2.382	0.032	2.445	0.032	3.070	0.026	3.321
0.052	2.346	0.048	2.655	0.034	2.589	0.036	3.26	0.028	3.479
0.056	2.422	0.056	2.779	0.036	2.707	0.040	3.382	0.032	3.695
0.062	2.495	0.064	2.823	0.038	2.807	0.044	3.452	0.034	3.765
0.068	2.532	0.068	2.826	0.040	2.883	0.048	3.488	0.036	3.818
0.072	2.542			0.044	2.998	0.052	3.500	0.038	3.865
0.076	2.544			0.048	3.072			0.040	3.882
				0.052	3.115			0.044	3.907
				0.056	3.136				
				0.060	3.142				

TABLE 7.13 (continued)

$\Delta H/V_e^2$	$W_0 V_e^2/A_0$	$\Delta H/V_e^2$	$W_0 V_e^2/A_0$	$\Delta H/V_e^2$	$W_0 V_e^2/A_0$	$\Delta H/V_e^2$	$W_0 V_e^2/A_0$	$\Delta H/V_e^2$	$W_0 V_e^2/A_0$
$\frac{A_0 - \boxtimes}{A_0} = 0.90$		$\frac{A_0 - \boxtimes}{A_0} = 0.92$		$\frac{A_0 - \boxtimes}{A_0} = 0.94$		$\frac{A_0 - \boxtimes}{A_0} = 0.96$		$\frac{A_0 - \boxtimes}{A_0} = 0.98$	
0.01038	0	0.00802	0	0.00583	0	0.00376	0	0.00182	0
0.012	1.086	0.010	1.687	0.006	0.027	0.004	0.587	0.002	0.935
0.014	2.039	0.012	2.755	0.007	1.543	0.0045	1.617	0.0025	2.850
0.015	2.400	0.014	3.461	0.008	2.472	0.005	2.425	0.003	4.098
0.016	2.685	0.016	3.935	0.010	3.687	0.006	3.600	0.0035	4.957
0.018	3.162	0.018	4.273	0.012	4.422	0.007	4.401	0.004	5.585
0.020	3.520	0.020	4.506	0.014	4.890	0.008	4.968	0.005	6.425
0.024	3.950	0.022	4.670	0.016	5.188	0.010	5.687	0.006	6.933
0.028	4.192	0.024	4.784	0.018	5.384	0.012	6.088	0.007	7.262
0.032	4.319	0.028	4.907	0.020	5.506	0.016	6.438	0.008	7.468
0.034	4.353	0.032	4.945	0.022	5.579	0.018	6.495	0.010	7.687
0.036	4.373			0.024	5.617	0.020	6.506	0.012	7.755
0.038	4.383			0.026	5.628				

TABLE 7.14

Tabulation of Data for Plot of Equation Giving Critical Velocity and Depth:

$$\frac{W_0 V_e^2}{A_0} = \frac{11.3}{\left(22.6 \frac{\Delta H}{V_e^2} + 1\right)^{3/2}}$$

$\frac{\Delta H}{V_e^2}$	$\frac{W_0 V_e^2}{A_0}$	$\frac{\Delta H}{V_e^2}$	$\frac{W_0 V_e^2}{A_0}$	$\frac{\Delta H}{V_e^2}$	$\frac{W_0 V_e^2}{A_0}$
0.012	7.884	0.048	3.754	0.096	2.002
0.014	7.481	0.052	3.522	0.102	1.880
0.016	7.114	0.056	3.314	0.106	1.806
0.020	6.459	0.060	3.125	0.110	1.736
0.024	5.899	0.064	2.953	0.114	1.671
0.028	5.416	0.072	2.654	0.120	1.580
0.032	4.995	0.076	2.522	0.125	1.510
0.036	4.627	0.080	2.401	0.130	1.446
0.040	4.301	0.086	2.238	0.135	1.386
0.044	4.012	0.092	2.091		

TABLE 7.15

Sinkage Observations in Panama Canal

Date		July 17, 1947	July 22, 1947	July 30, 1947	Oct. 10, 1947
Name of Ship		SANTANDER	MARORE	R.H. ALVEY	J.C. HARPER
Type			Ore Carrier	Liberty	Liberty
Beam	Feet	62.5	78.3	57.1	57.1
Fresh water draft (Bow	Feet	27.2	34.9	18.4	27.0
Fresh water draft (Stern	Feet	26.6	36.0	20.2	26.9
Length over all	Feet	473	583	442	442
Level of ship measured at (Distance from stem	Feet	54	75	63	66
Level of ship measured at (Distance from stern	Feet	50	120	64	63
Observations at Pedro Miguel					
Time		0845	0908	0921	0933
Ship speed	Knots	0	0	0	0
Mean water level above datum plane	Feet	84.0	83.95	84.45	85.40
Zero of stadia scale above mean water level (Bow	Feet	6.83	5.42	8.59	6.73
Zero of stadia scale above mean water level (Stern	Feet	4.39	3.81	7.28	4.62
Observations in Bas Obispo Reach					
Time		0954	1022	1020	1038
Ship speed	Knots	7.0	6.1	7.0	6.4
Mean water level above datum plane	Feet	84.2	84.0	84.45	85.20
Zero of stadia scale above mean water level (Bow	Feet	5.81	4.20	8.04	5.92
Zero of stadia scale above mean water level (Stern	Feet	3.91	2.55	7.10	4.12
Sinkage as compared with observations at Pedro Miguel (Bow	Feet	1.02	1.22	0.55	0.81
Sinkage as compared with observations at Pedro Miguel (Stern	Feet	0.48	1.26	0.18	0.50
Observations in Gamboa Reach					
Time		1033	1056	1052	1110
Ship speed	Knots	10.0	9.9	9.3	9.6
Mean water level above datum plane before passage of ship	Feet	83.8	83.85	84.30	85.05
Zero of stadia scale above mean water level (Bow	Feet	5.42	3.26	7.73	5.59
Zero of stadia scale above mean water level (Stern	Feet	3.62	1.96	6.56	3.79
Sinkage as compared with observations at Pedro Miguel (Bow	Feet	1.41	2.16	0.86	1.14
Sinkage as compared with observations at Pedro Miguel (Stern	Feet	0.77	1.85	0.72	0.83

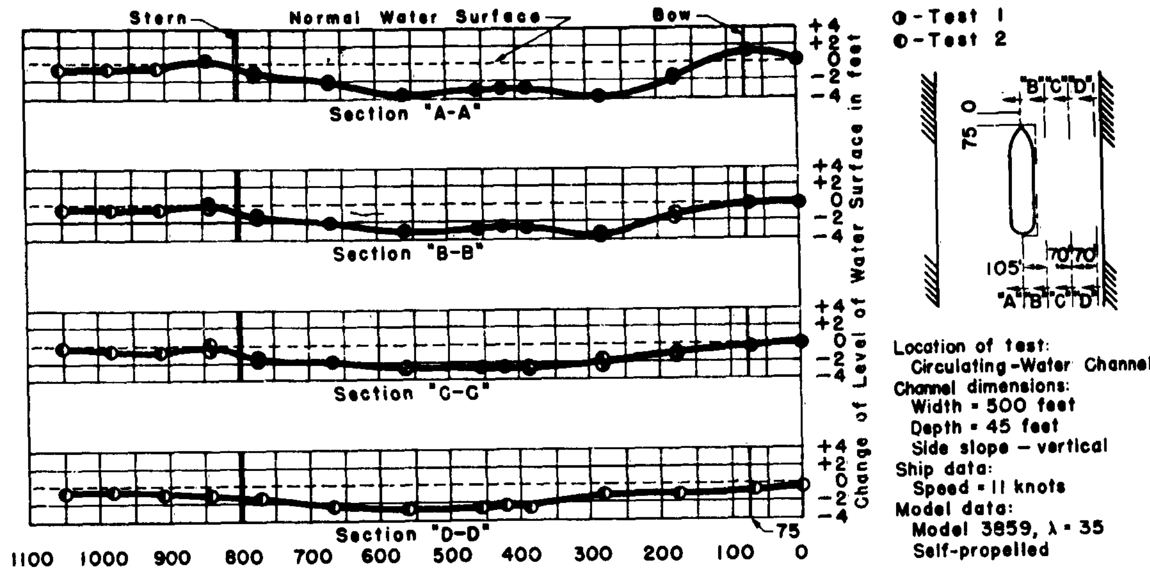


Figure 7.19 - Water Surface Profile at Various Longitudinal Sections for a Ship on Centerline of a Restricted Channel

Data are from two independent tests.

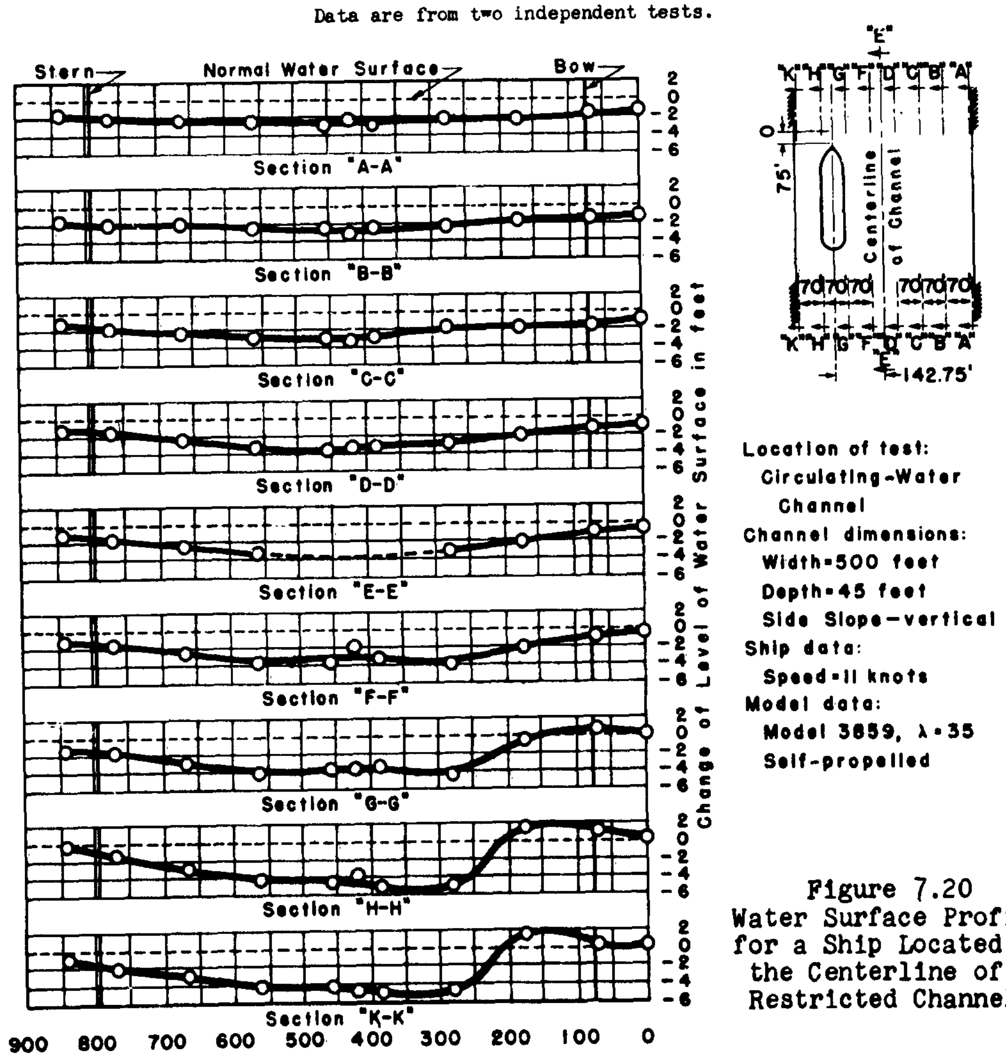
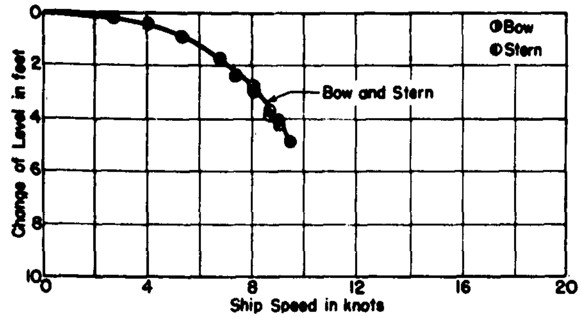
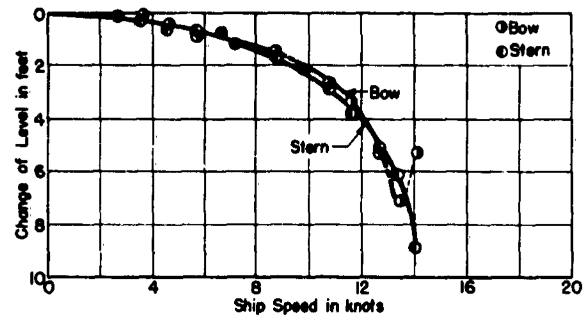


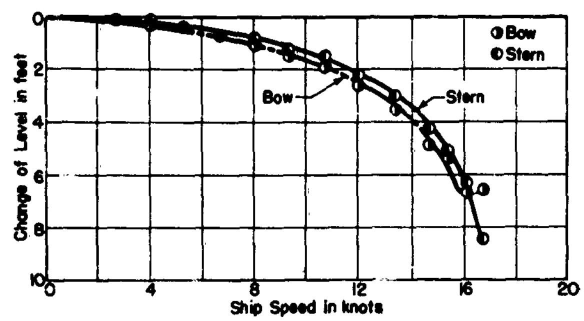
Figure 7.20
Water Surface Profile for a Ship Located off the Centerline of a Restricted Channel



a - Channel Depth = 45 Feet



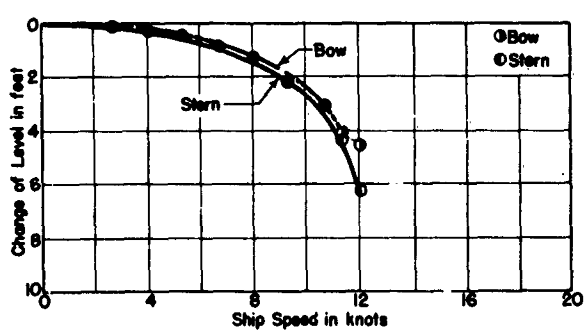
b - Channel Depth = 60 Feet



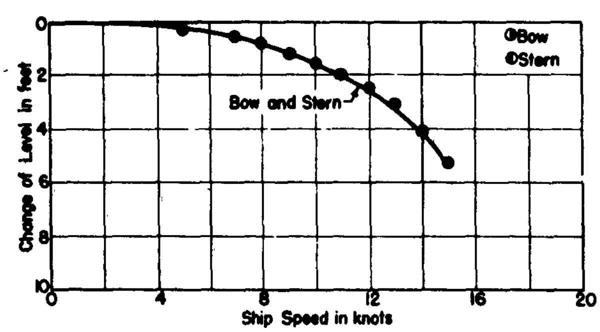
c - Channel Depth = 80 Feet

Location of test:
Shallow Water Basin
Channel dimensions:
Bottom width = 300 feet
Side slope = 45 degrees
Model data:
Model 3769, $\lambda = 45$
Self - propelled

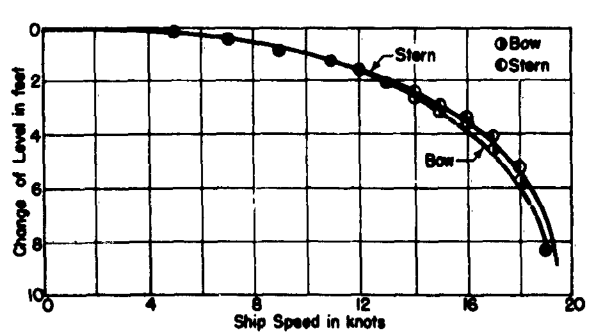
Figure 7.21 - Change of Level of a Ship on Centerline of a Restricted Channel 300 Feet Wide



a - Channel Depth = 45 Feet



b - Channel Depth = 60 Feet



c - Channel Depth = 80 Feet

Location of test:
Shallow Water Basin
Channel dimensions:
Bottom width = 500 feet
Side slope = 45 degrees
Model data:
Model 3769, $\lambda = 45$
Self - propelled

Figure 7.22 - Change of Level of a Ship on Centerline of a Restricted Channel 500 Feet Wide

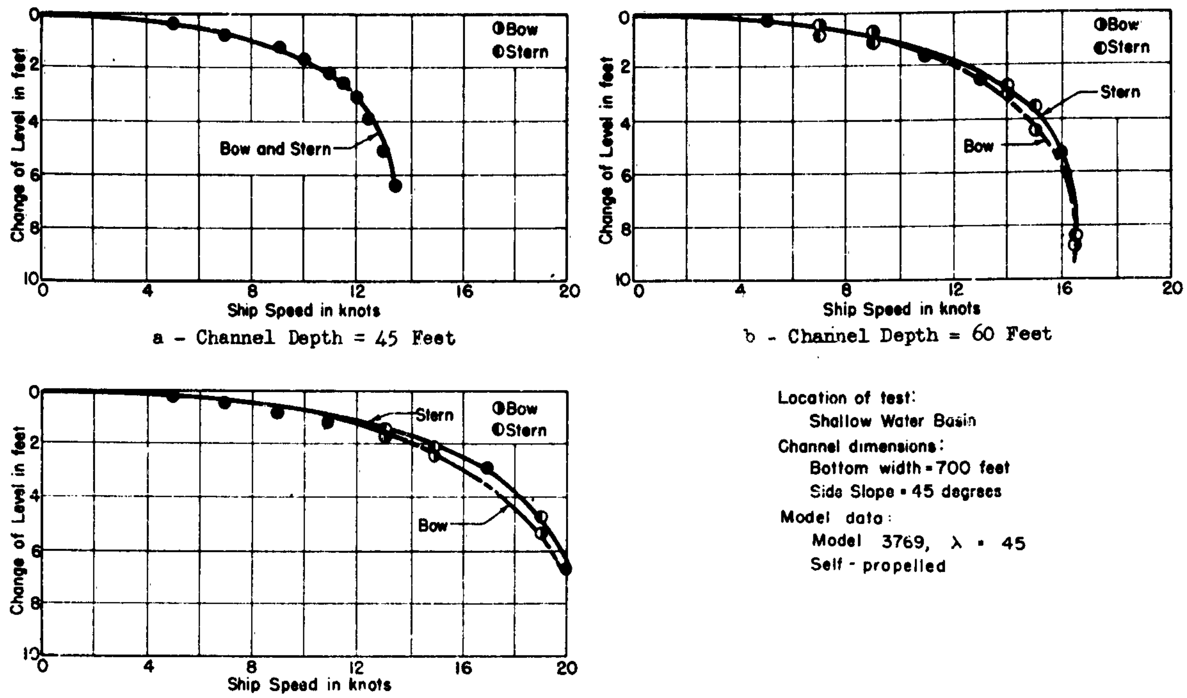


Figure 7.23 - Change of Level of a Ship on Centerline of a Restricted Channel 700 Feet Wide

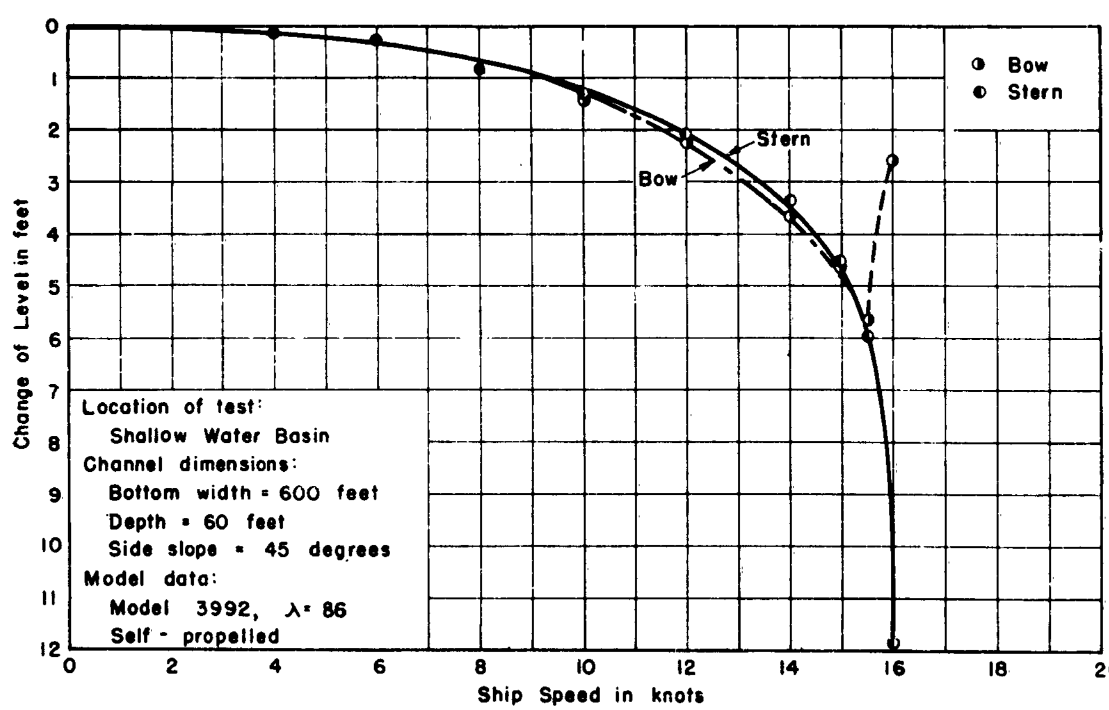


Figure 7.24 - Change of Level of Model 3992 on Centerline of a Restricted Channel

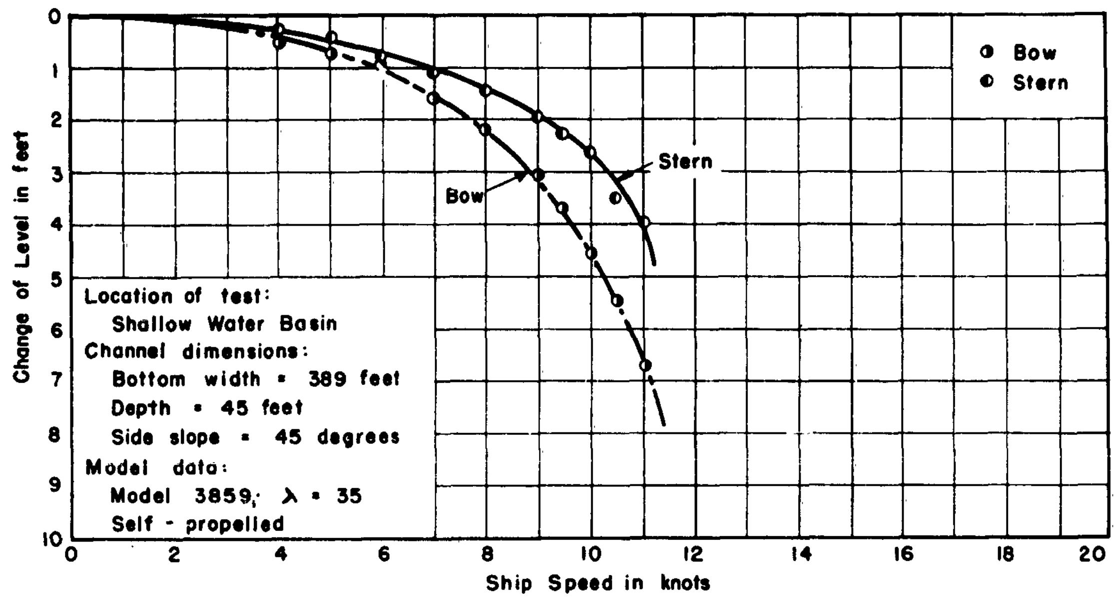


Figure 7.25 - Change of Level of Model 3859 on Centerline of a Restricted Channel

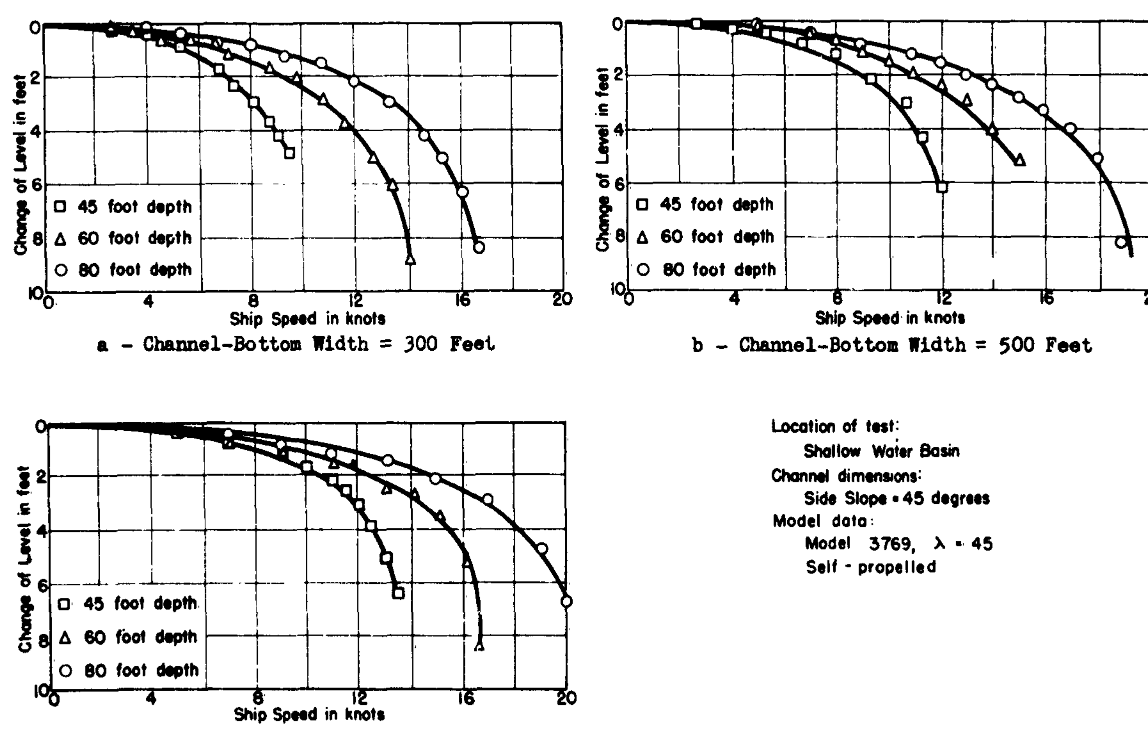
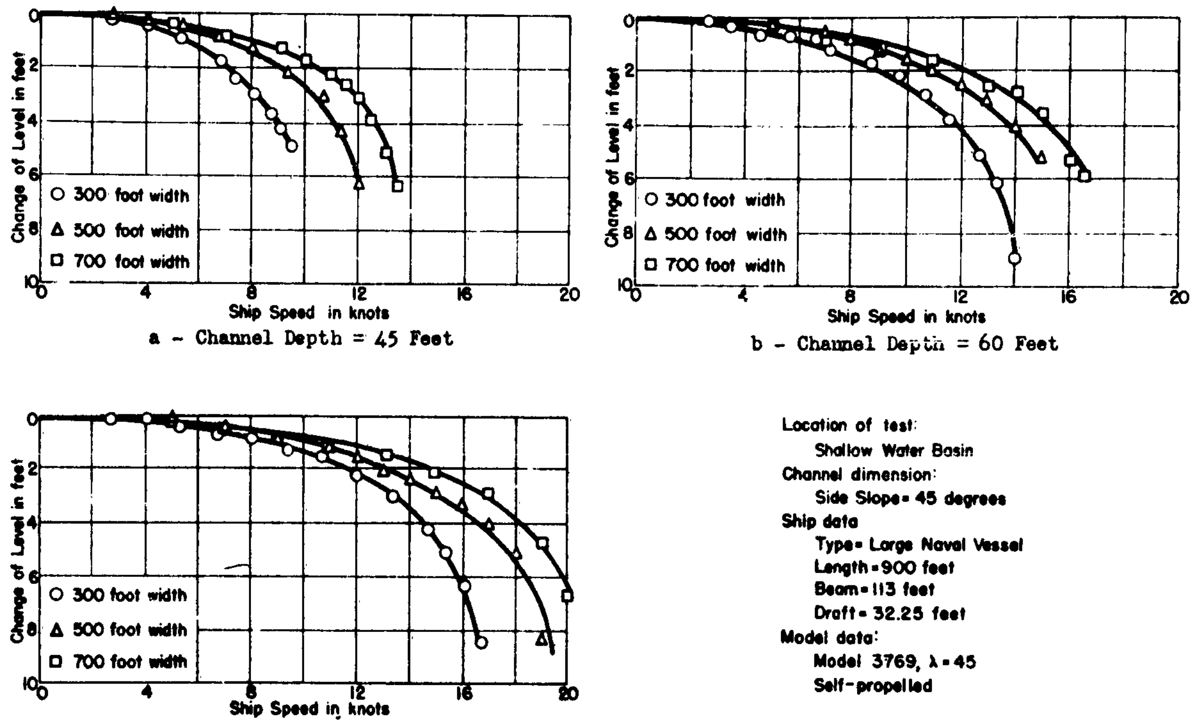


Figure 7.26 - Effect of Channel Depth on Change of Level of a Ship on Centerline of a Restricted Channel

The curves shown are for the stern only. The bow curves are similar.



a - Channel Depth = 45 Feet

b - Channel Depth = 60 Feet

c - Channel Depth = 80 Feet

Location of test:
Shallow Water Basin
Channel dimension:
Side Slope = 45 degrees
Ship data
Type = Large Naval Vessel
Length = 900 feet
Beam = 113 feet
Draft = 32.25 feet
Model data:
Model 3769, λ = 45
Self-propelled

Figure 7.27 - Effect of Channel Width on Change of Level of a Ship on Centerline of a Restricted Channel

The curves shown are for the stern only. The bow curves are similar.

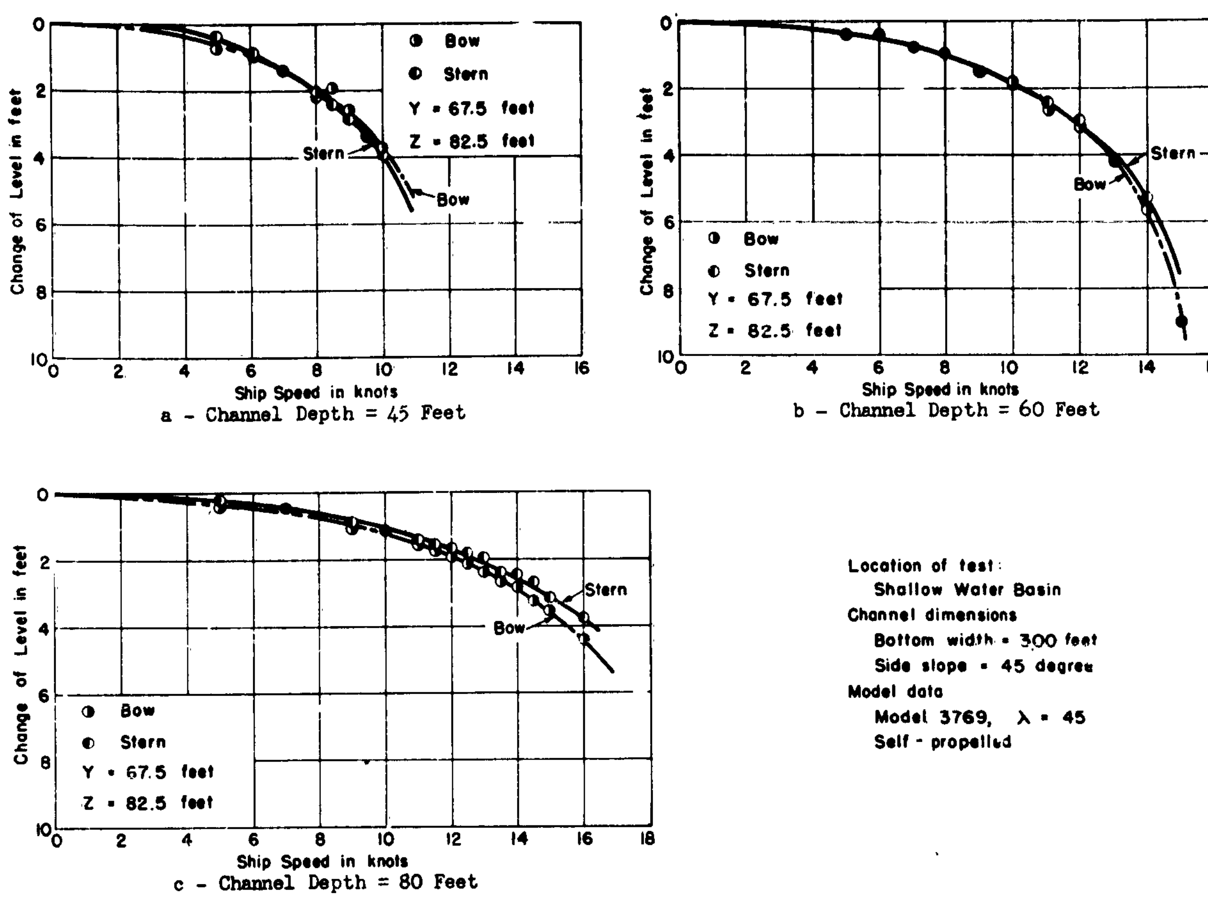
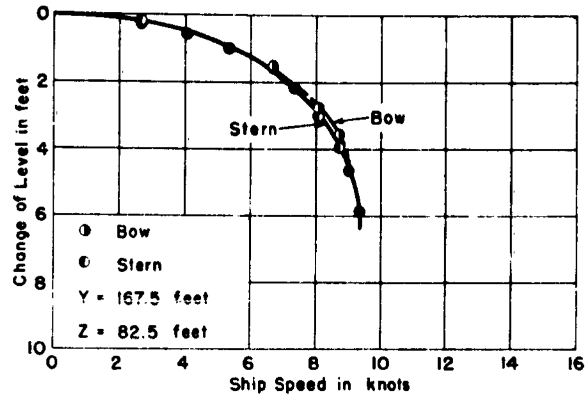
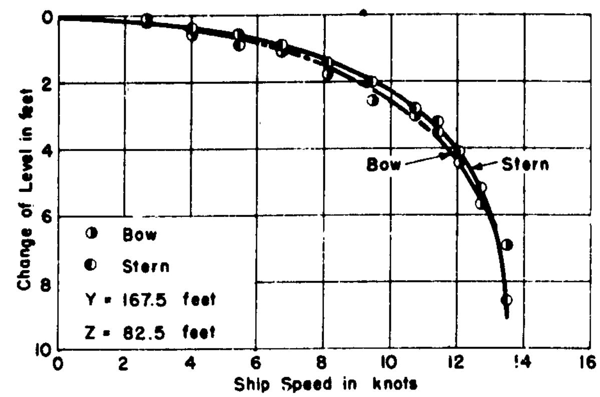


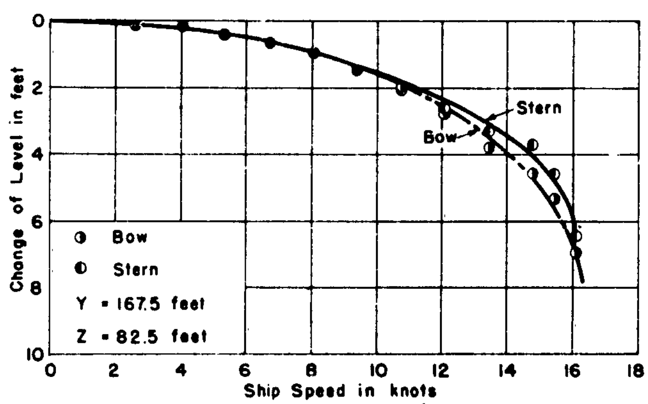
Figure 7.28 - Change of Level of a Ship Located 67.5 Feet off the Centerline of a Restricted Channel 300 Feet Wide



a - Channel Depth = 45 Feet



b - Channel Depth = 60 Feet



c - Channel Depth = 80 Feet

Location of test:
Shallow Water Basin
Channel dimensions:
Bottom width = 500 feet
Side slope = 45 degrees
Model data:
Model 3769, λ = 45
Self - propelled

Figure 7.29 - Change of Level of a Ship Located 167.5 Feet off the Centerline of a Restricted Channel 500 Feet Wide

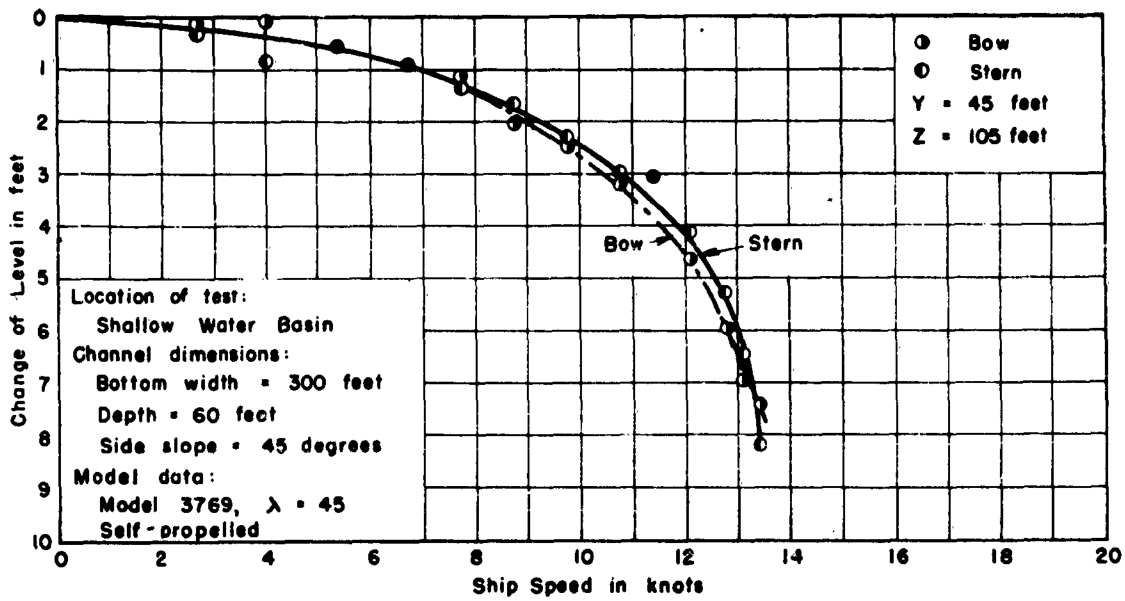


Figure 7.30 - Change of Level of a Ship Located 45 Feet off the Centerline of a Restricted Channel 300 Feet Wide and 60 Feet Deep

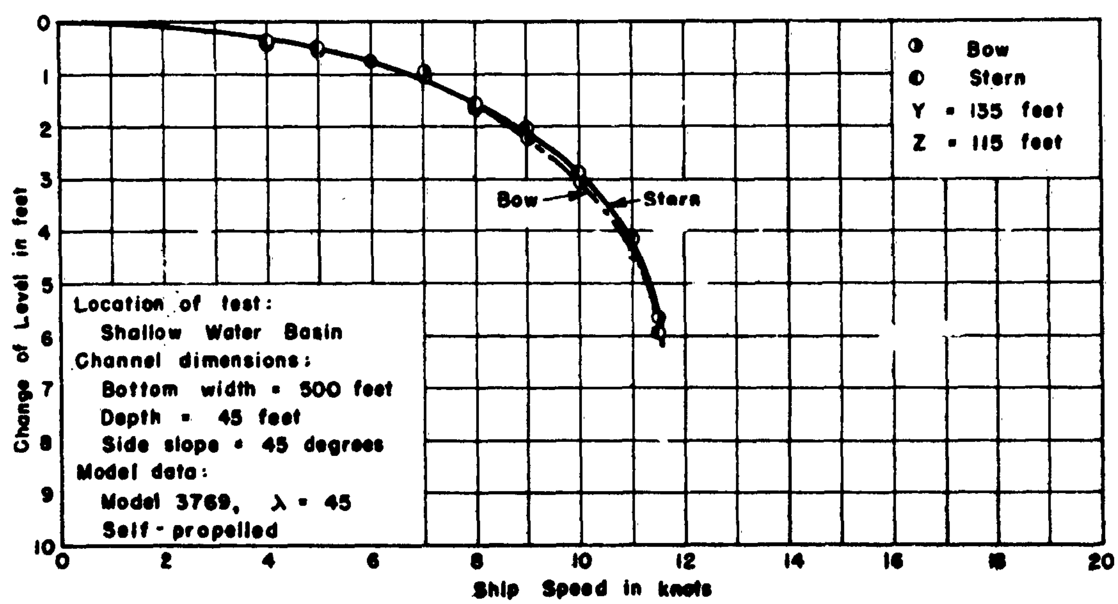
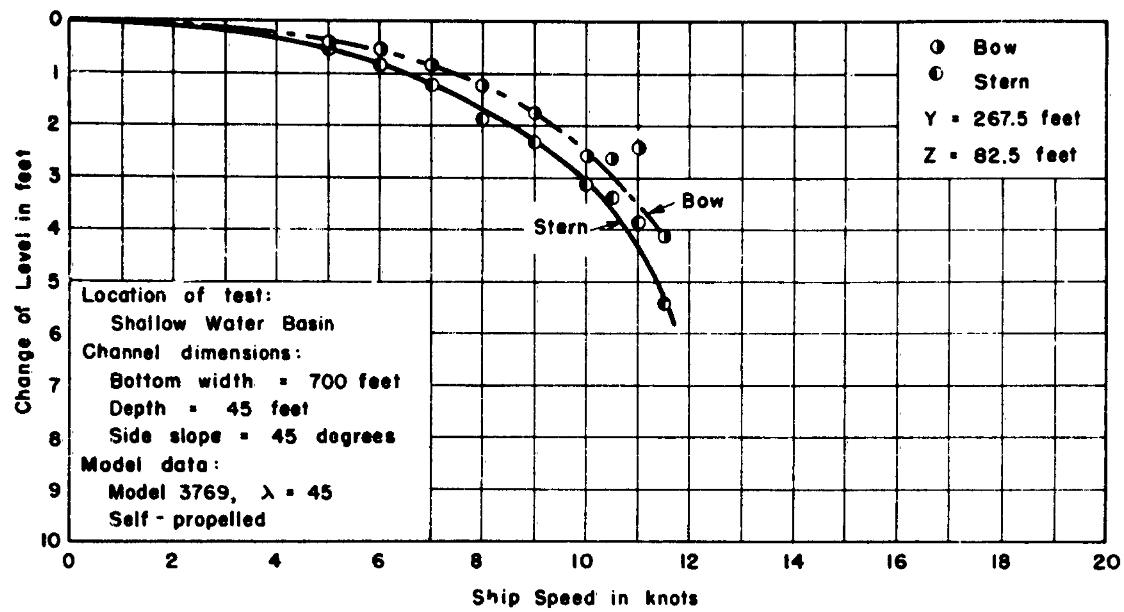
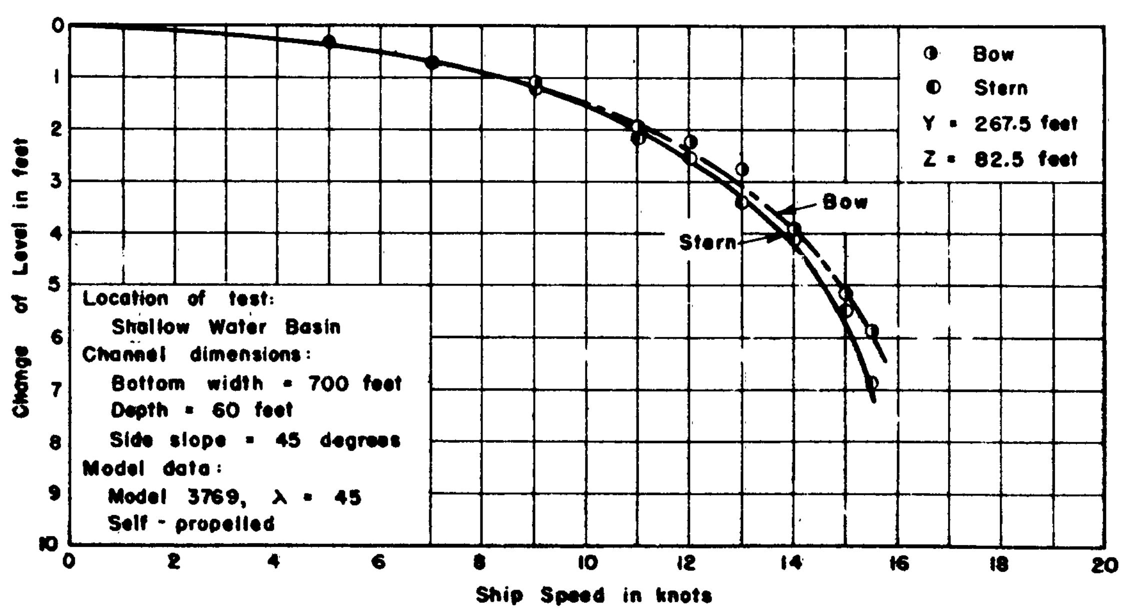


Figure 7.31 - Change of Level of a Ship Located 135 Feet off the Centerline of a Restricted Channel 500 Feet Wide and 45 Feet Deep

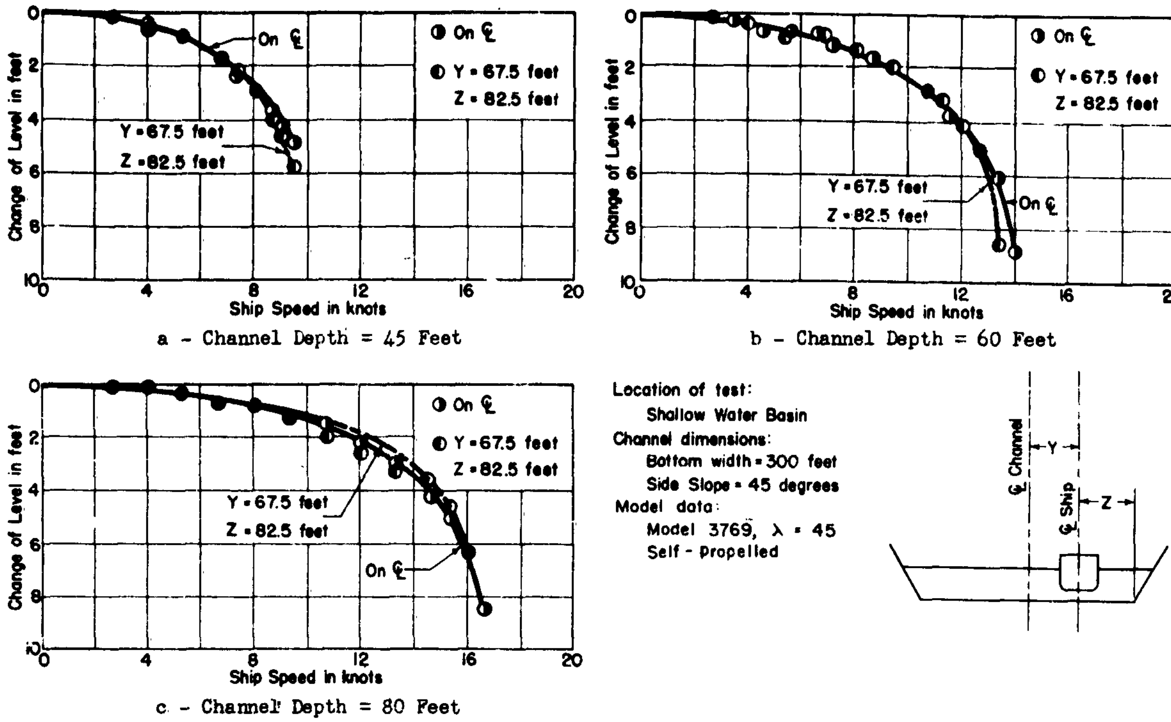


a - Channel Depth = 45 Feet



b - Channel Depth = 60 Feet

Figure 7.32 - Change of Level of a Ship Located off the Centerline of a Restricted Channel 700 Feet Wide

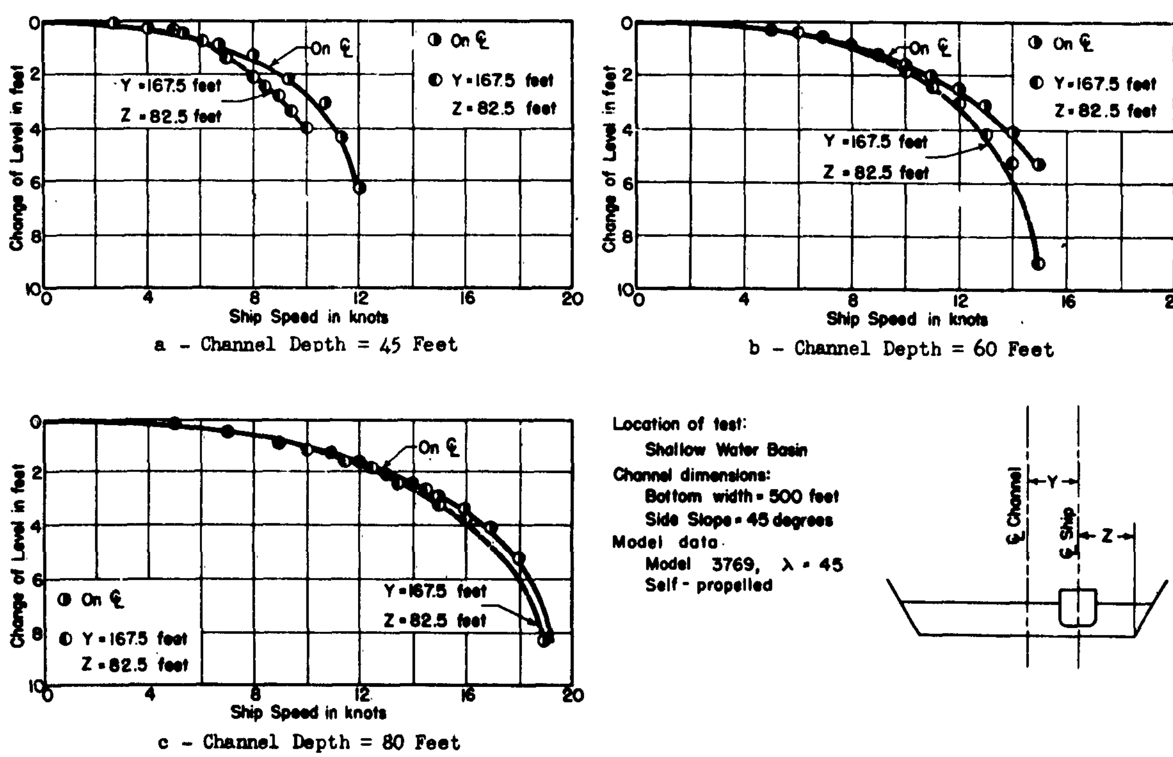


a - Channel Depth = 45 Feet

b - Channel Depth = 60 Feet

c - Channel Depth = 80 Feet

Figure 7.33 - Effect of Transverse Location on Change of Level of a Ship in a Restricted Channel 300 Feet Wide

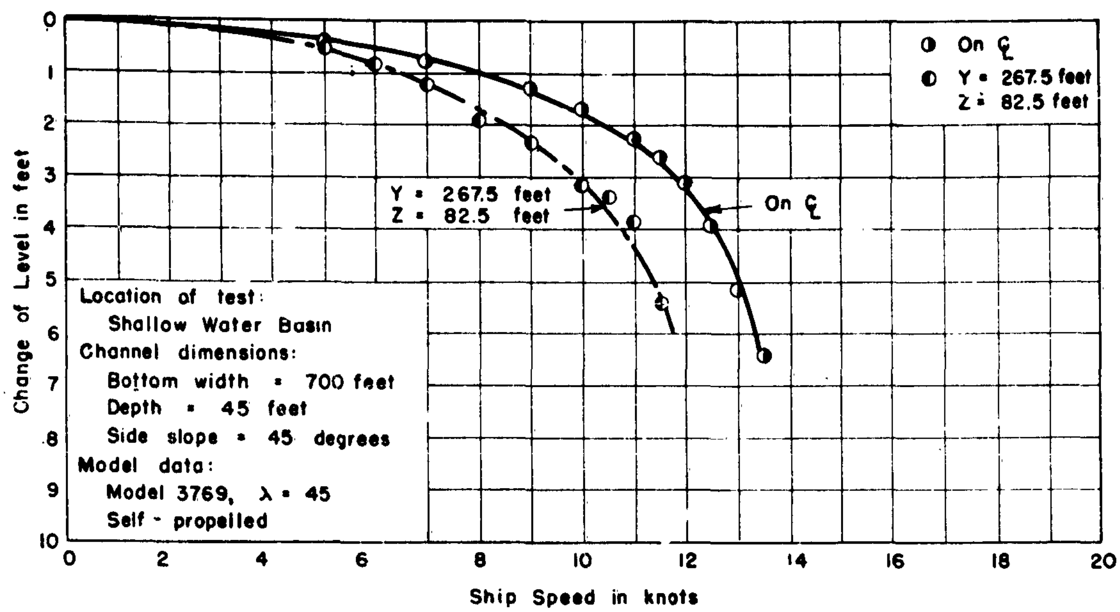


a - Channel Depth = 45 Feet

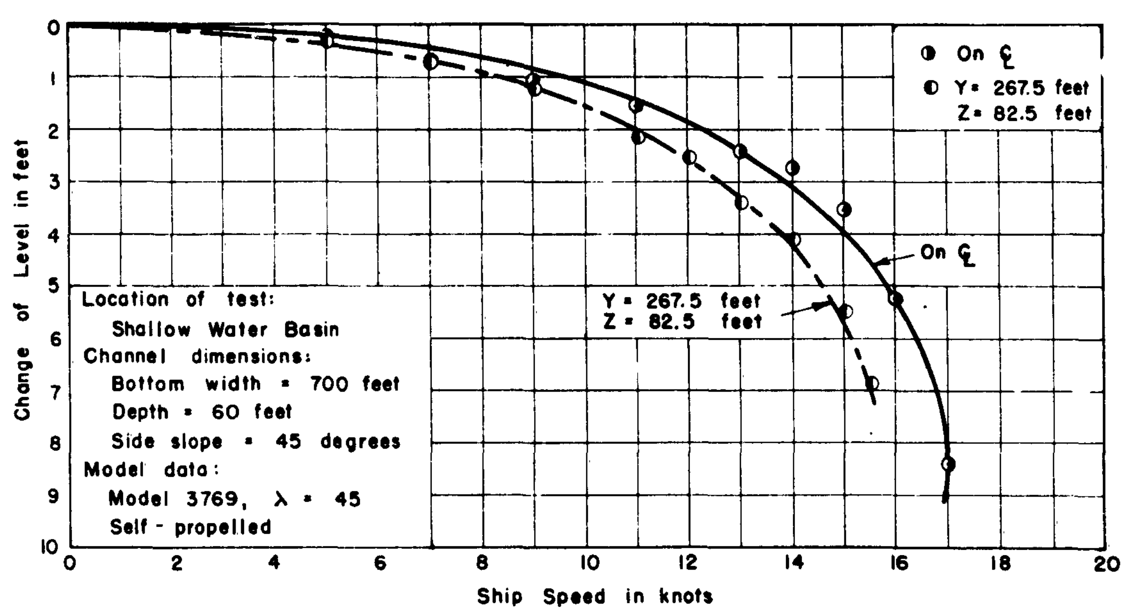
b - Channel Depth = 60 Feet

c - Channel Depth = 80 Feet

Figure 7.34 - Effect of Transverse Location on Change of Level of a Ship in a Restricted Channel 500 Feet Wide



a - Channel Depth = 45 Feet



b - Channel Depth = 60 Feet

Figure 7.35 - Effect of Transverse Location on Change of Level of a Ship in a Restricted Channel 700 Feet Wide

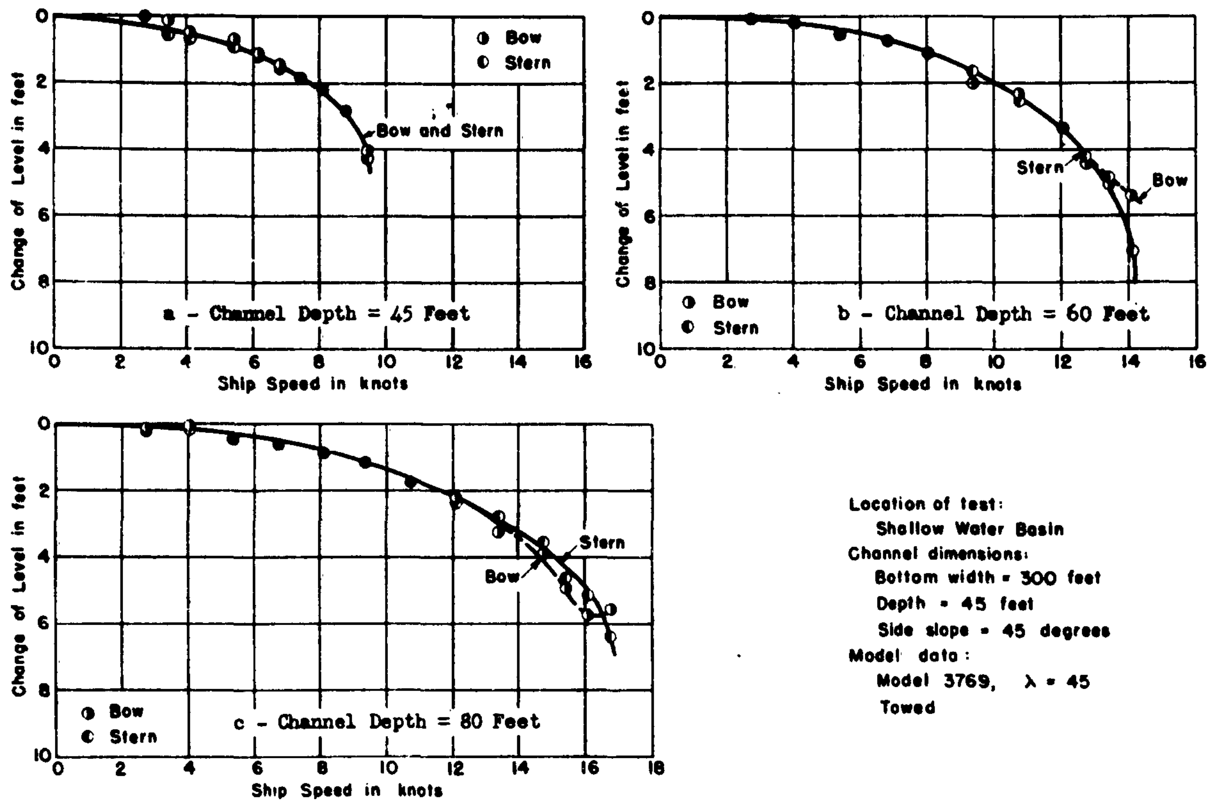


Figure 7.36 - Change of Level of a Ship Towed on Centerline of a Restricted Channel

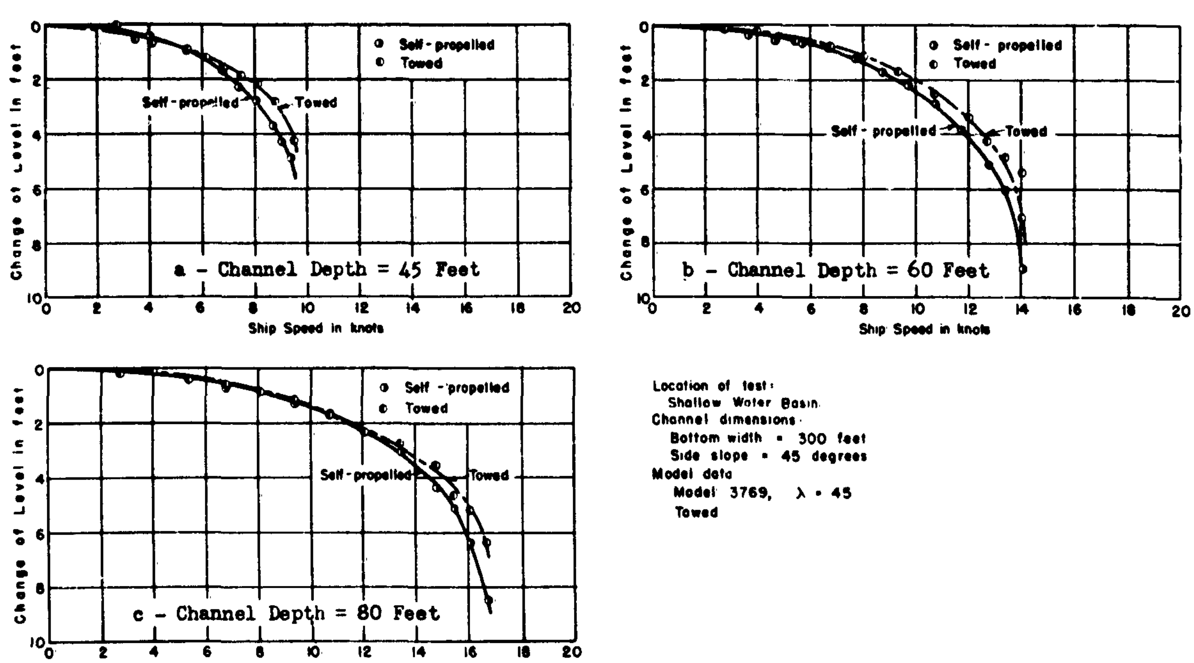
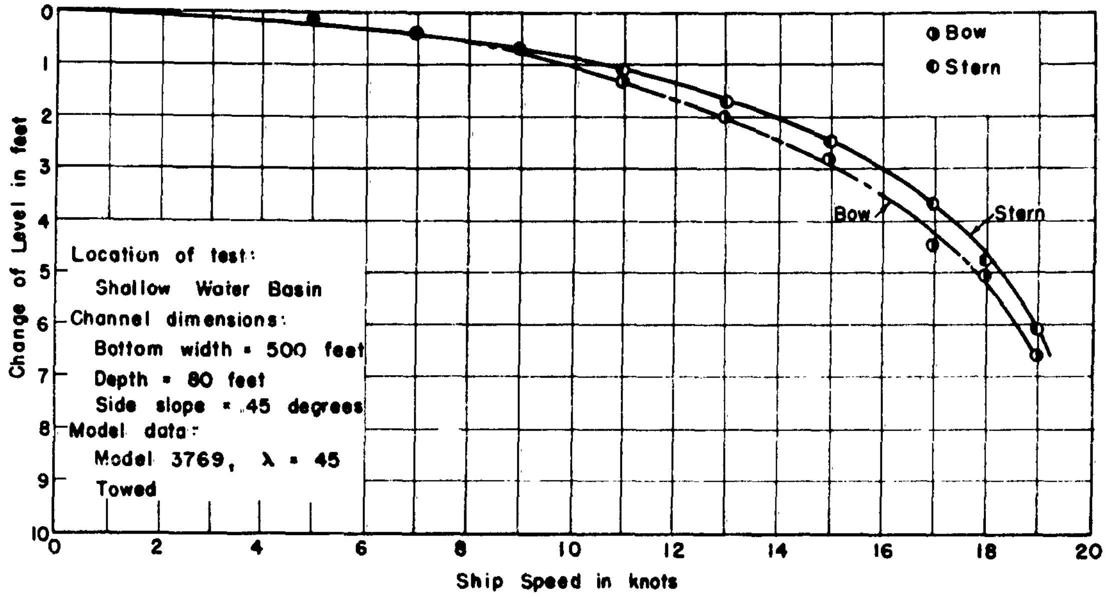
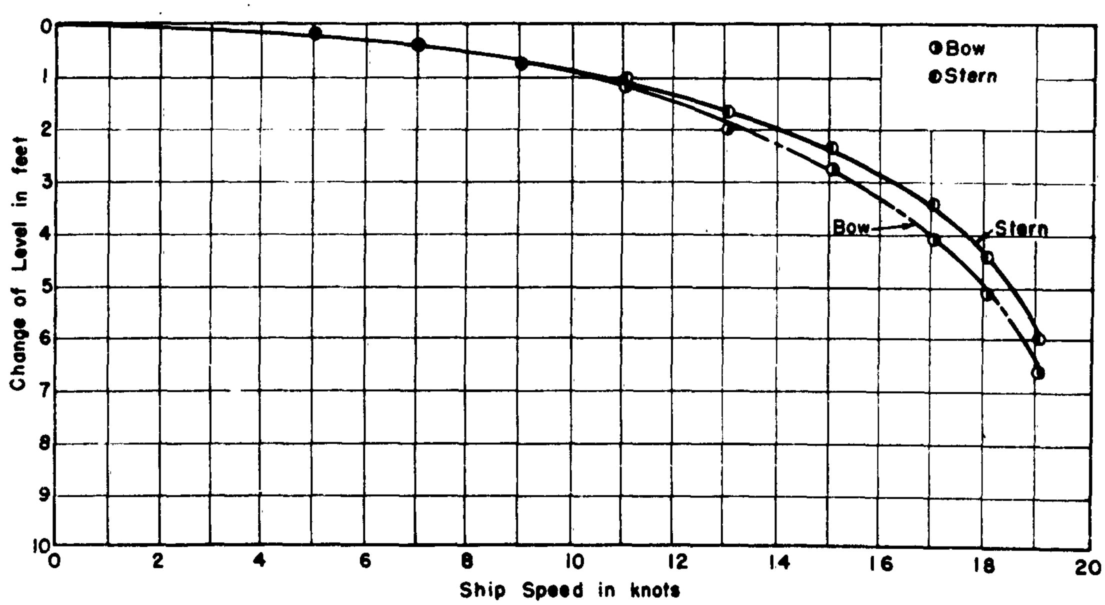


Figure 7.37 - Comparison of Change of Level for Towed and Self-Propelled Model on the Centerline of a Restricted Channel 300 Feet Wide

These curves are for the stern only. The bow curves are similar.



a - Regular Tow Brackets



b - Special Centerline Brackets

Figure 7.38 - Change of Level of a Ship Towed on Centerline of a Restricted Channel Using Two Types of Tow Brackets

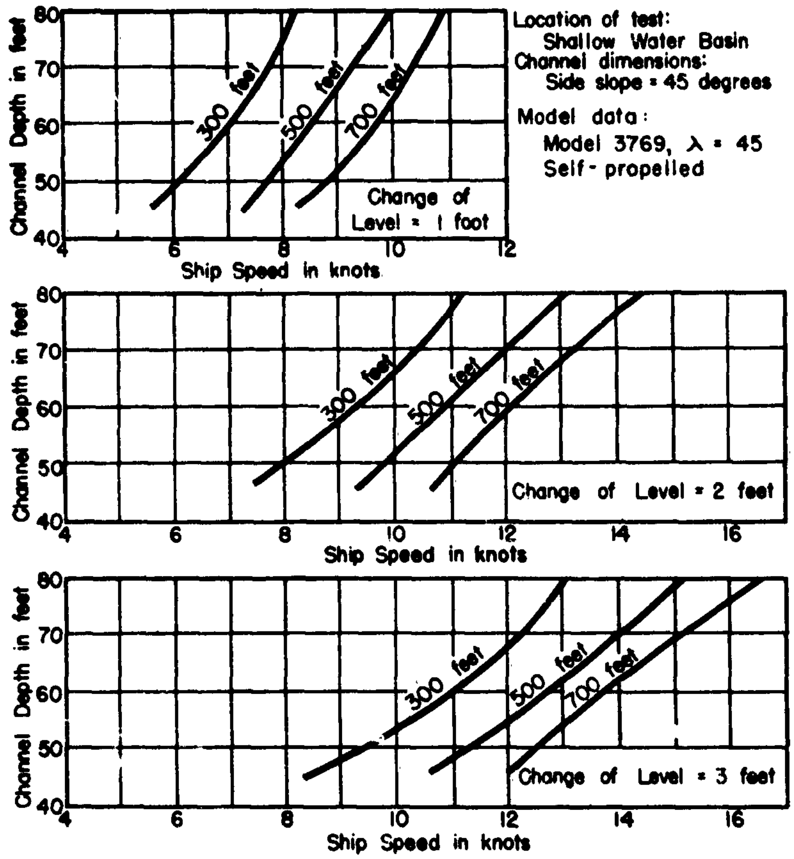


Figure 7.39 - Comparison of Channel Dimensions and Ship Speeds at Which a Change of Level of 1, 2, or 3 Feet Is Obtained

The data are plotted for the midship section so as to eliminate the effect of change in trim.

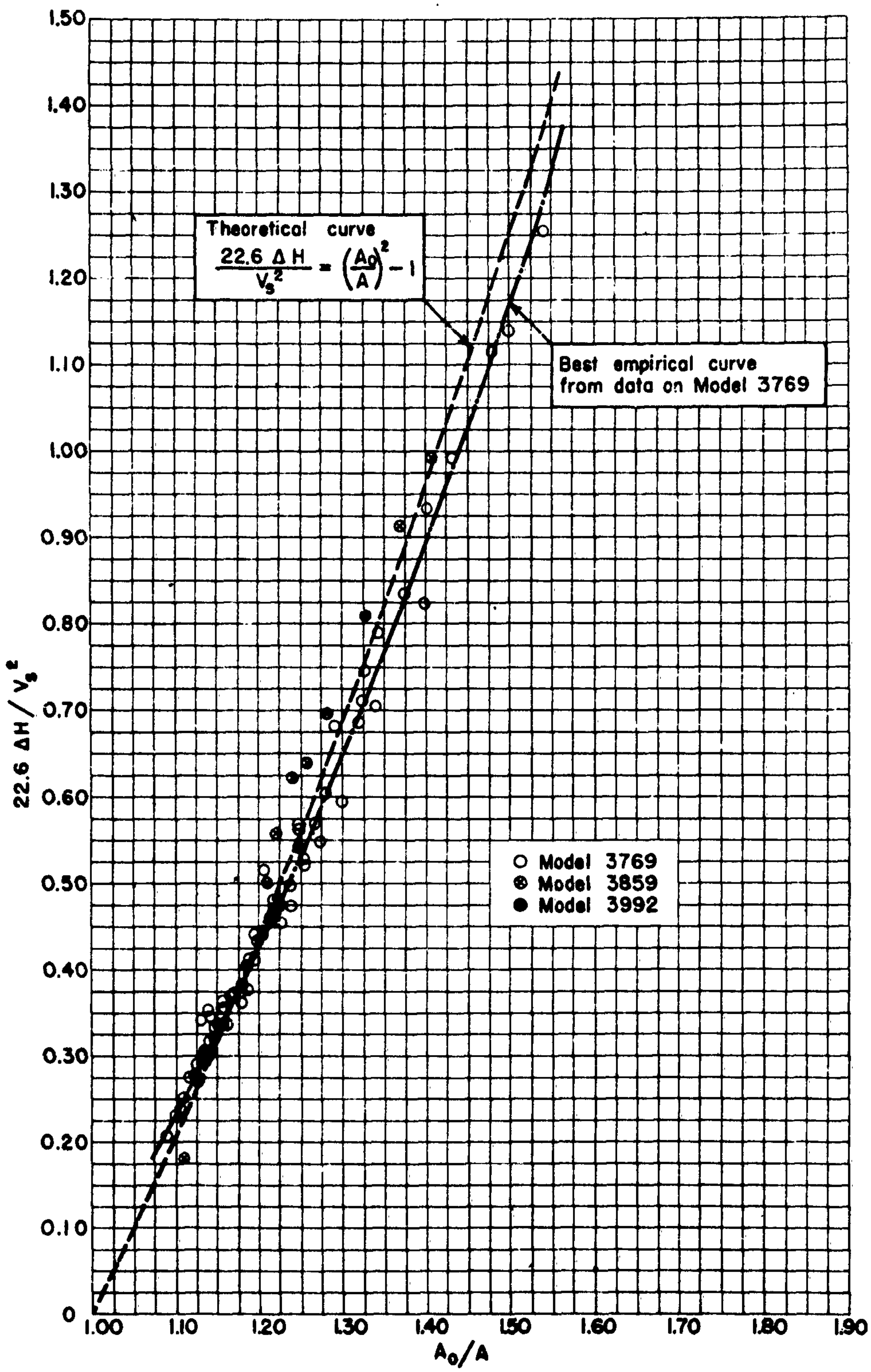


Figure 7.40 - Comparison of Theoretical Curve with Actual Values of 22.6 $\Delta H/V_s^2$ Plotted against A_0/A as Obtained from Model Tests

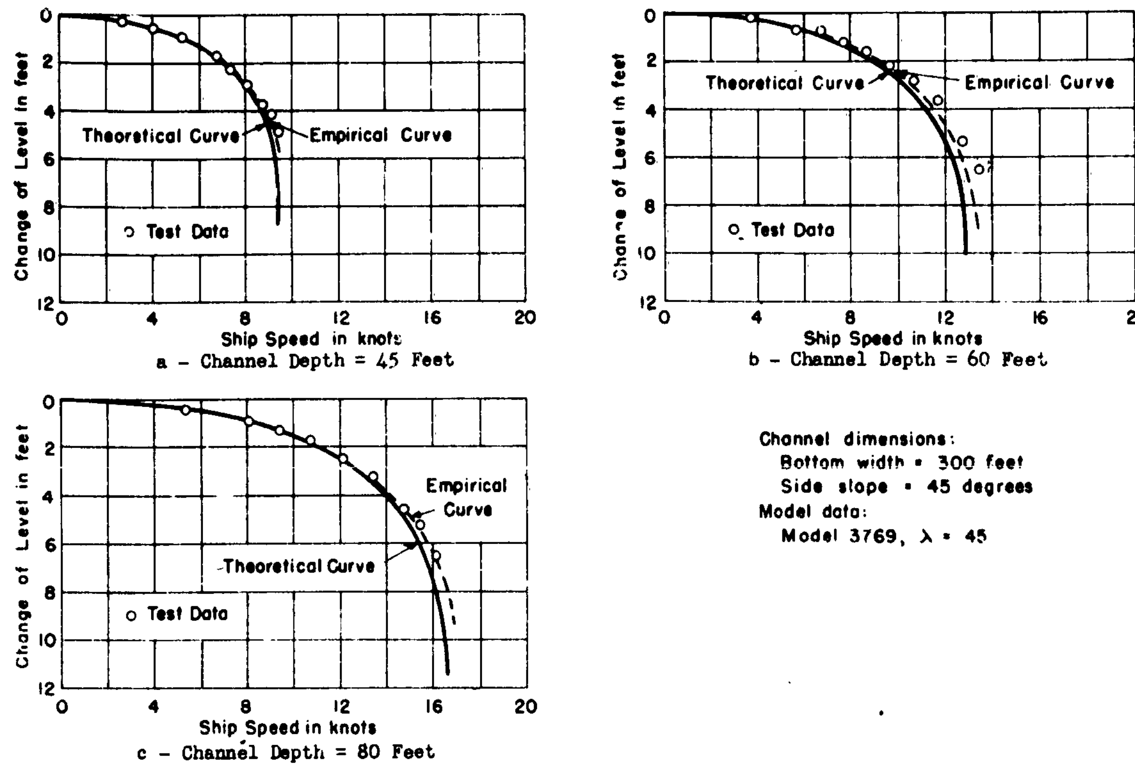


Figure 7.41 - Comparison of Theoretical and Empirical Sinkage Curves with Test Results for a Restricted Channel 300 Feet Wide

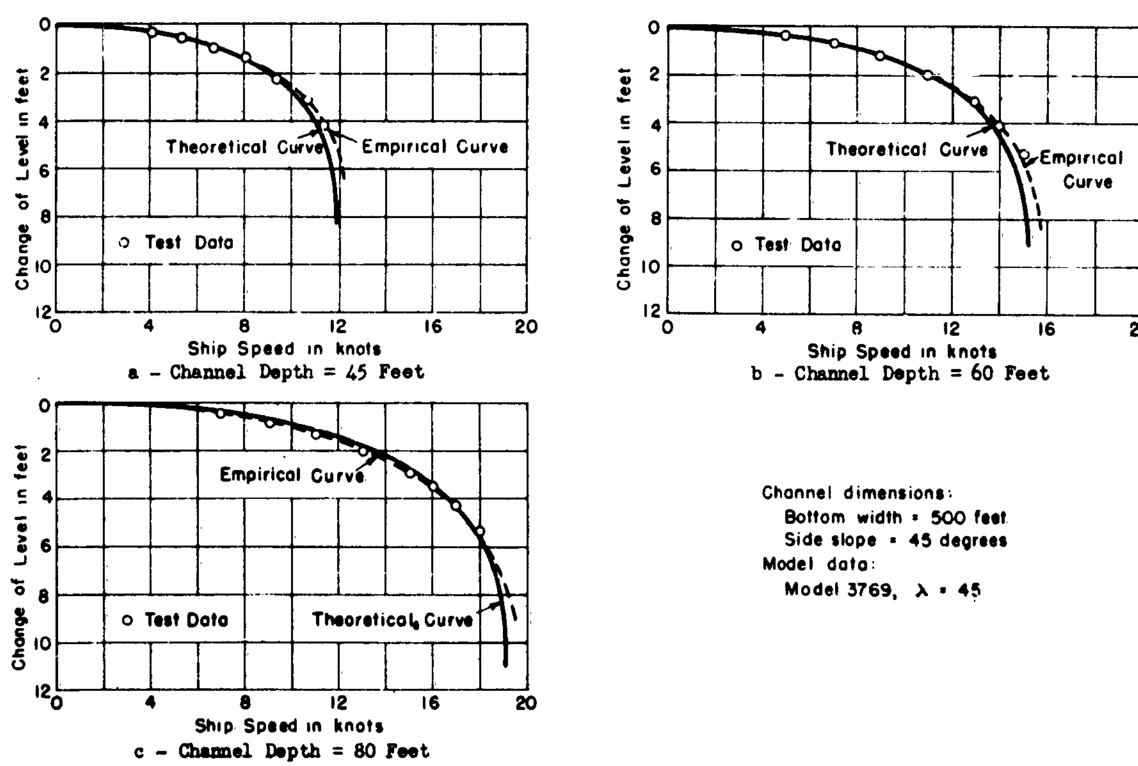
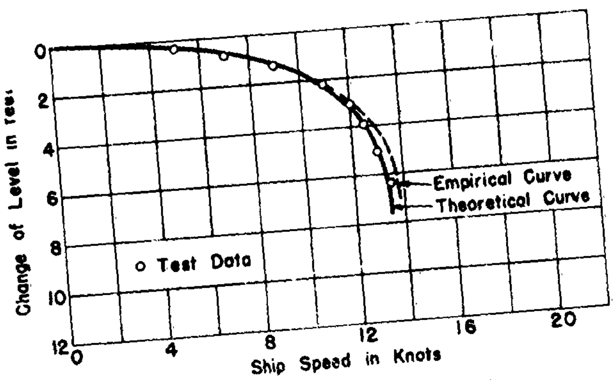
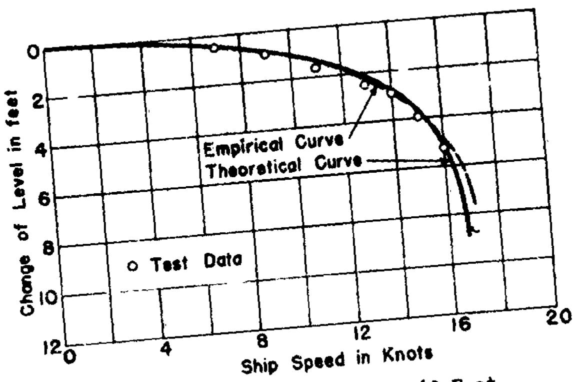


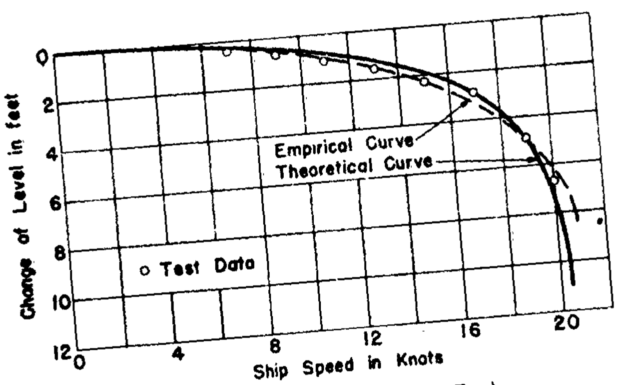
Figure 7.42 - Comparison of Theoretical and Empirical Sinkage Curves with Test Results for a Restricted Channel 500 Feet Wide



a - Channel Depth = 45 Feet



b - Channel Depth = 60 Feet



c - Channel Depth = 80 Feet

Channel dimensions:
Bottom width = 700 feet
Side slope = 45 degrees
Model data:
Model 3769, $\lambda = 45$

Figure 7.43 - Comparison of Theoretical and Empirical Sinkage Curves with Test Results for a Restricted Channel 700 Feet Wide

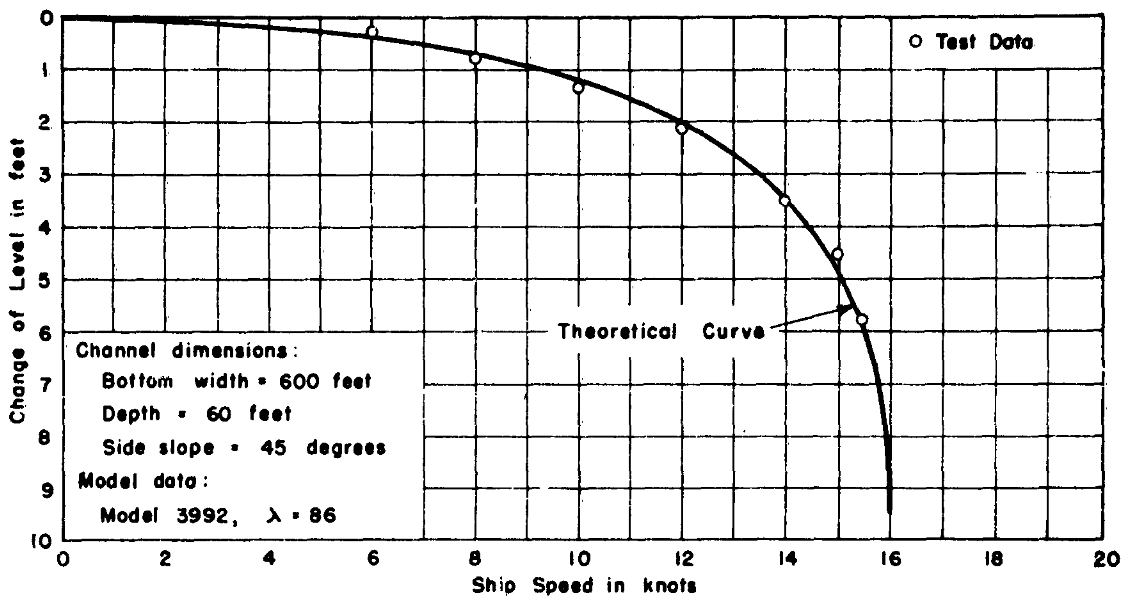


Figure 7.44 - Comparison of Theoretical Sinkage Curve with Test Results for Model 3992

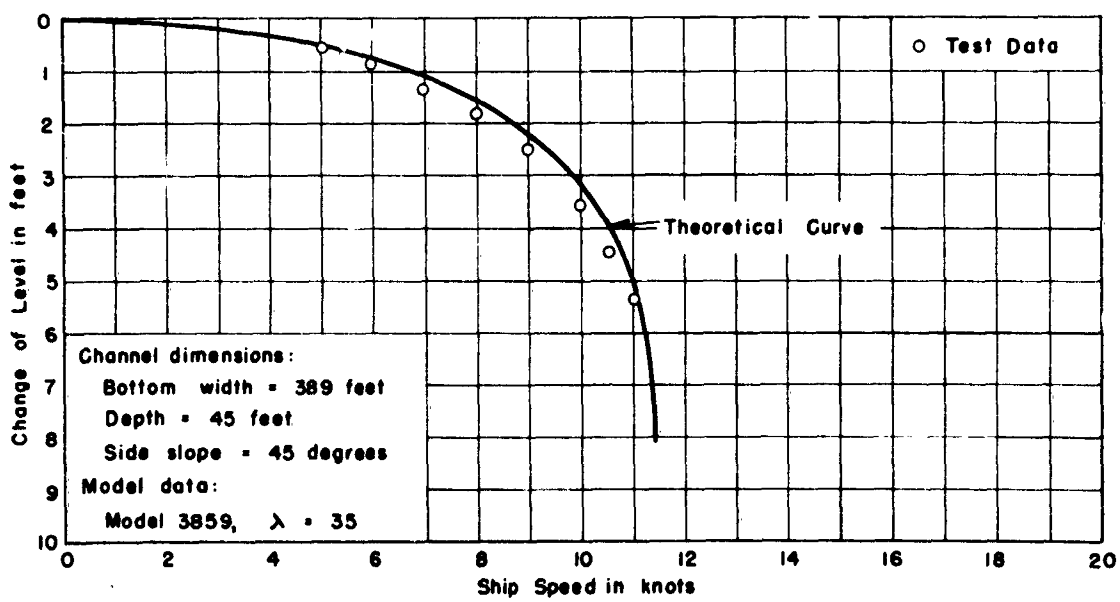


Figure 7.45 - Comparison of Theoretical Sinkage Curve with Test Results for Model 3859

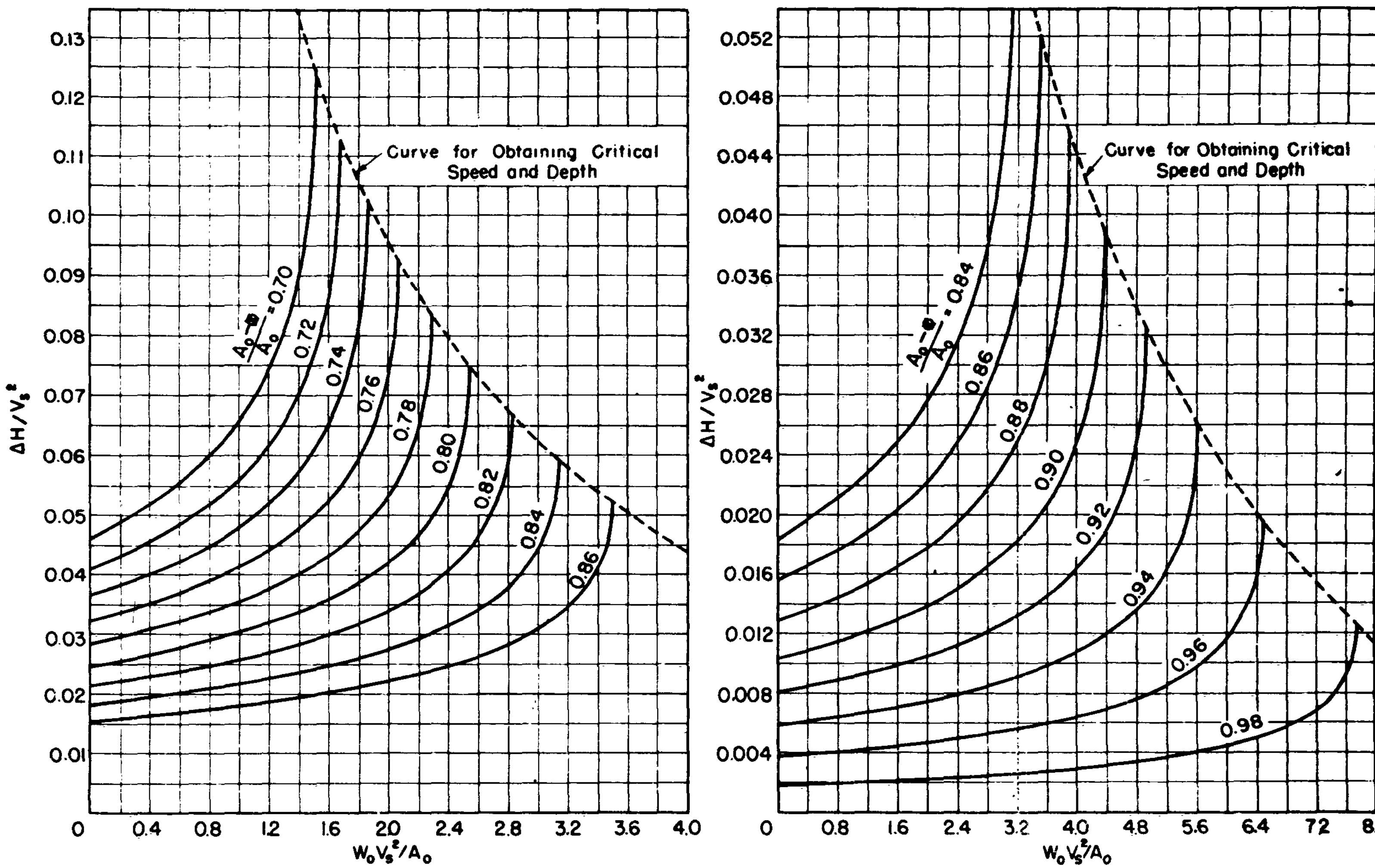


Figure 7.46 - Curves for Computing Sinkage of a Ship in a Restricted Channel

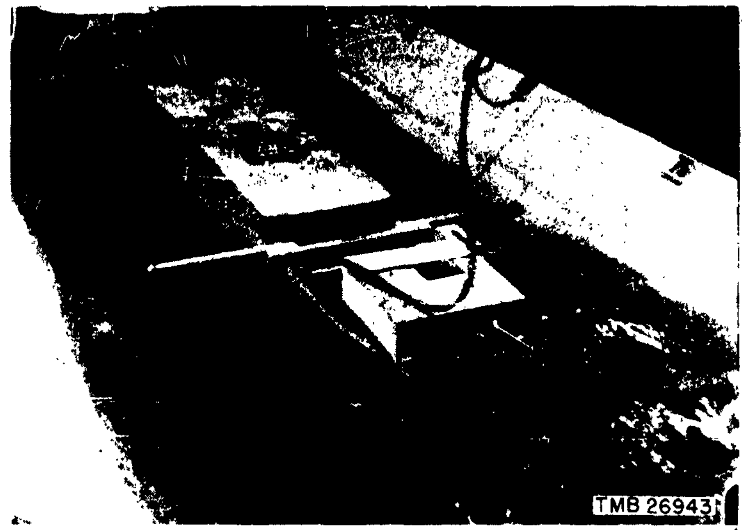


Figure 7.47 - Photograph Showing Water Surface when Vessel Is Transiting a Restricted Channel at Critical Speed

Hydraulic jump is noticeable, particularly near sides of channel.

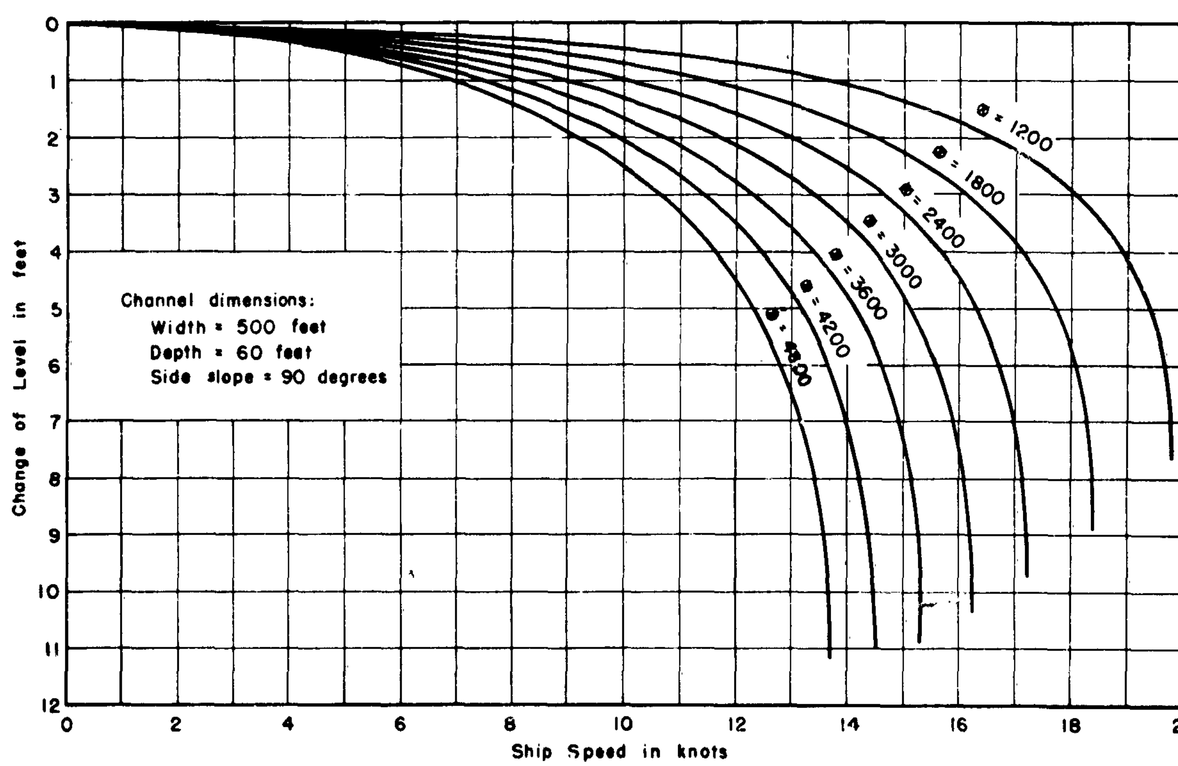


Figure 7.48 - The Effect of Ship Cross Section on Change-of-Level Curves

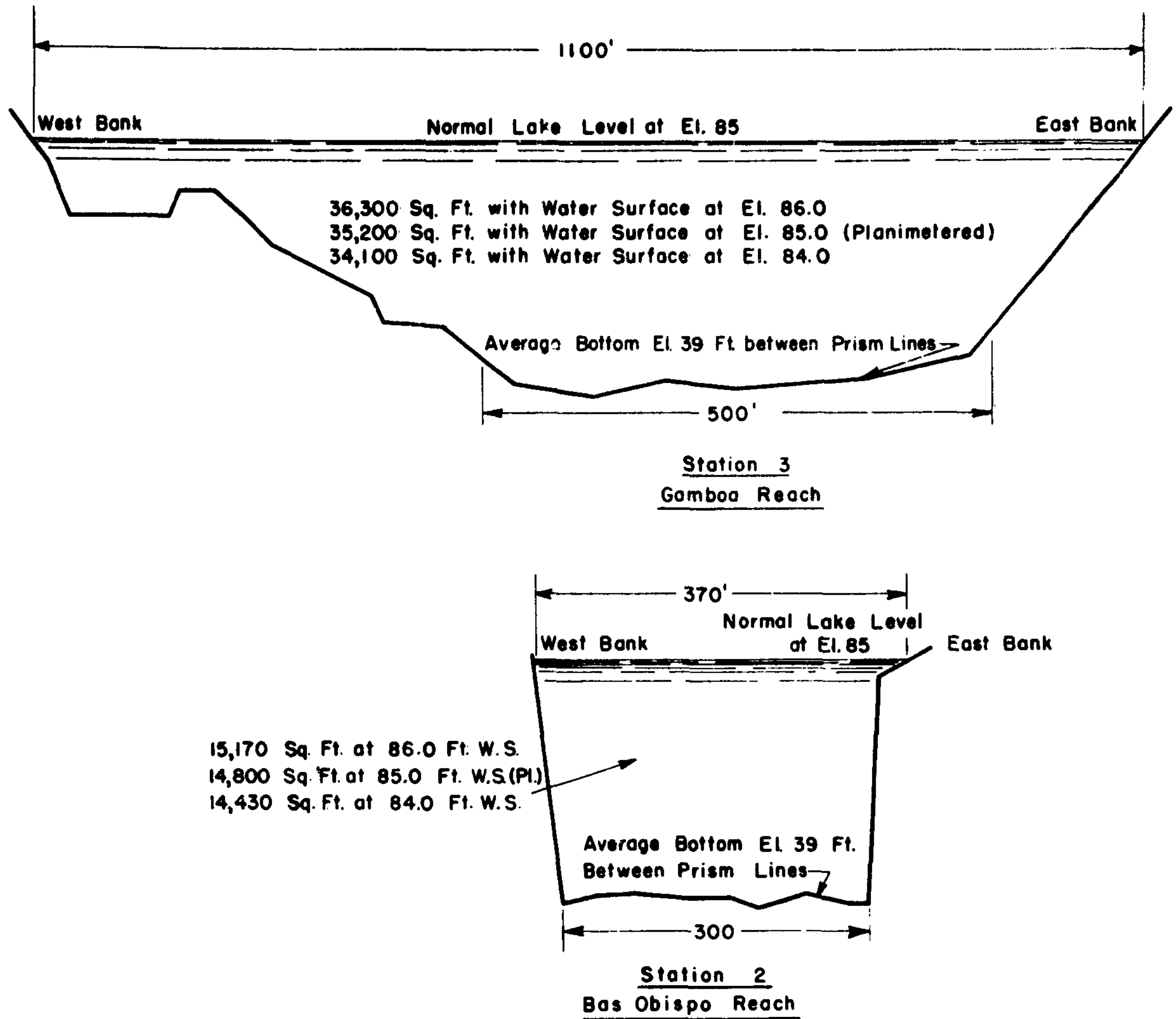


Figure 7.49 - Panama Canal Cross Sections Used for Full-Scale Change-of-Level Tests

SECTION 8

SUMMARY

SCOPE AND LIMITATION OF TESTS

In this section the scope and the limitations of the investigation are briefly reviewed and the significance of the test results in relation to the design of a ship canal is discussed.*

Three major hazards arising from navigation in restricted channels have been studied in this investigation. These hazards are change of level, bank suction, and interaction between ships.

From a practical standpoint the primary problems investigated were the variation in the controllability and in the change of level of selected ships as affected by variations in channel cross section, channel-bend design, channel current, ship speed, and other related factors.

In the straight-channel tests, 16 channel cross sections representing channels ranging from 268 to 979 feet in width and from 45 to 80 feet in depth were tested. The two-way-traffic studies, which were limited to tests in straight channels, were based primarily on the meeting of a large naval ship and a Liberty ship. These vessels were chosen because they are representative of the extreme condition which would be permitted for two-way traffic in the proposed canal. Five channel bend designs were tested.

The model channels and the model ships operating in those channels were constructed to the same linear ratio. The linear ratio ranged from 35 to 86 for the various phases of the test program. The tests at linear ratios of 35 and 45 simulate full-scale conditions very well. Even though the bend tests at a linear ratio of 86 show considerable scale effect the results are useful for comparison of bends.

The range of ship speeds tested was from 4 1/2 to 20 knots full scale. However most of the tests were at speeds of 10 knots and less because 10 knots was set as the top normal operating speed for vessels in the proposed canal.

The channel currents ranged from 5 knots following current to 5 knots ahead current because it was known that this range of currents would be slightly more than any value which might be expected in the event that a sea-level canal is constructed at Panama, or in the event that the tide-control structures are destroyed.

The variety of sizes, shapes, rudders, and propulsion characteristics of the many ships that will transit any channel is so great that only

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* No attempt is made to discuss all the conclusions and concepts previously presented in Sections 4, 5, 6 and 7.

representative types from different general groupings could be used for the experiments. On this basis the vessels represented in the tests were selected because of their large size, their poor handling characteristics in restricted channels, or their being representative of a large percentage of the present ships transiting the canal. It is believed that the ships represented in these tests bracket these conditions reasonably well. It was not feasible to test all of the ship models in all of the channels for all of the test conditions listed.

Many factors which may affect the final selection of channel cross-section and bend design were not studied in this investigation. The efficiency of operating a vessel is measured to some extent by the age of the ship and the number of days it has been underway since overhaul. Seldom do two ship captains or pilots come to perfect agreement on the proper methods to use in maneuvering a vessel. No systematic study of the effect of side slope of the channel was made. No study was made of the effect of irregularities in the channel boundaries. Wind, rain, fog, and mechanical failures are other items that have to be considered. To a limited extent these factors can be offset by artificial aids to navigation, such as range markers, buoys, and beacon lights, but there are always special conditions through which a ship must be navigated. There are many other factors which affect the selection of the final channel design that have little or nothing to do with the performance of the ships themselves.

TEST RESULTS IN RELATION TO THE DESIGN OF A SHIP CANAL

The conclusions as to the proper width and depth of channel and the proper bend design, which are presented in this summary, do not constitute a design intended for the Panama Canal. However, the information obtained and the concepts and techniques developed in this investigation should be of use to the Panama Canal authorities in the design of a modernized Panama Canal.

SELECTION OF CHANNEL CROSS SECTION

Before the channel width and depth can be selected the pertinent extreme traffic conditions to be permitted in the channel must be decided. In the following illustration the pertinent traffic conditions are taken to include: straight-channel one-way traffic with a large naval vessel, Model 3769, and straight-channel two-way traffic with the large naval vessel passing an oncoming Liberty ship. The maximum normal operating speed to be permitted is 10 knots. Channel currents up to 5 knots in either direction may exist.

CHANNEL DEPTH

The model tests indicate that adequate channel depth is of prime importance to ease of navigation and therefore selection of a reasonable channel depth appears to be a logical first step. The straight-channel one-way-traffic tests indicate that the large naval vessel handles considerably better at 80-foot channel depth than at 45-foot channel depth. However as indicated by Figures 4.6, 4.10, 4.16, 4.17, 4.18 and the discussion thereof the greater part of this improvement occurs in increasing the channel depth from 45 to 60 feet. This, as might be expected, is especially true of the narrow channels. The sinkage tests with the model of the large naval vessel indicate that a 500-foot by 60-foot channel would be ample to prevent excessive sinkage. In such a channel even an 80,000-ton vessel would be in no danger from excessive sinkage at speeds below 10 knots. On the basis of the model tests and other background information, the Panama Canal tentatively selected a channel depth of 60 feet as reasonable for the further study of channel width as related to two-way-traffic and bend studies.

CHANNEL WIDTH

It is assumed that any vessel navigating in a restricted channel would attempt to hold its course on the centerline of the channel except when passing oncoming ships. The straight-channel one-way-traffic tests indicate that maneuvering a ship is much more difficult for an off-center position than for a centerline position. In view of these statements it is logical that the space requirements for completing the meeting maneuver are important in connection with the selection of the channel width. On the basis of two-way-traffic conditions the width of a restricted channel may be divided into 5 parts. Figure 8.1 not only identifies these parts as Bank Clearances (A and E), Maneuvering Lanes (B and D), and Ship Clearance (C) but also presents the estimated minimum width for each part.

The ship lanes correspond to the maximum width of path as described in Section 4. Figures 4.19 and 4.20 and the discussion thereof indicate that 181 feet, or 160 per cent of the beam, is a conservative estimate of the minmum ship lane for the large naval vessel. In this connection it should be noted that the width-of-path data presented in Figures 4.19 and 4.20 are quite limited. However, it is believed that the data present a conservative picture because the meeting maneuver takes much less time than the maneuvering run as represented in the tests. Figures 4.19 and 4.20 also indicate that the width of path is not materially affected by the ship's lateral position in tne canal provided that the ship is maneuvered at a reasonable distance from the near bank. The ship lane for the Liberty ship is estimated to be 102 feet, or 170 per cent of the beam. The larger percentage for the Liberty ship is a rough estimate based on the fact that the Liberty ship is less maneuverable than the large naval vessel. The conclusion as to the minimum ship lanes are in fair agreement with opinions expressed by the Panama Canal pilots.

The ship clearance is taken to be the distance between the inner boundaries of the ship lanes inasmuch as the ships might be in those positions during the meeting maneuver. Both ships participating in this maneuver are subjected to bank suction and to interaction between ships. The relative importance of these two hazards of restricted-channel navigation depends upon the lateral position of the two ships with respect to the channel banks and with respect to each other. The tests indicate that if the maneuvered ship came too close to the near bank it was apt to develop a very noticeable sheer towards the far bank after the sterns cleared each other. On the other hand, if the bank clearances were greater and the ship clearances were sufficiently reduced this tendency was partially nullified or, in extreme situations, reversed. Based on the model tests and on pilots' opinions it is believed that 113 feet, the beam of the large naval vessel, is a conservative estimate for the ship clearance. With this ship clearance interaction between the ships created no appreciable hazard. However the pilots hesitate to reduce this clearance with a ship the size of the large naval vessel.

The bank clearance is the distance between the outer boundary of the ship lane and the near prism line of the channel. The determining factor in the selection of an adequate bank clearance is the magnitude of the bank suction which can safely be permitted. As discussed in Section 4, the equilibrium rudder angle is a practical measure of bank suction. Drawing upon the experience of well-qualified Panama Canal and Cape Cod Canal pilots participating in the tests it was decided tentatively that 5 degrees equilibrium rudder angle would represent bank suction of a reasonable magnitude and still provide ample reserve rudder in case of emergency. The great variations in the size and controllability of vessels and the fact that every pilot will maneuver differently help to explain the small equilibrium rudder angle selected.

The bank clearances which correspond to 5 degrees equilibrium rudder angle are shown in Figure 8.1b. In the case of the large naval vessel the clearance corresponding to 5 degrees equilibrium rudder angle is 126 feet. This value is derived from the Z-curve for 60-foot channel depth which is shown in Figure 4.7a. It should be noted that the Z-distance is greater than the bank clearance by one half the ship beam. Also it will be noted that the bank clearance selected in this manner will vary slightly with channel width for channels between 500 and 700 feet wide. Hence it is necessary to assume

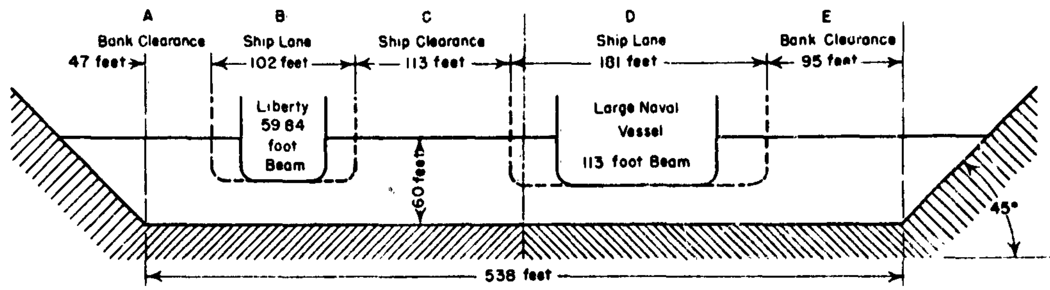

Figure a - Bank Clearance of Large Naval Vessel and Liberty Ship Based on 7 Degrees Equilibrium Rudder Angle

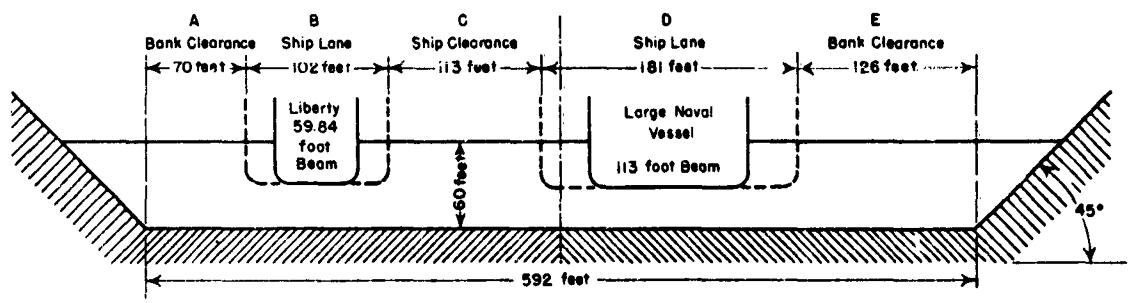

Figure b - Bank Clearance of Large Naval Vessel and Liberty Ship Based on 5 Degrees Equilibrium Rudder Angle

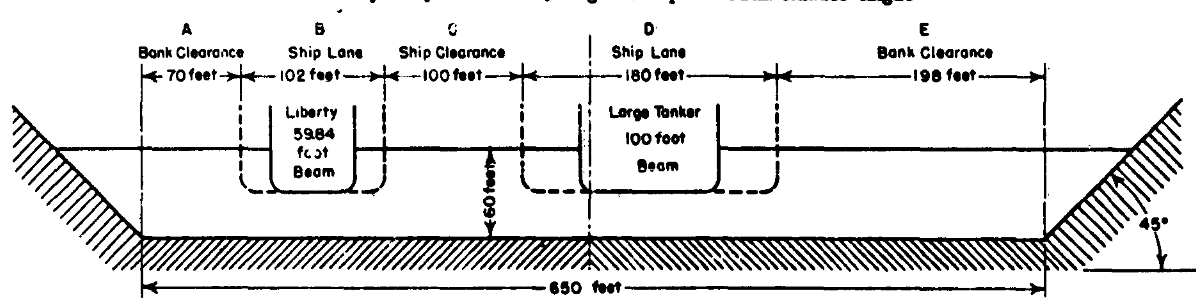

Figure c - Bank Clearance of Large Tanker and Liberty Ship Based on 5 Degrees Equilibrium Rudder Angle

Figure 8.1 - Estimated Channel Widths for Two-Way-Traffic Conditions

The ship lanes for the large naval vessel, the Liberty ship, and the large tanker are 160, 170, and 180 per cent of their respective beams. The ship clearances in each figure are the beam of the larger ship.

a channel width until a width is found such that the sum of the width of the 5 parts of the channel will equal the assumed channel width.

The bank clearance for the Liberty ship, as estimated from Figure 4.13, is 70 feet. Figure 4.13 is based on rather limited data and therefore this estimate was based on the maximum rudder curve, that is, the curve for 9-knot ship speed with a 5-knot following current. These tests were made in a 500-foot channel. However it is believed that the far-wall effect is negligible on this ship under these conditions. Therefore a 70-foot bank clearance would be satisfactory for a channel width of 500 feet or more. The channel width then becomes 592 feet.

Figure 8.1a shows a channel 538 feet wide. This width was selected in the same manner except that 7 degrees equilibrium rudder angle was used in determining the bank clearances for the two ships. It should be realized that with the reduced bank clearances the ships might be in serious difficulty as a result of a momentary mechanical failure or an improper rudder setting. Also the equilibrium rudder angles begin to increase rapidly if for any reason the bank clearances are further reduced. This is particularly true of the Liberty ship.

In Figure 8.1c the same technique was used to determine the channel width necessary for two-way traffic with the larger tanker meeting an oncoming Liberty ship. The bank clearances are based on an equilibrium rudder angle of 5 degrees.

The bank clearance for the large tanker, as estimated from Figure 4.25, is 198 feet. In this connection it should be noted that the Z-distance for this vessel in a 500-foot by 60-foot channel is 212 feet. Also, it is apparent from an examination of the Z-curves for a 45-foot channel depth that the Z-distances increase quite rapidly with increases in channel width, even at the 770-foot width. In effect this means that the far wall of the channel is still an important factor in the total bank suction under these conditions. This is to be expected because the tanker is only 40 feet off the channel centerline. Also in the 500-foot by 60-foot channel the tanker is only 38 feet off the channel centerline and therefore the far-wall effect is again large. These facts are the justification for the seemingly large bank clearance given for the tanker. If tests had been made in a 770-foot by 60-foot channel the selection of the required bank clearance would have been greatly simplified.

The tanker is very difficult to maneuver and therefore the ship lane is taken to be 180 per cent of the beam. The ship lane and the bank clearance for the Liberty ship are 102 feet and 70 feet respectively as in the previous example. The ship clearance is 100 feet, that is the beam of the tanker.

The estimated channel width is 650 feet. It should be noted that the tanker represents a ship with very poor controllability and is somewhat larger than any comparable ship existing or planned.

CHANNEL BENDS

The one-way-traffic maneuvering runs that were made at the quarter points in the channel indicate that two-way traffic with a large vessel and a Liberty ship would be hazardous in any of the bends tested. The ships were more easily controlled in the 26-degree parallel bend than in any of the other bends. This was particularly noticeable with respect to the tests in channel currents. This bend, which was tested with a bottom width of 560 feet and a depth of 60 feet with a side slope of 45 degrees, provided satisfactory controllability on centerline runs for ship speeds between 5 and 10 knots with channel currents up to 5 knots in either direction.

Widening of the channel in the bend or before entrance to the bend is desirable in order to obtain additional space for two-way traffic. It may be possible by further study and testing to design a bend which will provide greater width in the bend and still assure satisfactory controllability in channel currents up to 5 knots in either direction.

SECTION 9

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PSNC-6818-7-21-48-600