Curve	Identity
	Columbia River—
1	Foster Creek project above Wenatchee, Wash.
2	Priest Rapids project near Ellensburg, Wash.
3	McNary project above Umatilla, Ore.
	Yazoo River—
4	At Yazoo City, Miss.
5	At Greenwood, Miss.
	Tallahatchie River—
6	At Swan Lake, Miss.
7	At Lambert, Miss.
	Big Black River—
8	At West, Miss.

b. The bankfull roughness coefficients do not vary greatly for rivers and canals in different kinds of material and in widely separated locations. From the summary in Table 19 for channels having hydraulic radii exceeding 20 ft, all but one show roughness coefficient values in the range from 0.024 to 0.031.

Roughness Measurements in Gaillard Cut.—Measurements were made of the roughness of the Gaillard Cut channel of the existing canal, to obtain data under conditions as nearly comparable as possible to those in a new canal channel. A flow of water through the cut was established by opening all the culvert valves at Pedro Miguel Locks after the last ship transit in the evening, and continued until necessary to shut down before the first transit in the morning.

TABLE 20.—ROUGHNESS COEFFICIENTS, GAILLARD CUT

Reach (stations)	Difference in Water-Surface Elevation		Average energy gradient slope, S	Mean section area (sq ft)	Mean velocity (ft per sec)	Mean hydraulic radius, R (ft)	Chézy C	Manning n (a)	Kutter n	Modified Kutter n	Bazin m	Kármán-Prandtl k
	Sept. 18	Sept. 19										
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)
1516–1597	0.040	0.041	0.0000060	14,900	1.48	36.5	101	0.0268	0.052	0.025	3.4	0.35
1597–1640	0.033	0.032	0.0000052	15,800	1.39	36.4	100	0.0271	0.053	0.024	3.5	0.38
1640–1716	0.025	0.025	0.0000055	16,500	1.34	37.4	101	0.0270	0.053	0.024	3.4	0.37
1716–1800	0.033	0.031	0.0000023	21,500	1.02	38.0	108	0.0252	0.054	0.022	2.8	0.22
1800–1887	0.021	0.024	0.0000046	18,000	1.22	36.0	103	0.0261	0.052	0.023	3.1	0.29
1516–1640	0.073	0.073	0.0000057	15,200	1.44	36.4	101	0.0269	0.053	0.024	3.4	0.36
1640–1887	0.079	0.080	0.0000041	18,600	1.18	37.2	103	0.0263	0.053	0.023	3.2	0.31
1516–1887	0.152	0.153	0.0000046	17,200	1.28	37.0	102	0.0265	0.053	0.023	3.3	0.33

[a] From water-surface profile computations. The remaining coefficients have been determined from n, R, and S as tabulated. The slope term, $0.00281/S$, of the Kutter equation is omitted in the modified Kutter equation.

Six temporary gages were established for these tests and their zero elevations were determined by simultaneous readings of all gages during a preliminary run with quiet water surface and no flow through the cut. An average discharge of 22,000 cu ft per sec was measured by current meter at each end of the test reach for each of the two tests.

Areas and hydraulic radii for the channel cross sections were obtained from a detailed survey made in 1945. Fig. 28 shows the locations of gages and the observed water-surface profiles, and Table 20 lists the coefficient values found for different flow formulas. The depth of the channel was quite uniformly 41 ft and the minimum bottom width was 300 ft, but the width and cross-sectional area varied considerably in reaches where the channel passes through bends and old slide areas. The nature of the bed and bank material varies from very hard rock to soft rock and clay. Fig. 29 shows the nature of the channel just before water was admitted, superimposed lines indicating the ultimate water level.

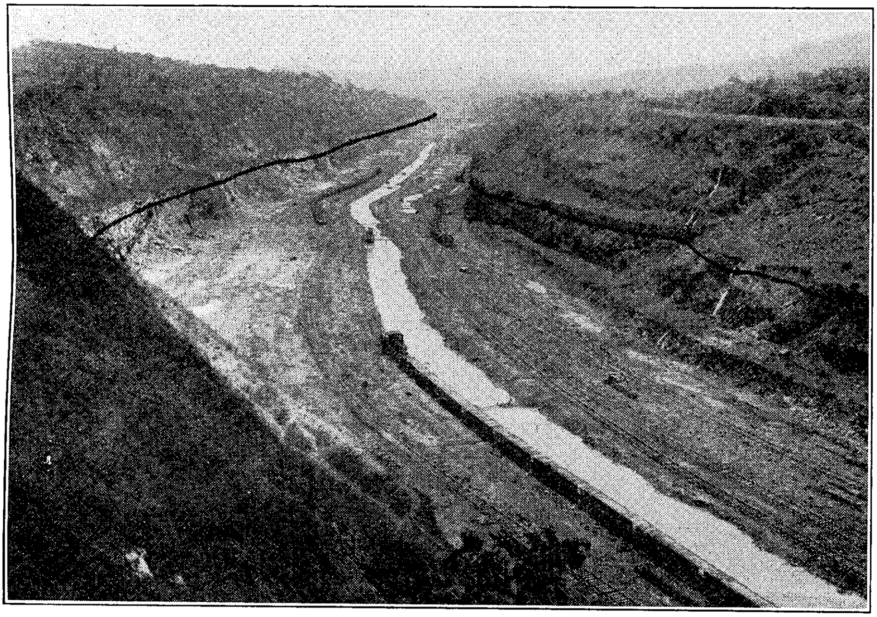

Fig. 29.—Culebra Cut (Later Named Gaillard Cut) at Empire, After the Completion of Excavation

The measurements were made with great care, working at night to avoid interference from traffic and wind, and allowing several hours on each of the two test dates for water levels to become well stabilized. Roughness coefficients for each of the five reaches into which the 7-mile test section was subdivided are very consistent, as shown by Table 20. Observed coefficient values of 0.0265 for the Manning formula, 3.3 for the Bazin formula, and 0.33 for the Kármán-Prandtl formula fall within the expected range. The unmodified Kutter formula, however, gave the high coefficient value of 0.053 because of the very flat slope of 2 in. in 7 miles. An n-value of 0.023 was indicated for the Kutter formula with the slope term omitted.

Selected Value for Roughness Coefficient.—The sea-level canal channel would have a mean hydraulic radius of about 55 ft, and would be cut through a variety of materials ranging from muck to basalt, but at least 87% of the length would fall within the classifications of hard, medium, and soft rock. Therefore, a roughness coefficient representative of a rock surface like that of the existing Gaillard Cut should be used.

The Manning formula was adopted for use in the studies for the improvements of the Panama Canal. The range of Manning roughness coefficients

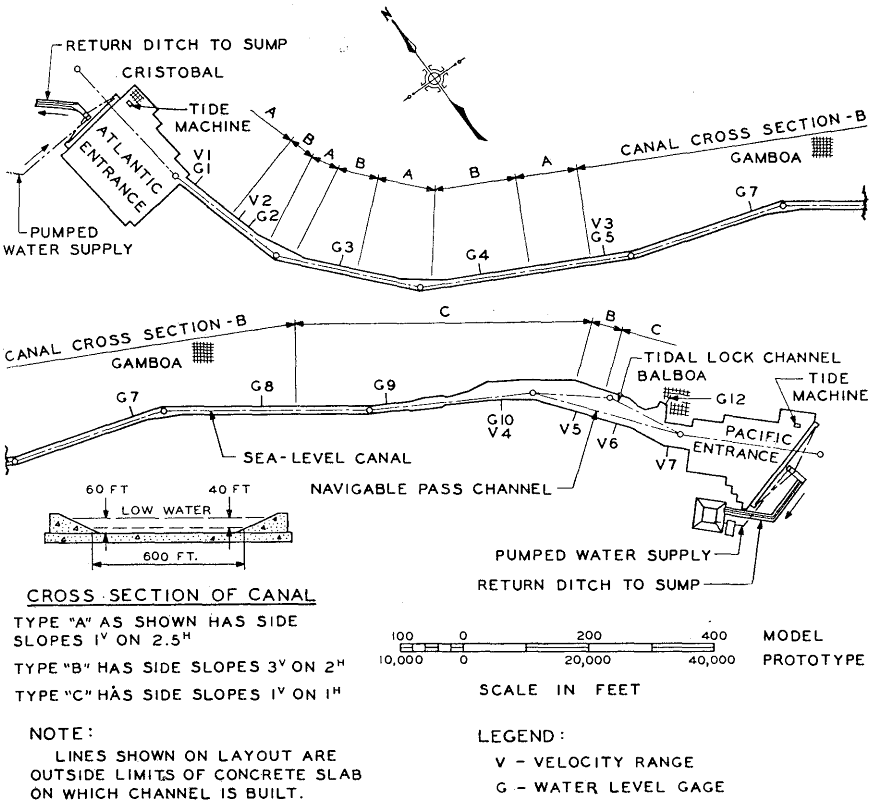

FIG. 30—LAYOUT OF 1:100 MODEL OF PANAMA SEA-LEVEL CANAL

from all sources is generally between 0.024 and 0.031, which include the Gaillard Cut observations of 0.026. A coefficient of 0.024 was selected for the computation of velocities in a sea-level canal, where the use of the highest velocity that could reasonably be expected would result in a more conservative design.

MODEL OF SEA-LEVEL CANAL

Fig. 30 shows the layout for the hydraulic model channel that was built and tested in the Canal Zone for the study of maximum tidal currents and of the general hydraulic problems that would arise in the design and operation of a sea-level canal. The entire length of the proposed 60-ft by 600-ft navigation channel was reproduced, and also the Atlantic and Pacific entrances out to deep water, to insure accurate simulation of flow into and out of the canal. At the scale of 1:100, the model was nearly half a mile long, simulating a total prototype length of about 45 miles and including some 35 miles of restricted channel. Varying side slopes were used, to agree with the design slopes for the different geological materials through which the channel would be cut. The model was built outdoors, with a cover of corrugated sheet metal laid across the top of the channel side walls and roofs over the entrances to prevent disturbance of the water levels by rain and wind.

Model Scale.—The scale of 1:100 was selected because it permitted satisfactory measurement of velocity and of differences in water level and because it was expected to reproduce the flow conditions correctly. Experience with other models had indicated that an ordinary concrete surface in a model of this scale would simulate the roughness of the full-size channel more accurately than would a larger or a smaller model. This expectation was fulfilled when the resistance coefficient for the model channel, measured under conditions of steady flow with differential head equal to that for the maximum tides, was found to correspond to the selected Manning coefficient of 0.024 for the full-size canal, and no adjustments were needed.

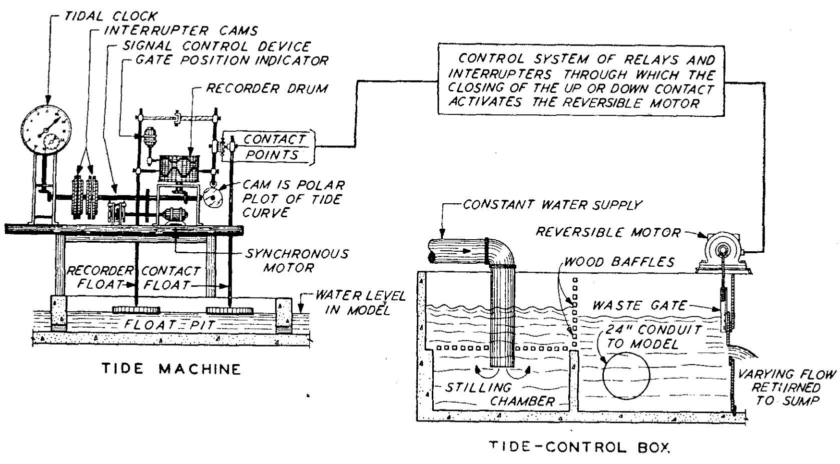

FIG. 31—SCHEMATIC LAYOUT OF TIDE-REPRODUCING APPARATUS, MODEL OF SEA-LEVEL CANAL

The model was built without distortion to insure, as far as possible, that dynamic similitude was obtained, because the absence of an existing prototype prevented making the extensive tests that are essential for the verification of a distorted model. Since gravity is the predominant force in this case, the time, discharge, and velocity factors were used strictly in accordance with the Froude law, which considers gravity as the only factor affecting the motion of the water. Flow at the Atlantic end of the model for maximum tidal conditions would meet the Reynolds' criterion for turbulence about 96% of the time (based on a Reynolds number of 2,000).[22] This situation covers all the critical conditions where accuracy is needed. Regardless of scale, laminar flow cannot be avoided entirely in this model since the velocity must be zero at each reversal of the tide.

Tide Machines.—Tide-control mechanisms were installed at each end of the model to reproduce the tidal variations of the prototype to proper time and height scales. The machines were made by the United States Waterways Experiment Station at Vicksburg, Miss., following the design which had proved satisfactory in other models, and installed at Panama under their supervision of Experiment Station personnel. Figs. 31 and 32 show the tide-

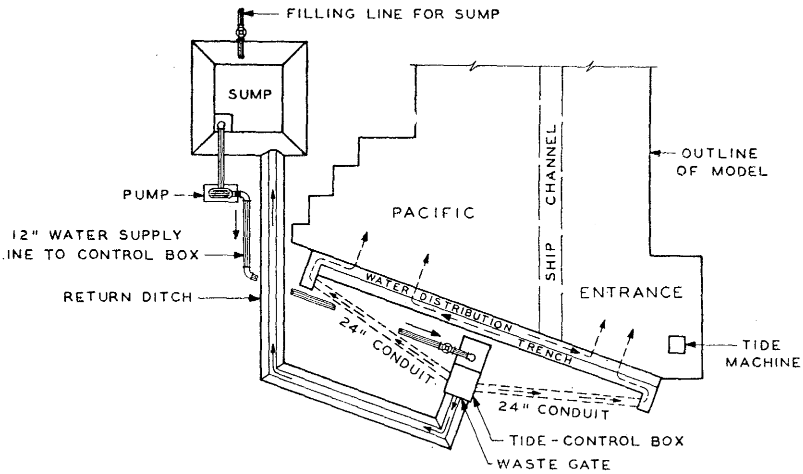

FIG. 32.—WATER-SUPPLY SYSTEM AT PACIFIC END, MODEL OF SEA-LEVEL CANAL

reproducing apparatus and the water-supply system at the Pacific entrance. The solid arrows in Fig. 32 indicate continuous flow in one direction, whereas dashed arrows indicate reversing flow that changes in direction with every change in tide. The basic element of each tide machine is a replaceable cam cut to represent the desired tidal cycle. Mechanical and electronic devices operate a waste gate in the water-supply system which controls the rate of model inflow or outflow so that the actual water surface closely follows the indications given by the cam.

Principle of Tidal-Model Operation.—The principle of operation for this model was to control the water levels at the two ends to follow the desired tides, and to make observations of the water flowing back and forth in the channel under the influence of those tides. Any desired combination of tides could be used, and any desired modifications could be made in the operation of tidal-regulating structures. To observe the effects of any modification, it was always necessary to operate the model through one or more complete tidal cycles, and to coordinate a series of measurements at frequent intervals at a number of locations. This procedure differs essentially from that used on the usual river model, where tests are normally made with steady flows, and

[22] "Hydraulic Models," *Manual of Engineering Practice No. 25*, ASCE, 1942, p. 36.

leisurely adjustments and observations can be made until the experimenter is certain that a test run is satisfactory. To repeat any measurement on a tidal model, however, a full tidal cycle must first be run—which, for a 1:100 scale, requires 1.25 hours—and a crew of observers must then make the desired measurements in as short a time as possible, before conditions change appreciably.

Model Measurements.—Fig. 30 shows the locations at which observations were made in the model. Water levels at the extreme ends were measured by recording gages which form part of each tide machine, and by automatic recorders and manually operated hook gages along the canal channel. Velocities were measured with pigmy current meters of the United States Geological Survey type, which were recalibrated at frequent intervals. For velocities lower than about 0.2 ft per sec (corresponding to full-scale velocity of 2 ft per sec), the meters were supplemented by measurements with floats consisting of corks supporting metal vanes suspended at a six-tenths depth. Observations were made simultaneously by observers at the different stations, at intervals varying from 5 min to 30 min of prototype time—the frequency of the observation depending on its importance and rapidity of change. Electric bells and signal lights were actuated by the tide machines at intervals corresponding to 30 min of prototype time—about 3 min of actual time—to assist in correlating the observations.

Currents in an Open Sea–Level Canal

As previously stated, the maximum current that would be created at the Atlantic end of an open sea-level canal by the combination of 20-ft Pacific and

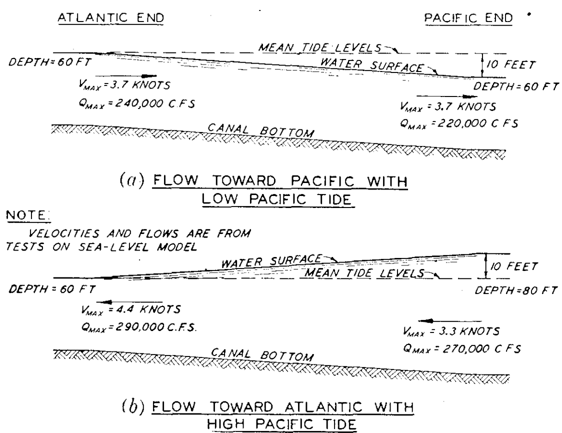

Fig. 33.—Location of Maximum Velocities for Tidal Flow

2-ft Atlantic tides has been indicated as 4.4 knots by the sea-level model, as 4.5 knots by the Pillsbury method of computation, and as 4.6 knots by steady-flow computations.

Location of Maximum Velocity.—Fig. 33, showing velocities and discharges taken from a test on the sea-level model, indicates how the maximum velocity *occurs* at the opposite end of the canal from the strong tide that creates it. The upper diagram indicates conditions for maximum flow toward the Pacific, when depths and velocities are nearly constant throughout the canal. With maximum flow toward the Atlantic, however, as indicated in Fig. 33(*b*), the depths and velocities vary considerably, the discharge is greater, and the highest velocity occurs at the point of smallest cross-sectional area, which is at the Atlantic end of the channel.

Fig. 34 shows water-surface profiles as observed in the model for successive hours during the tidal cycle. The changing slopes indicate the direction and relative velocity of the flow. When the Pacific tide was high (hour 12, Fig. 34), water throughout the length of the canal would flow toward the Atlantic.

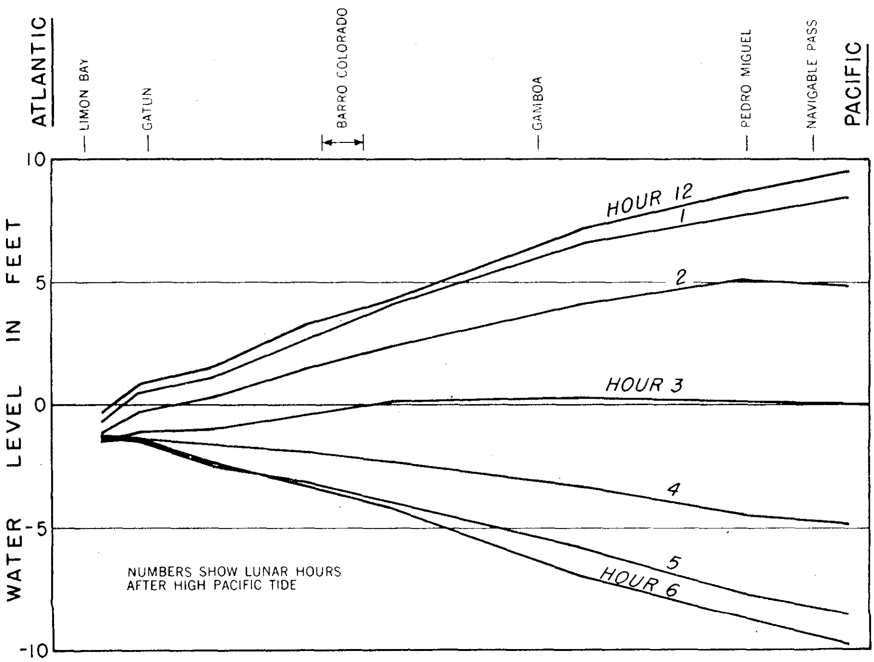

FIG. 34.—WATER-SURFACE PROFILES FOR AN UNREGULATED 20-FT PACIFIC TIDE, MODEL OF AN OPEN SEA-LEVEL CANAL

As the Pacific tide dropped, the flow would slacken and then change direction. For a short period during the change, water would flow out of each end of the canal, and then the flow throughout the canal would gradually increase to maximum strength toward the Pacific (hour 6, Fig. 34). A similar sequence of flows in the opposite direction would occur during the next half-cycle of 6 hours while the tide returned to its starting point. The current in the canal would always vary gradually and continuously with no abrupt differences, and would always change direction every 6 hours. A sinusoidal curve would be a good representation of the velocity at any point.

Comparison of Model Velocities and Computed Velocities.—Fig. 35 shows the observed velocities for unregulated tidal flow at the measuring stations nearest the ends of the model, and also the velocities as computed by the Pillsbury method when carried to different degrees of refinement. The agreement is very close throughout the tidal cycle as well as at the maximum points. The "second adjustment" computations which show the best agreement were carried out only for the combination of 20-ft and 2-ft tides. For most of the analyses

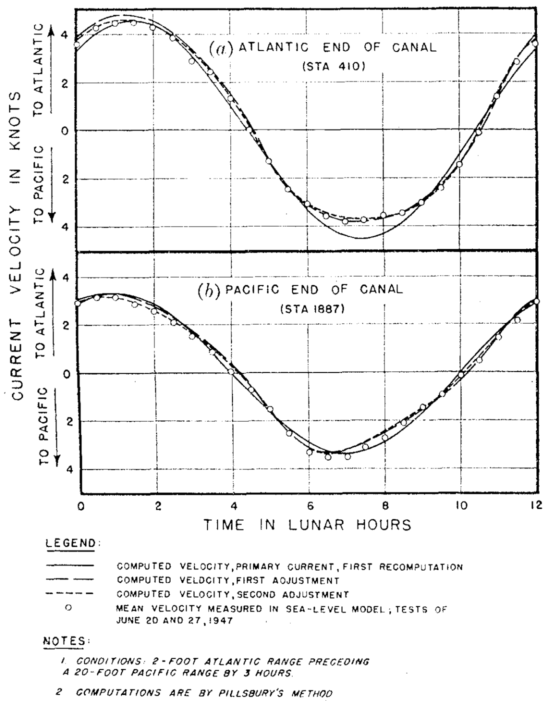

FIG. 35.—COMPUTED AND OBSERVED CURRENT VELOCITIES, UNREGULATED SEA-LEVEL CANAL

the simpler "primary current" computation was used, which agrees very closely for the maximum velocities and is approximate only for the less important smaller velocities. In applying his computation method to an example of tidal flow in a Panama sea-level canal, General Pillsbury (in a letter to The Panama Canal, dated February 1, 1946) has concluded:

> (1) " * * * that the corrections produced from the somewhat extensive computations required for the second adjustment are quite small and are in fact well within the uncertainties inherent in the selection of the proper coefficient of roughness, and in the dimensions of the canal as actually dredged, and as eroded by the strong currents";

and that

> (2) " * * * primary currents afford a reliable indication of the magnitude of the currents to be expected in an open sea-level canal across the Isthmus."

Table 21 shows a summary of computed (the Pillsbury primary current) and model velocities for the open sea-level canal. All velocities are the maxima reached during the tidal cycle. The model values listed are the average of velocities measured at seven points across the width of the channel. Velocities at the center of the canal (measured at six-tenths depth) are about 5% greater than these averages.

TABLE 21.—COMPARISON OF COMPUTED AND MODEL VELOCITIES FOR MAXIMUM TIDAL CURRENTS IN UNREGULATED SEA-LEVEL CANAL

Tidal Range (Ft)		Computed velocity at Atlantic end (knots)	Observed Velocity in Model (Knots)	
Pacific	Atlantic		Atlantic end	Pacific end
20	2	4.5	4.4	3.7
16	1	4.0	3.8	3.0
13	1	3.5	3.3	2.5
10	1	3.0	2.7	2.0
6	1	2.1	2.1	1.5

Fig. 36 shows, for any time during a tidal cycle and for any position along the channel, the velocity that would be found at that point. The "contours," which were drawn beween values observed for several cycles in the sea-level model, indicate the regimen of velocity for the combination of 20-ft Pacific tides and 2-ft Atlantic tides. Sets of diagrams of this kind, for the full range of tides, have been useful in navigation studies, since lines can be drawn upon them to represent ship transits at different speeds and directions.

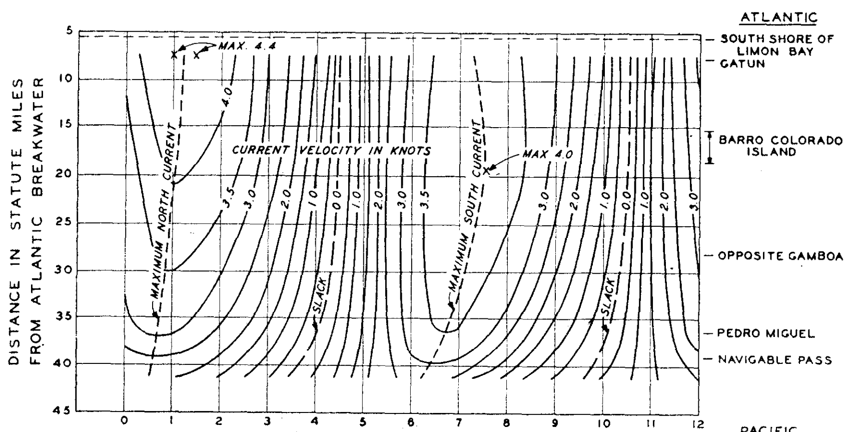

FIG. 36.—TIME-POSITION-VELOCITY DIAGRAM; UNREGULATED FLOW, 20-FT PACIFIC TIDE

New Flow Toward the Atlantic.—An indicated in Fig. 33, there would be a greater flow toward the Atlantic during half of each tidal cycle than toward the Pacific during the other half. The water in the channel would move alternately toward the Atlantic and then toward the Pacific with the changing tides, with a net advance of about 5 miles per day toward the Atlantic indicated by the model for the 20-ft and 2-ft tides. For the same tidal ranges, but with the Pacific mean level higher than the Atlantic mean level, the total movement would increase. The most extreme situation of this kind which was found was that of December 19, 1937, when the 19.44-ft Pacific tide range averaged 1.74 ft higher than the Atlantic mean level, and the computed net movement of water (a second adjustment computation made by General Pillsbury) would have been about 20 miles per day.

Comparison of Steady-Flow and Tidal-Flow Velocities.—Table 22 compares maximum velocities for steady flow and tidal flow for different tidal ranges, as observed in the sea-level model. With minor exceptions (which are attributable to experimental error), steady-flow velocities are slightly higher. Computed velocities for steady flow agree closely with model results. The data support the opinion that tidal velocities should not exceed velocities for steady flow between the corresponding extreme water levels. Velocity computations on the assumption of steady flows are not difficult to make, but this procedure indicates only the maximum velocity in either direction. The Pillsbury method, on the other hand, provides successive values for velocities and water levels at all times during the tidal cycle. For this reason it was generally used as the basic computation method for analytical studies of velocities in the sea-level canal.

TABLE 22.—TIDAL–FLOW VELOCITIES AND STEADY–FLOW VELOCITIES IN SEA–LEVEL MODEL

Water Levels				End at which velocities are measured	Maximum Velocity (Knots) for:			
For Tides		For Steady Flow			Flow to Atlantic		Flow to Pacific	
Feet (1)	End (2)	Feet (3)	End (4)	(5)	Steady (6)	Tidal (7)	Steady (8)	Tidal (9)
20	Pacific	±10	Pacific	Atlantic	4.6	4.4	3.5	3.7
2	Atlantic	0	Atlantic	Pacific	3.7	3.3	3.8	3.7
16	Pacific	± 8	Pacific	Atlantic	3.7	3.8	3.3	3.4
1	Atlantic	0	Atlantic	Pacific	3.3	2.8	3.4	3.0
13	Pacific	± 6.5	Pacific	Atlantic	3.3	3.3	3.0	3.1
1	Atlantic	0	Atlantic	Pacific	2.9	2.4	3.0	2.5
10	Pacific	± 5	Pacific	Atlantic	3.0	2.7	2.6	2.5
1	Atlantic	0	Atlantic	Pacific	2.4	2.0	2.6	2.0
6	Pacific	± 3	Pacific	Atlantic	2.4	2.1	2.0	1.8
1	Atlantic	0	Atlantic	Pacific	1.7	1.5	2.0	1.4

Minor Velocity Reduction by Channel Enlargement.—As has been indicated in Fig. 33, the maximum tidal current in a sea-level canal with constant width and constant depth below a line connecting the low water levels would occur at the Atlantic end where the cross-sectional area is least. This velocity could be decreased to some extent by deepening or widening the canal at the Atlantic end. Any such enlargement, however, would increase the total flow capacity of the channel, and the velocities would be increased throughout the tidal cycle in the part of the channel not enlarged.

The greatest reduction in velocity could be obtained by a gradually tapered enlargement for about two thirds of the length of the canal, starting near Gamboa and extending to the Atlantic end, where the cross section would need to be enlarged by 16%. The maximum current for a 20-ft Pacific tide could be reduced from 4.5 knots (as computed by the Pillsbury method) to 4.0 knots which would then prevail for most of the length of the canal—the current at the Pacific end being increased while that at the Atlantic end was decreased.

Currents in a Regulated Sea-Level Canal

Reduction of Current by Tidal-Regulating Structures.—Tidal currents in a sea-level canal could be regulated effectively by the structures shown in Fig. 9. The maximum current could then be regulated to any desired limiting value between 0.5 knots and 4.5 knots. The value of 0.5 knot would be the current produced by the action of a 2-ft Atlantic tide in a canal closed at the Pacific end, and the value of 4.5 knots would be that produced by the combination of 20-ft Pacific and 2-ft Atlantic tides in the open channel. Fig. 37 shows the

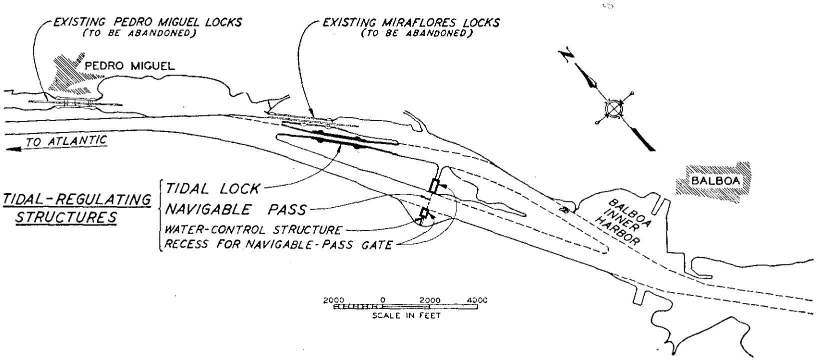

FIG. 37.—LAYOUT OF TIDAL-REGULATING STRUCTURES

proposed layout for a tidal lock and navigable pass. The pass would normally be closed when the tide was at a high level or a low level to exclude the entry of tidal flow into the canal which would cause currents in excess of the selected maximum value. Ships would use the tidal lock when the navigable pass was closed.

Fig. 38 shows schematically the operation of the regulating structures during a tidal cycle. The action of such structures may be considered as replacing the natural Pacific tide (range A-D, Fig. 38) with a smaller regulated tide (range B-C) on the canal side of the structures which would produce currents not exceeding the selected limits. For a 2-knot limit the regulated tide would be about 6 ft. For a higher limiting current, the regulated range would be greater and the navigable pass could be kept open longer. The water level in the canal would return approximately to Atlantic tide level if no water were released through the tidal-regulating structures after point C, Fig. 38. Reopening of the navigable pass would then be delayed beyond point E until the natural tide level rose to meet the canal level. The function of the water-control structure is to permit the release of a limited flow of water from the canal to the Pacific during this period and to bring the canal level to the desired elevation at point E. The navigable pass could then be opened promptly on schedule,

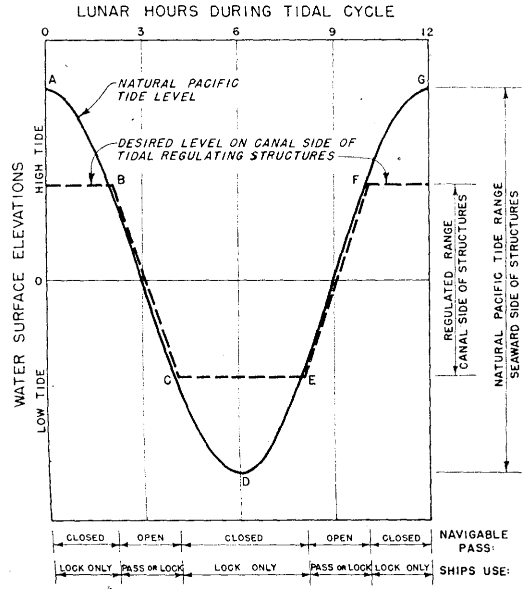

FIG. 38.—OPERATION OF TIDAL-REGULATING STRUCTURES

and would stay open for a longer total time. A similar sequence of events, but in the opposite direction, would occur during the remaining half of each tidal cycle.

On the basis of the idealized conditions indicated in Fig. 38, the permissible ranges of water levels on the canal side of the tidal-regulating structures were

TABLE 23.—DAILY AVAILABILITY OF NAVIGABLE PASS

Permissible current (knots)	Hours per Day Navigable Pass Could Remain Open for Pacific Tidal Ranges of:				
	6 ft	10 ft	13 ft	16 ft	20 ft
1	8.5	4.5	3.5	2.9	2.3
2	20.2	9.7	7.2[a]	6.0	4.9[c]
3	24	24	14.9[b]	11.6	9.1[d]
4	24	24	24	24	19.8
4.5	24	24	24	24	24

[a] In model test, pass was kept open 8 hours per day. [b] In model test, pass was kept open 16 hours per day.
[c] In model test, pass was kept open 3.8 hours per day. [d] In model test, pass was kept open 8 hours per day.

computed for different velocity limits in the canal. If the controlled water level can range the vertical distance between points E and F, then the period when the pass could remain open is the horizontal distance along the time scale between points E and F, which will vary with the rate of rise of the natural tide. This analytical indication of the relation between controlled velocity, natural tide range, and time of opening is summarized in Table 23, which shows hours per day when the navigable pass would be available for traffic.

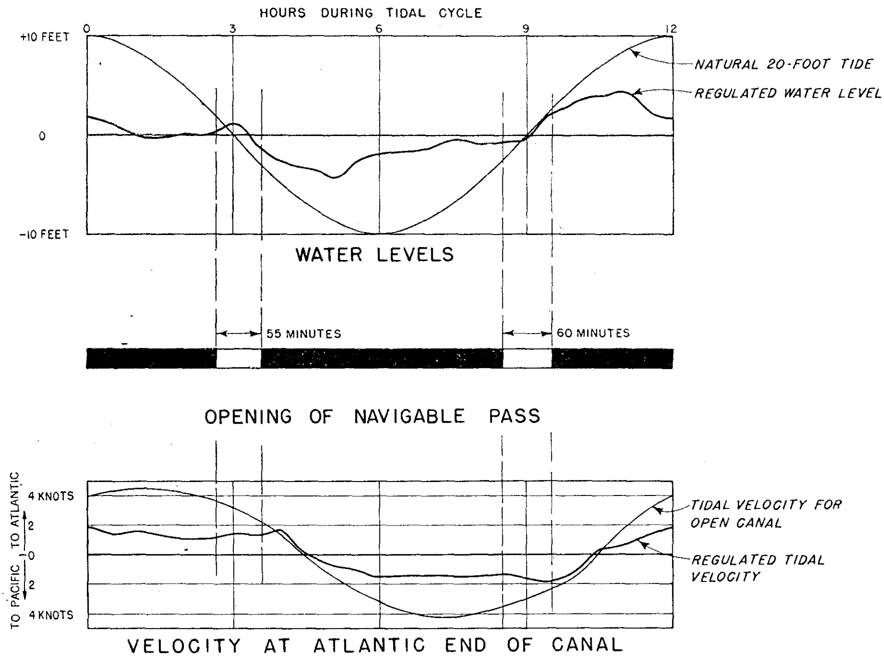

FIG. 39.—MODEL TEST; REGULATION TO 2 KNOTS, 20-FT PACIFIC TIDE

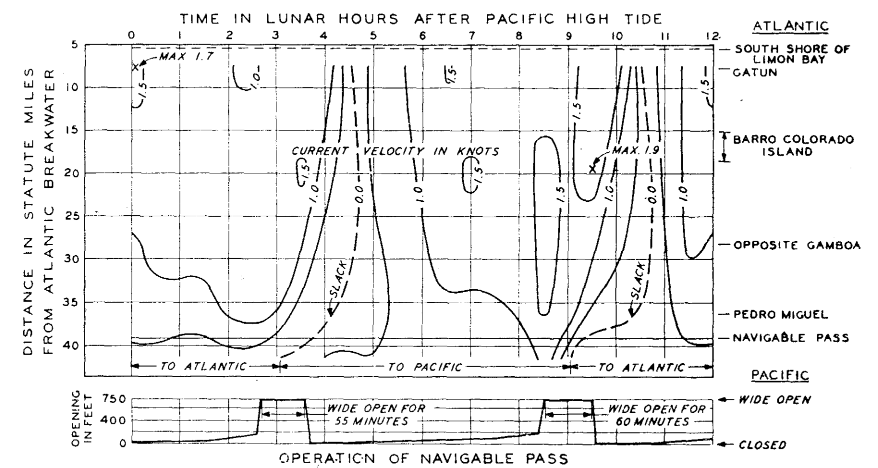

FIG. 40.—TIME-POSITION-VELOCITY DIAGRAM; 2-KNOT REGULATED CURRENT; 20-FT PACIFIC TIDE

Regulated Flow in Sea-Level Canal Model.—Fig. 39 shows one cycle of model test observations for current regulated to a maximum of 2 knots with a 20-ft

Pacific tide, for which the navigable pass remained open for one 55-min period and for one 60-min period during each 12 hours. In this test the navigable pass was used for flow regulation instead of the water-control structure. The regulated velocities are shown also in the time-position-velocity diagram of Fig. 40. Comparison with the similar diagram (Fig. 36) for unregulated tidal velocities shows much the same general velocity pattern, but, of course with reduced maximum values. The model tests made thus far (October, 1947), which have also covered other tidal ranges and velocity limits as indicated in Table 23, have demonstrated the possibility of controlling currents and keeping the pass open for periods approximating the computed values. Additional testing and analysis of model results will be necessary, however, to provide data for gate schedules for routine daily operation of the canal.

SHIP PERFORMANCE IN RESTRICTED CHANNELS

By C. A. Lee[23] and C. E. Bowers,[24] Juniors, ASCE

Synopsis

The purpose of the restricted channel model tests at the David Taylor Model Basin was to obtain information which would be of assistance in the selection of the cross-sectional dimensions and in the design of bends for specified conditions of canal operation. The tests were sponsored by the Panama Canal under the authority of Public Law No. 280, Seventy-ninth Congress. The model studies included:

1. An investigation of the effect of varying the cross-sectional dimensions of the channel for both one-way and two-way traffic;
2. The comparative handling characteristics of several different types of ships under various conditions;
3. The effect of current in the channel on the handling characteristics of the ships; and
4. A comparison of several types of bends.

The first tests were conducted with a single ship in a straight channel and in still water. The experience gained from these tests is fundamental to a complete understanding of the more special problems which follow the description and the results of the straight channel, still-water, one-way traffic conditions.

TABLE 24.—General Information Concerning Models Tested in Restricted Channels

Model No.	Scale ratio, λ	Dimensions of Model (Ft)			Dimensions of Full-Scale Ship (Ft)			Propellers		No. of rudders
		Length[a]	Beam	Draft	Length[a]	Beam	Draft	No.	Rotation	
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
3769......	45	20.00	2.51	0.717	900	113	32.25	4	Outward	2
3859......	35	20.58	2.855	0.914	720.6	100	32.13	2	Outward	1
3992......	86	10.00	1.256	0.4025	860	108	34.625	4	Outward	2
3748-4....	45	10.01	1.33	0.6326	455	59.84	24.48	1	Right hand	1
3673-A....	44.5	20.00	2.585	0.815	890	115	36.27	4	Outward	2
4018......	45	16.00	2.221	0.714	720.6	100	32.13	2	Outward	1

[a] Water-line length of loaded vessel.

It was thought that the two primary problems in the selection of canal characteristics were (*a*) the controllability of full-scale ships operating at selected speeds in the canal, and (*b*) the change of level of ships in the canal.

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The controllability of full-scale ships from model studies appeared to be the more difficult to evaluate and as a result the test program emphasized this part of the studies.

The models representing larger ships were selected for test on the basis of difficulty of handling in restricted channels. The model of a "Liberty" ship was selected for test as representing an average ship transiting the canal. A particular object of study was to discover the effects on the Liberty ship when meeting and passing the larger vessels. Table 24 gives general background information on the various ship models used during the investigation.

NOTATION

Referring to Fig. 41, let: b_y be the distance from the center line of the channel to the gravity center of the ship (point G); b_z be the distance between the gravity center of the ship and the prism line; V_c be the water speed; V_s be the ship speed (with respect to water); δ be the rudder angle; λ be the scale ratio; and ψ be the angle of yaw. In the restricted channel investigations, Froude's law is used as a basis for adjusting velocity, rate of change of rudder, and revolutions per minute on the propellers, to produce conditions similar to full-scale operations. Froude's law sets forth a nondimensional parameter which is used for model studies in which gravitational influences predominate. Another nondimensional parameter used to express the effect of viscosity on the flow about a vessel is the Reynolds number, **R**.

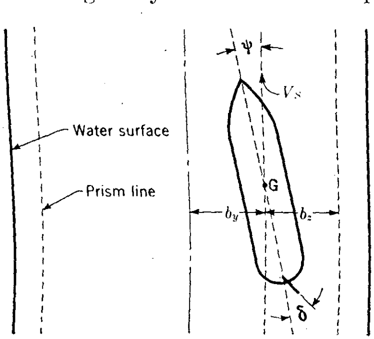


FIG. 41

The model vessels and the models of the restricted channels were constructed geometrically similar for the various test conditions—that is, all linear dimensions were reduced directly in accordance with the selected scale ratios. Under these circumstances the flow characteristics (velocity and pressure) would be similar if the fluid properties were such that the Froude and Reynolds numbers, respectively, are equal for model and full-scale conditions in all cases. The Froude number, which allows for the influence of gravitational forces, may be defined as:

$$\mathbf{F} = \frac{V^2/a}{\gamma/\rho} \qquad (1)$$

The Reynolds number, which allows for the effect of viscosity, is

$$\mathbf{R} = \frac{V\,a}{\mu/\rho} \qquad (2)$$

in which V is the velocity, in feet per second; a is a convenient linear dimension, in feet, defining a fixed boundary condition; γ is the specific weight, in pounds per cubic foot; ρ is the density in slugs per cubic foot; and μ is the dynamic viscosity, in pound-seconds per square foot.

The effects of viscosity will not be large enough to read by scale if the Reynolds number is so small that a large part of the boundary layer is laminar rather than turbulent. The actual size and scale ratios of the models used in this investigation insure that the Reynolds numbers are large enough to preclude the scale effects produced by viscosity. Consequently, it was only considered necessary to employ the same Froude number for the model as for the full-scale condition. Thus, the following relationships for time rates and velocity result:

(1) Time rates for the model (that is, rate of rudder movement, revolutions per minute of the propellers, rate of calling orders from "pilot" to "quartermaster," and any other time rates) should equal the time rates for the various elements on the full-scale ship multiplied by the square root of the linear ratio.

(2) Velocity for the model (that is, speed of the model ship and velocity of the water in the channel during moving water studies) should equal the velocity of the full-scale vessel divided by the square root of the linear ratio.

Ship-Handling Considerations in Restricted Channels

Navigation in restricted channels or canals is very difficult, not only because of the limited space available but also because of various hydrodynamic phenomena that introduce additional hazards. One of these phenomena is popularly referred to as "bank suction." Bank suction occurs when a vessel is closer to one side of a restricted channel than it is to the other side 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. As a result of this effect, an asymmetrical flow distribution develops on the two sides of the vessel, creating unbalanced forces which tend to force the vessel off its original course. If the vessel is under way in a restricted channel, on a course parallel to but to one side of the center line 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 instances 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 this effect. Thus, if a large vessel were near the right bank, it would be necessary 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 heading of the vessel can be 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 this heading is maintained for a time, the vessel will move bodily into the near bank. However, if the vessel is given a slight angle of yaw away from the near bank and a rudder angle just sufficient to counteract the yawing moment, both the side force and moment will be neutralized and the vessel will maintain a path parallel to the bank.

Another hydrodynamic phenomenon that may be serious during the transiting of vessels through restricted channels is the change of level of the vessel. When the vessel is under way in shallow water or in a restricted channel, the water surface in the vicinity of the vessel drops below the level of the normal water surface because of the increase in the velocity of the water as it flows around the vessel, and the vessel drops with it. If the initial draft of the vessel is quite large with respect to the depth of water in the channel, the ship may touch bottom if under way at relatively high speeds, whereas it would have ample clearance if it were stationary or traveling at a low speed. The magnitude of this change of level is a function of the ship speed, the dimensions and lines of the ship, and the channel dimensions.

Studies of One-Way Traffic

Relative to the straight-channel, one-way traffic, still-water studies of ship performance in restricted channels, primary emphasis was placed on an investigation of (*a*) the relative controllability of specified ships in channels of various cross-sectional dimensions, and (*b*) the change of level of ships in restricted channels. Another factor that may be of general interest, but which was 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. Information on ship resistance in shallow water is available in several places.[25,26,27,28,29,30,31,32] Most available information on ship resistance in restricted channels appears in papers by G. S. Baker,[33] Francis Roubiliac,[34] F. E. Nelson,[35] and T. Izubuchis and S. N. Z. Kidkai,[36] although additional data on barges have been obtained.

[25] "Model Studies of Ship Motions in Canals," by Charles E. Bowers, David Taylor Model Basin, Washington, D. C., November, 1946.

[26] "Barge Canals—Dimensions," by J. M. Rankine, *Encyclopædia Brittanica*, 14th Ed., 1929, Vol. 4, pp. 720–727.

[27] "The Relation of Depth of Water to Speed and Power of Ships," *Engineering News*, Vol. 53, 1905, pp. 275–276.

[28] "Der Schiffswiderstand im bergrenzten Fahrwasser und sein Einfluss auf die Grössenverhältnisse der Schiffahrtskanäle" (On Ship's Resistance in Limited Waters and Its Effect on the Relationships Between the Sizes and the Channel), by M. Graevell, *Der Civil Ingenieur*, 1887, pp. 87–110.

[29] "The Influence of Depth of Water on the Resistance of Ships," by Charles P. Paulding, *Marine Engineering*, May, 1903, pp. 239–243.

[30] "The Resistance of Some Merchant Ship Types in Shallow Water," by Herbert C. Sadler, *Transactions*, Soc. of Naval Architects and Marine Engrs., Vol. 19, 1911, pp. 83–86.

[31] "Modell-Schleppversuche für Lastkähne im Kanalprofil" (Model Towing Tests for Barges in the Channel Profile), by Karl Schaffran, *Schiffbau*, Vol. 16, No. 13, 1914/1915, pp. 321–326.

[32] "A General Discussion of Resistance and Power Consumption of Ships in Different Depths of Water," by David W. Taylor, *Engineering News*, Vol. 53, 1905, pp. 276–279.

[33] "Steering of Ships in Shallow Water and Canals," by G. S. Baker, *Transactions*, Institution of Naval Architects, Vol. 66, 1924, pp. 319–340.

[34] "Speed of Canals," by Francis Roubiliac, *Minutes of Proceedings*, Inst. C. E., Vol. 76, 1884, pp. 160–265.

[35] "Handling Vessels in Restricted Waters," by F. E. Nelson, *Proceedings*, U. S. Naval Inst., June, 1928, pp. 446–456.

[36] "Experimental Investigations on Influence of Depth of Water Upon Resistance of Ships," by T. Izubuchis and S. N. Z. Kidkai, *Paper N4 Autümwerting*, Soc. of Naval Architects—Japan, 1937 (in Japanese).

An investigation of the controllability of ships in restricted channels is necessarily quite complex. It involves the effect of interaction between the vessels and the channel boundaries (bank suction), the steering characteristics of the vessel, and the effect of the restricted channel on the steering characteristics of the vessel. If an attempt is made to maneuver the model in a manner similar to the 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 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 under way 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 moving water. The side force and 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 interaction was determined.

Observational Tests.—The observational tests were conducted in a Taylor Model Basin facility known as "the shallow water basin." This basin consists of a concrete-lined channel, 52 ft wide, 10 ft deep, and approximately 300 ft long. Fig. 42 is a photograph of the basin. The central part 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° 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 in Fig. 42, is operated by distant control from the special platform under the towing carriage. The water depth can be set at any value up to 10 ft. 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 (1) to tow models that are being tested for resistance or other performance characteristics; (2) to provide a movable observational and photographic platform, and power supply, for studies of self-propelled models; and (3) to accelerate self-propelled models to the desired speed in a short time. The two steel walls were placed on the floor of this basin to form a smaller channel. The over-all length of this channel was 180 ft, which is equivalent to approximately 1.5 miles of full-scale channel. Its width could be varied from 0 to 23 ft. The side slope of the walls could be varied from an angle with the horizontal of from 18.25° to 90°. During the observational phase of the tests, the walls were set at an angle of 45°. Fig. 43 is a photograph of a model running through a restricted channel 60 ft deep and 300 ft wide with side walls set at 45°. The "pilot" issues orders to the helmsman who steers the self-propelled model by the remote-control rudder gear located on the lower platform of the towing carriage. The flexible cable at the stern carries the electrical leads and is held in position by the movable boom. The reflector mounted

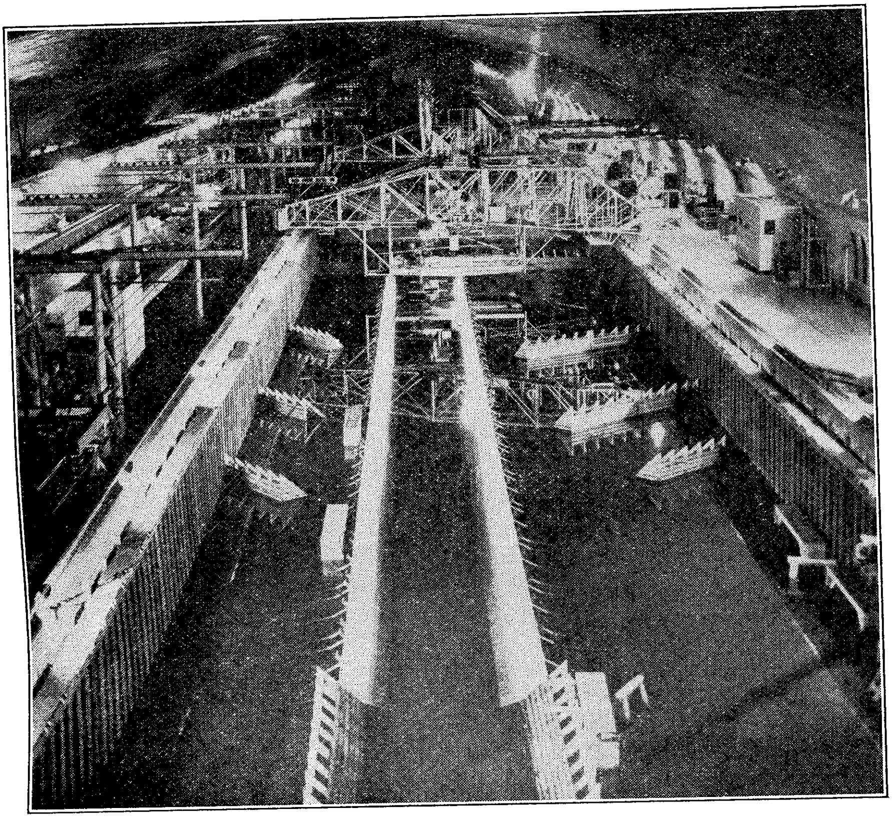


FIG. 42.—GENERAL VIEW OF BASIN BUILDING, SHOWING THE RESTRICTED CHANNEL SETUP IN THE SHALLOW WATER BASIN

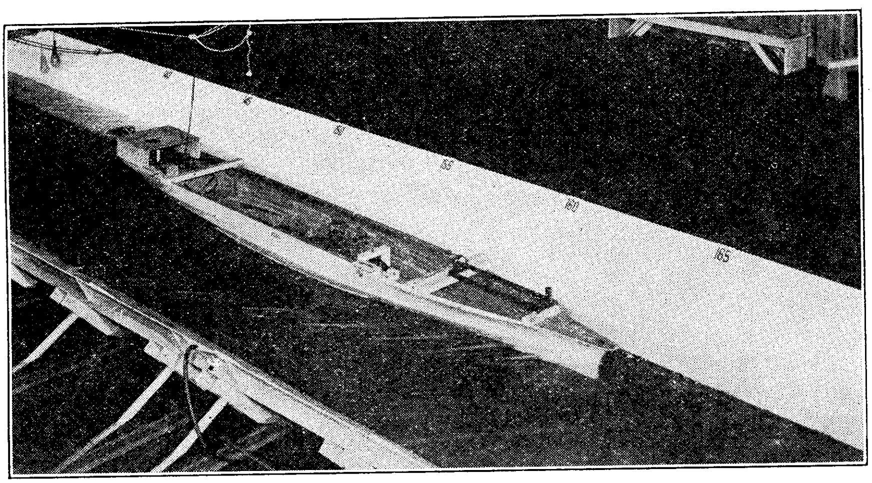


FIG. 43.—MODEL 3769 UNDER WAY IN A STRAIGHT CHANNEL

near the bow casts a beam of light on a horizontal scale at the far end of the channel, thus giving the pilot a good indication of changes in the ship's heading.

The tests in this shallow water basin were conducted using Taylor Model Basin models 3769, 3748-4, and 4018; and they represented channels of 300 ft, 500 ft, and 700 ft wide at the bottom with a 1:1 side-wall slope. Each width was tested with depths of water of 45 ft, 60 ft, and 80 ft. The scale ratio for the model studies was 1:45. On the basis of Froude's law, the model speed during the tests was equal to the full-scale speed divided by the square root of 45. For example, the model speed corresponding to 10 knots full scale was 10 divided by 6.71, or 1.49 knots.

Two types of observational tests were conducted. One type (referred to as the "rudder release tests") was for the purpose of obtaining a comparison of the bank suction or interaction for various off-center positions of the ship in the channels. The nature of the tests was such that the magnitude of the yawing moment, caused by interaction between the ship and the channel boundaries, was obtained in terms of the rudder angle required to counteract it.

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 that can be used is approximately 35°. Thus, if the rudder angle required to counteract the bank suction or interaction, for some specified condition, is from 25° to 30°, 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, in some instances, is that the turning moment developed by the rudder may not be directly proportional to the rudder angle at large rudder angles.

In conducting the first type of observational tests, the model was attached to the towing carriage by two pins which held the longitudinal axis of the model parallel to the center line of the model canal channel. The towing carriage was then accelerated to the desired speed and at the same time the speed of the propellers of the model was increased to that 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 that supplied power to the propeller 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 2-in. beam of light along an extension of the model center line to a horizontal scale at the end of the channel. By observing the movement of the beam, the observer could note, instantly, the 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, thus providing the maximum length of the channel available for observation of the unrestrained model. The model was attached to the towing carriage on a line parallel but to one side of the center line. If the rudder had previously been set at zero, it would be noted that the model sheered away from the near wall on release from the carriage. As soon as this sheer was observed, the model and carriage were stopped and the model was again attached to the carriage at the same off-center position. Before releasing it a second time the rudder would then 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 would be increased. This procedure was repeated until a rudder angle was selected which would just counteract the yawing moment caused by the interaction. 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 was 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.

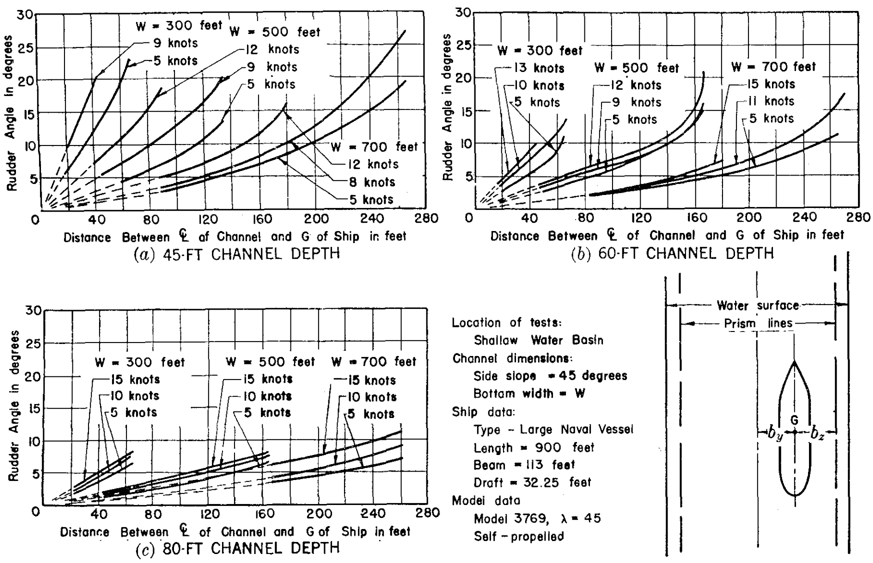
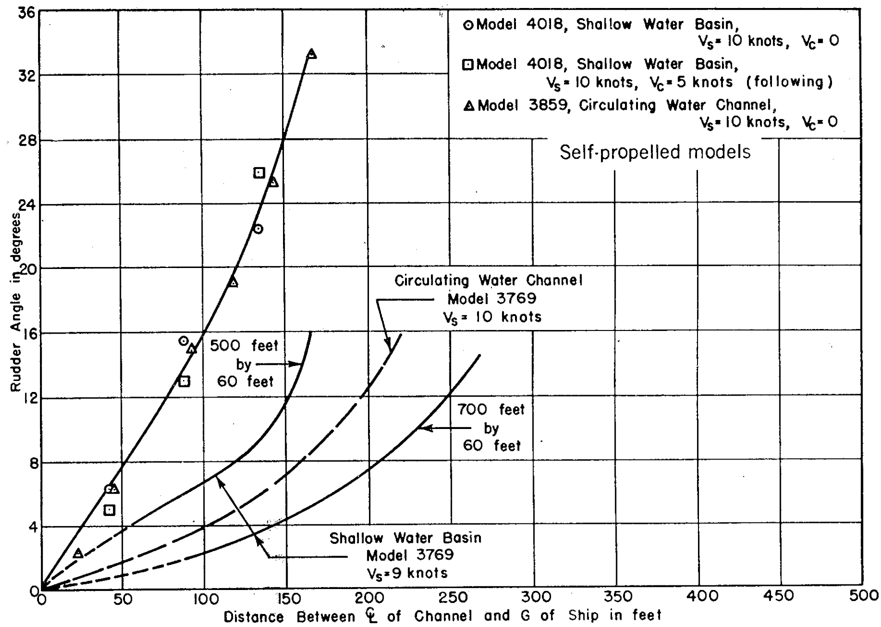


FIG. 44.—RUDDER ANGLE FOR EQUILIBRIUM AS A FUNCTION OF THE DISTANCE BETWEEN THE CENTER LINE OF THE CHANNEL AND THE CENTER OF GRAVITY (POINT G) OF THE SHIP

Fig. 44 is a plot of the rudder angle required to counteract interaction or bank suction against distance between the center line of the channel and the center of gravity of the ship. Specifically, these rudder angles are required to counteract the yawing moment that exists when self-propelled model 3769 is released parallel to, and at various distances from, the center line of the channel. Data for several channel widths and ship speeds have been plotted on each graph for purposes of comparison. For a given speed the distance that the ship can navigate off center in the channel without exceeding a specified rudder angle may be selected for each channel width. It may be noted from these data that the rudder angle required to counteract the effects of interaction is especially dependent on the ship speed at a 45-ft depth. Furthermore, the slope of these curves, or the rate at which the rudder angle increases, is much steeper at the shallower depths and narrower widths. In most instances the rudder angle for equilibrium was measured for at least three off-center positions of the ship. These positions were varied for each width of channel so as to cover the proper range of rudder angles. For selected channel widths and ship speeds, the curves are indicative of the effect of channel depth on the



	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

FIG. 45.—RUDDER ANGLE FOR EQUILIBRIUM AS A FUNCTION OF THE DISTANCE BETWEEN THE CENTER LINE OF THE CHANNEL AND THE CENTER OF GRAVITY (POINT G) OF THE SHIP

yawing moment caused by interaction. It may be noted that, for the 300-ft width, the yawing moment caused by interaction at a channel depth of 60 ft is less than half as great, in terms of rudder angles, as it is for the 45-ft depth. An increase in depth from 60 ft to 80 ft causes a further decrease in the required rudder angle but the additional change is much smaller. For channel widths of 500 ft and 700 ft, there is a similar decrease in the required rudder angle with increasing depth.

Subsequently, additional tests were conducted on the model of the naval vessel as well as on models of a large tanker and a Liberty ship. Some of these tests were conducted in moving water for the purpose of checking the effect of currents in the channel on the interaction between the ship and the channel boundaries. Others were conducted in the circulating water channel for the purpose of comparing results between that facility and the shallow water basin. The results of some of these tests are presented in Figs. 45 and 46.

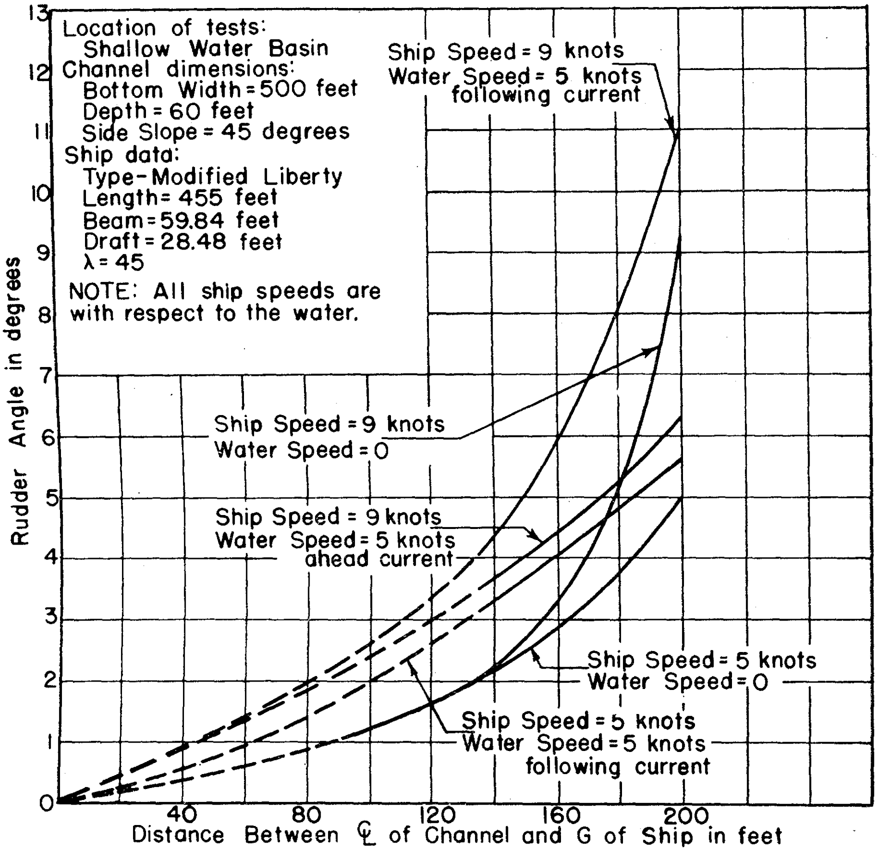


FIG. 46.—RUDDER ANGLES FOR EQUILIBRIUM AS A FUNCTION OF THE DISTANCE BETWEEN THE CENTER LINE OF THE CHANNEL AND THE CENTER OF GRAVITY (POINT G) OF THE SHIP

With reference to Fig. 45, the data for model 3859 (tanker) in the circulating water channel were obtained by holding the model stationary at various transverse positions in a moving stream of water. The test methods are described in the section entitled "Force-Measurement Tests." Similar data were obtained in the shallow water basin, by the methods just described, for both still water and currents. The data indicate that the two facilities produce nearly identical results. Also, the interaction between the ship and the channel boundaries is apparently the same for both still and moving water at the same ship speed with respect to the water.

In Fig. 46, data are shown for the rudder angles required to counteract interaction for a Liberty ship in both still and moving water. (These data are based on self-propelled tests of model 3748-4. The rudder angles are required to counteract the yawing moment that develops when the ship is nearer one wall then the other.) For the same ship speed with respect to the water, the curves indicate that the rudder angles are dependent on the current. However, the maximum difference between the curves for practical operating conditions is less than 3°, which is not considered significant in view of the limited amount of data obtained on this model.

A second type of observational test was based on maneuvering a self-propelled model by remote control. Throughout the tests an effort was made to duplicate full-scale operating conditions as closely as possible. In these tests, the model, when accelerated to the desired speed, was 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. By observing the movement of the beam of light from the bow, the observer or pilot could note, instantly, any 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 center line of the channel. On orders from the pilot, an assistant manipulated the controls which actuated the rudder. Soon after the model was released from the carriage, it was photographed at intervals of about 1 sec 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, an attempt was made to maintain a course parallel to, and at a specified distance from, the center line, as well as directly on the center line of the channel. This procedure differs somewhat from actual full-scale operating conditions in that the pilots usually attempt to stay on the center line of a canal except when meeting another ship. However, it was thought that the off-center runs might provide additional information. Maneuvering runs were taken at about three transverse positions in channels with bottom widths of 300 ft and 500 ft and with depths of 45 ft, 60 ft, and 80 ft. An attempt was also made to conduct separate runs for various speeds ranging from 5 knots to 15 knots, but in numerous instances it was not possible to reach the top speed of 15 knots because of excessive change of level of the model or because of other hazardous operating conditions.

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-ft and 80-ft 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-ft depths. This condition was especially noticeable at channel widths of 300 ft and 500 ft.

During these tests (which were made to find the maximum off-center distances at which specified ship models could be satisfactorily maneuvered), certain phenomena were allowed to develop and the resultant action of the vessel was observed. It was noted that, in any off-center position in the channel, if the bow was allowed to swing a few degrees away from the near bank there was a sudden drop in the water surface between the stern of the vessel and the near bank. As a result of these conditions, a moment was produced which tended to increase the rate of swing of the bow. If the condition was not corrected immediately, the vessel would develop such a sheer that application of rudder would not bring the vessel into a condition of equilibrium. As a result, the vessel would sheer across the channel and the bow would strike the far bank or the stern would be forced into the near bank. If the heading of the model was maintained exactly parallel to the near bank during an off-center run, by using the correct rudder angle, the model would drift laterally toward the near bank. As it moved closer to the wall, the yawing moment became larger and it was necessary to increase the rudder angle to maintain the heading of the model parallel to the bank. Eventually the model would ground unless the yawing moment became so large that a sheer developed. Therefore, the angular position of the vessel in the channel, especially in an off-center position, is important. Considerable judgment is required of the pilot in balancing the forces acting on the bow and stern by application of rudder and slight changes in heading. It should be understood that application of rudder alone will not always bring the vessel into equilibrium for an off-center position in a restricted channel but that a proper amount of heading must also be maintained.

When the total of all the rudder angles used for a given run were averaged arithmetically and plotted against the average distance between the center line of the channel and the center of gravity of the ship during the run, the resultant curves closely approximated the rudder angles for equilibrium which were obtained in the first part of the observational tests. The primary value of these data is that they substantiate the equilibrium rudder angles which were derived in the first part of the test, as an indication of the yawing moment caused by interaction.

The maneuvering data are still being analyzed and it is hoped that additional quantitative information on controllability may be obtained from them. The preceding results are based on only one model and are intended primarily to indicate some of the general characteristics of the interaction or bank suction between a ship and the channel boundaries. It would undoubtedly be desirable to obtain information on the effect of varying the cross-sectional dimensions of the ship, holding the length constant, as well as information on a variety of ship types and designs. However, a program of this type would be too extensive for the present investigations.

Force-Measurement Tests.—The purpose of the force-measurement tests was to supplement the observational tests in order to evaluate the various factors affecting the controllability of ships in restricted channels. As the term implies, the tests consisted of measuring the forces resulting 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 ft wide, 9 ft deep, and 60 ft long, a return channel beneath which the water passes from the downstream end of the test section back to the entrance of the test section, 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 0 to 9 ft. Movable walls may be placed in the test section to vary the width of the channel. The water speed in the channel may be varied as desired up to 10 knots.

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 lies in the fact 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 do the observational tests, which are of the dynamic type. In the force-measurement tests, the model was restrained while the forces that tended to make it move were measured. It is recognized that this is an artificial condition, with respect to a normal operating condition for the full-scale ship, but the data obtained provide the background for an analysis of the dynamic tests.

The models were tested at various off-center positions in channels with various cross-sectional dimensions and at the equivalent full-scale speeds of from 4.5 knots to 10 knots. During the tests the model was attached to the dynamometer in the desired position by three arms which extend downward from the dynamometer. Two of the arms were 2.5 ft forward and 2.5 ft aft, respectively, of the center of gravity of the model. These two arms measured the side force acting on the model and restrained 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 can be attached at any desired transverse position in the channel. When it is desired to give the model an angle of yaw, the entire dynamometer is turned. Thus, all forces acting on the model are measured parallel or perpendicular to the center line of the model regardless of its angle of yaw.

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 releasing the model at a specified distance from the center line and trying various rudder angles until equilibrium was obtained. It was also pointed out that, in addition to the rudder angle, it was necessary to give a slight angle of yaw away from the near wall to produce a true condition of equilibrium. In the force-measurement tests, equilibrium rudder angles were determined by measuring forces on the model at various angles of yaw. This result was accomplished by varying the rudder angle and the angle of yaw until both the yawing moment and the side force became zero. The model was self-propelled and the speed of the propellers was varied until the drag of the model was equalized. Fig. 47 is a graph of the rudder angle required for equilibrium plotted against the distance between the center line of the channel and the center of gravity of the ship. (If the ship is near the right bank, it is neces-

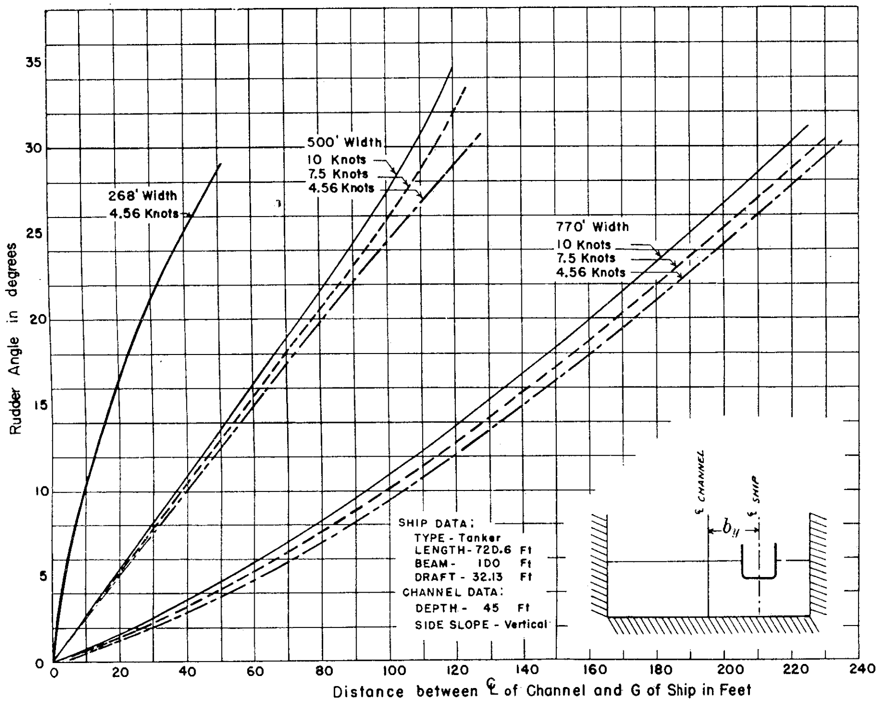


FIG. 47.—RUDDER ANGLES NECESSARY TO PRODUCE A CONDITION OF EQUILIBRIUM FOR VARIOUS DISTANCES BETWEEN THE CENTER LINE OF A RESTRICTED CHANNEL AND THE CENTER OF GRAVITY OF A SHIP

sary to use "right rudder" and to yaw the ship to port to counteract the moment and side force that develop. The reverse would be true if the ship were near the left bank.) The data are for a large tanker in channels with widths of 268 ft, 500 ft, and 770 ft. The side walls of the channel were vertical.

In addition to determining the rudder angle and the angle of yaw required for equilibrium, measurements were taken of the side force and yawing moment that developed when the model was held parallel to the wall and at various transverse positions in the circulating water channel. These tests were conducted for the purpose of determining the magnitude of the interaction or bank suction in terms of force and moment as opposed to the preceding data which indicate the magnitude of these effects in terms of the rudder angle and the angle of yaw required to counteract them. The yawing moment and the side force were plotted with respect to the distance between the center line of the channel and the center of gravity of the ship. Fig. 48 is a comparison of the side force and yawing moment acting on the tanker (length 720.6 ft and beam 100 ft) at various transverse positions in channels with three different widths (268 ft, 500 ft, and 770 ft) for one depth (45 ft) and for one ship speed (4.56 knots). The scale ratio was 3.5. The data in Fig. 48 are based on self-propelled tests of model 3859. They are plotted for the condition with the ship to starboard of channel center line. The rudder angle was set at 0° when the yawing moment and the lateral force were measured. The rudder angle required to counteract the yawing moment of zero yaw has also been plotted for comparison. During these tests the rudder angle and the angle of yaw were set at 0°. The rudder angles required to counteract the yawing moment were

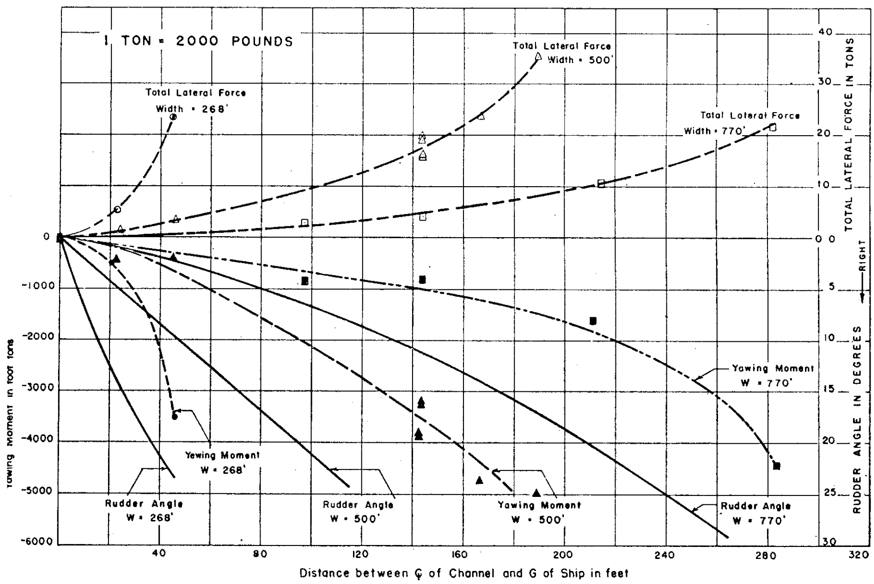


FIG. 48.—YAWING MOMENT AND LATERAL FORCE ACTING ON A SHIP THAT IS PARALLEL TO, AND AT VARIOUS DISTANCES FROM, THE CENTER LINE OF A RESTRICTED CHANNEL

measured, following the measurement of side force and yawing moment. Previous tests had indicated that there was a slight difference between the true rudder angle for equillibrium and the rudder angle to produce zero moment at zero yaw—thus necessitating separate measurements for the equilibrium condition. The rudder angle for zero moment at zero yaw has been plotted in Fig. 48 for comparison with the moment curves.

Summary of Observation 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 Panama Canal, the observational studies on the tanker were deferred until a later date to expedite other phases of the studies.

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 has been determined. Rudder angle is believed to be the most practical term for use 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, ship lines, rudder and propeller characteristics, ship speed, and the position of the ship in the channel. Thus, the rudder required by two different ships for a specified off-center position will be affected by the steering characteristics of the ships. The study of rudder angles required for many different ships would be valuable for purposes of ship design and for the operation of ships in restricted channels. However, for the immediate purpose of indicating the necessary size and proportions of a canal channel, it is believed that study of the models of the large naval vessel 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 the large ships. The naval vessel 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 quite poor.

During the present studies, the models were tested in channels with a considerable variation in width and depth. The data have been plotted to facilitate a comparison of the effect of width and depth on 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 these effects provide a comparison of the actual difficulty the pilot 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 dangerous for the ship. Available data on the relationship of yawing moment to rudder angle are quite limited.

Change-of-Level Test.—When a vessel is under way in still water, it is found that 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 negative flow continues to within a short distance of the stern where the water closing in and upward behind a vessel has a forward motion. Wherever changes in velocity or direction of flow occur, there is usually a change in the elevation of the water surface. In shallow water or canals, the region of disturbed water about the ship is confined to a much smaller area than in water of unlimited width and depth. Thus, in a restricted channel, the reverse flow past the vessel has a greater velocity for the same ship speed. The net result is a larger change in the elevation of the water surface, with respect to the normal water surface, in the vicinity of the ship. In the past, considerable study has been devoted to the variation in the resistance of ships in shallow water and restricted channels, but very little work has been done on the change of level of ships under these conditions. Studies of ship resistance in shallow water and restricted channels are described extensively elsewhere.[25,27,28,30,32,36,37,38,39] In 1904, Henry N. Babcock[40] described a series of measurements that was taken on change of level of ships that were under way in shallow channels. Measurements were taken from shore with the use of a surveyor's level. He reported a change of level of 4 ft for one of the ships tested. Some additional information on the change of level of model or full-scale ships under way in shallow water or canals has been presented elsewhere by Mr. Bowers.[25]

Fig. 49 is a plot of some actual measurements, during two independent tests, taken on the elevation of the water surface of a model. The lowering of

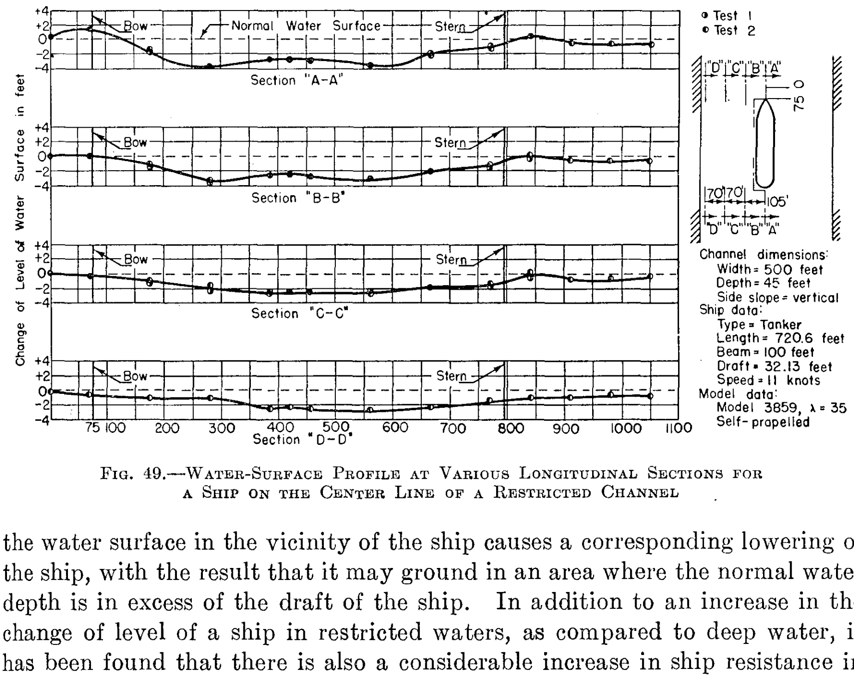


FIG. 49.—WATER-SURFACE PROFILE AT VARIOUS LONGITUDINAL SECTIONS FOR A SHIP ON THE CENTER LINE OF A RESTRICTED CHANNEL

the water surface in the vicinity of the ship causes a corresponding lowering of the ship, with the result that it may ground in an area where the normal water depth is in excess of the draft of the ship. In addition to an increase in the change of level of a ship in restricted waters, as compared to deep water, it has been found that there is also a considerable increase in ship resistance in restricted waters. For shallow water of unlimited width, the increase in resistance depends on the depth of water. In a restricted channel the resistance is also a function of the channel width.

As a part of the Taylor Model Basin investigation of ship performance in restricted channels, the change of level of model 3769 was measured for a range of ship speeds from 5 knots to 15 knots, full scale, in channels with the cross-

[37] "Tidal Currents and Their Effect on Navigation," by J. A. Conwell, Special Eng. Div., The Panama Canal, Diablo Heights, Canal Zone, 1941.

[38] "Tests on the Wall Interference and Depth Effect in the Royal Aeronautical Experimental Seaplane Tank and Scale Effect Tests on Hulls of Three Sizes," by L. P. Coombes, W. G. A. Perring, V. W. Battle, and L. Johnston, *Technical Report*, Aeronautical Research Committee, Vol. 2, 1934–1935.

[39] "The Effect of Size of Towing Tank on Model Resistance," by John P. Comstock and C. H. Hancock, *Transactions*, Soc. of Naval Architects and Marine Engrs., Vol. 50, 1942, pp. 149–197.

[40] "Some Model Experiments on Suction of Vessels," by David W. Taylor, *ibid.*, Vol. 17, 1909, pp. 1–21.

sectional dimensions previously given. It was not possible to reach a speed equivalent to 15 knots in some instances due to excessive change of level which caused the model to touch the bottom of the channel. In these tests the model was attached to the towing carriage by connections that permitted a small amount of fore and aft movement and also allowed the model to trim freely. Indicators, which were mounted on the carriage, were attached to the model near the bow and stern by a cable arrangement so that vertical movements of the bow and stern could be read on large dials. The carriage was accelerated to the desired test speed and at the same time the propeller revolution was increased until the model was fully self-propelled. Readings were then taken of the level of the bow and stern with respect to the level when the model was stationary.

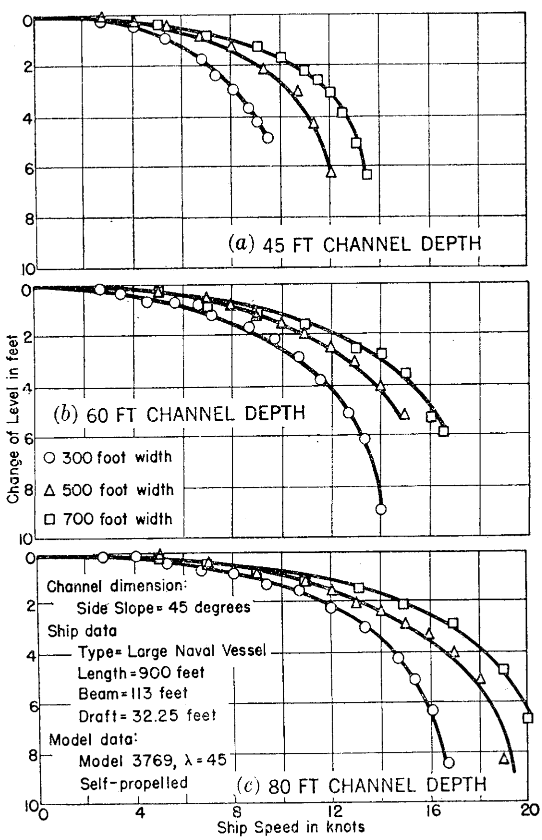


FIG. 50.—EFFECT OF CHANNEL WIDTH ON THE CHANGE OF LEVEL OF A SHIP ON THE CENTER LINE OF A RESTRICTED CHANNEL

From tests it was noted that the bow and stern change level at approximately the same rate up to the critical speed, where the bow curve reverses direction, and the slope of the stern curve becomes quite large. The critical speed of a vessel in a restricted channel is roughly defined as the speed at which the relative velocity between the ship and the reverse flow past the beam of the ship is equal to the speed at which the relative velocity between the ship and the reverse flow past the beam of the ship is equal to the speed of the wave of translation for that particular depth of water. Near the critical speed, the water-surface level around the ship changes quite rapidly with any slight change in relative speed. The models were not tested at speeds above the critical because of possible damage to the model and because there is little possibiltiy of operating the full-scale ship under these conditions, even at the greater depths where there is no danger of grounding. For a specified channel, the change of level of the ship varies approximately as the square of the velocity.

In Fig. 50 the data have been plotted to illustrate the variation in change of level with variations in the width and depth of the channel. (The curves shown are for the stern only. The bow curves are similar.) A large change of level would probably be indicative of excess bank wash and unstable handling conditions due to interaction or bank suction.

The effect of the transverse position of the ship in the channel on its change of level was also investigated. Measurements were taken for various off-center positions of the model for channel widths equivalent to 300 ft and 500 ft and for channel depths equivalent to 45 ft, 60 ft, and 80 ft. The differences recorded for these tests were not of sufficient magnitude to·present and would not be determining factors in the selection of channel dimensions.

To determine the effect of the propellers on the change of level of the ship, the model without propellers was towed on several occasions and the results compared with those obtained from the self-propelled tests. In the towed tests the shape of the curves was quite similar to that in the self-propelled tests. The bow and stern curves had the same relationship as in the self-propelled tests, and the critical speed was approximately the same. However, for most of the speed range up to the critical, the towed tests indicated from 8% to 15% less change of level than did the self-propelled tests.

Discussion of Change-of-Level Tests.—The change of level of a ship under way in restricted waters is of importance in the present investigation because (*a*) at relatively high ship speeds, the ship may ground due to excessive change of level; (*b*) a large change of level is indicative of the formation of large waves which may result in serious bank wash; and (*c*) at subcritical speeds a large change of level is indicative of a high ship resistance as compared to the resistance at the same speeds in deep water. The change of level of a ship under way in a restricted channel is a function of the dimensions and lines of the ship, the ship speed, the cross-sectional dimensions of the channel, and the position of the ship in the channel.

In general, an increase in ship speed produces an increase in the change of level at all speeds up to the critical. For a specified channel, the change of level of a ship increases approximately as the square of the speed for subcritical speeds. The exact relationship between the change of level of the ship and the ship speed is apparently dependent on the cross-sectional area of the channel. At speeeds above the critical, an increase in ship speed may result in a reduction in the change of level of the ship. During the present investigation, the range of ship speeds used in the tests did not exceed the critical speed.

Studies of Two-Way Traffic

The purpose of the two-way traffic studies was to obtain information that would be of assistance in the selection of the cross-sectional dimensions of a channel adequate for the meeting of two ships of specified types. As part of this study it was desired to obtain information on the interaction between the two ships and between the ships and the channel boundaries.

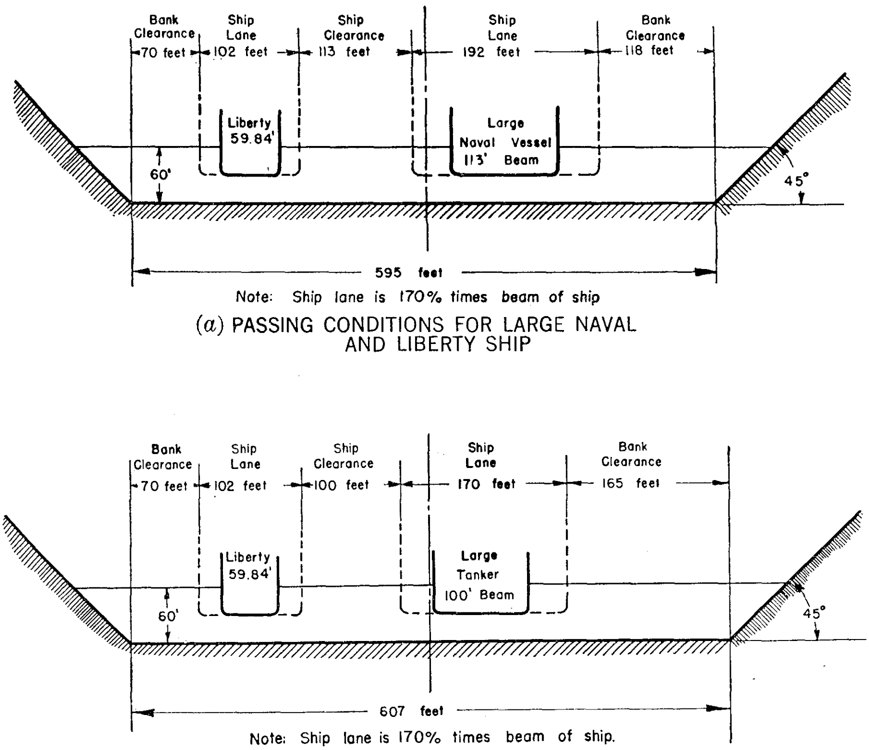
Prior to this phase of the studies it was decided by The Panama Canal that two-way traffic studies be based primarily on the meeting of a large naval vessel and a Liberty ship. It was further requested that the tests be conducted for: (1) Still water and currents of 3 knots and 5 knots, (2) ship speeds up to 10 knots with respect to the water, and (3) various widths and depths of channel.

When two ships are meeting each other in a restricted channel, each ship interferes with the lines of flow about the other vessel with the result that asymmetrical pressures develop on the two sides of each vessel, tending to divert the ship from its original path. Throughout the maneuver, the turning moment caused by these pressures changes direction several times. For example, as two vessels approach each other, the pilots maneuver them out of the center of the channel. When the bows of the two vessels are almost directly opposite each other there is a tendency for the water surface to build up between the bows forcing them apart, or causing the vessels to yaw away from each other. As the vessels draw abreast of each other, the bow of each vessel tends to move toward the low water surface in the vicinity of the stern of the other, with the result that they yaw toward each other. When the sterns are almost directly opposite each other, there is a tendency for the sterns to move toward each other, thus reversing the direction of yaw. Superimposed on these effects (which result from interaction between the two vessels) is the effect caused by interaction between each vessel and the channel boundaries. In general, this latter effect tends to cause the vessel to yaw away from the near bank. Thus, the maneuvering of the vessels is affected not only by the size, speed, and paths of the vessels but also by the cross-sectional dimensions of the channel.

At the conclusion of most of the straight-channel, one-way traffic studies, certain general criteria were established by The Panama Canal. The decision was made to establish 60 ft, tentatively, as a reasonable depth to be used in further studies of width as related to two-way traffic and bend studies. Drawing upon the experience of well-qualified Panama Canal pilots and Cape Cod Canal pilots, it was decided to establish, tentatively, a reasonable average rudder angle for the maneuvering of a vessel off center in a restricted channel. This average rudder angle would then be used to determine a safe width of canal. Because the vessels vary in size, form characteristics, and rudder power, in addition to the fact that every pilot will maneuver differently, it seemed advisable to set the average rudder angle for equilibrium as low as possible to provide for ample reserve rudder in case of emergency. Pilots considered that a 5° rudder angle was reasonable.

For example, in selecting a width of channel, the following procedure could be used: Fig. 51 shows two cross sections of a channel as determined from model studies, with outlines of the midship sections of (*a*) the large naval vessel and Liberty ship and (*b*) the large tanker and Liberty ship. The dotted outlines represent the average ship lane of the vessels, as determined from observational studies previously mentioned. The widths of the ship lane are approximately 170% of the beam of the vessel for a channel 500 ft wide and 60 ft deep, at a ship speed of 10 knots. The distances of the ships from the prism lines were computed from Figs. 44 to 47 for a rudder angle of 5°, and for a ship speed of from 9 knots to 10 knots. The distance between the vessels was selected as the beam of the larger vessel. This fact was later confirmed with model studies. The curves of Fig. 46 are based on rather limited data and it was thought desirable to select the maximum curve of rudder angle required, which was for the 9-knot ship speed with a following current of 5 knots.

The sum of the various distances from Fig. 51 gives a channel width of 595 ft for the large naval vessel and the Liberty ship, and a width of 607 ft for the



(*a*) PASSING CONDITIONS FOR LARGE NAVAL AND LIBERTY SHIP

(*b*) PASSING CONDITIONS FOR LARGE TANKER AND LIBERTY SHIP

Fig. 51.—Proposed Widths for Two-Way Traffic

large tanker and the Liberty ship, thus presenting one method of analyzing the data. Other selected rudder angles and channel depths will give widths in accordance with the selected values. It should be emphasized that such assumptions will only vary the distance between the ship and the near bank. The widths of the ship lanes and the distance between vessels offer reasonable values for this specific problem. Other combinations of vessels would vary these values. The data in Fig. 51 do not constitute a design intended for the Panama Canal. Other considerations may be necessary in the selection of proper width and depth. The sixth paper in this Symposium will develop this phase of the problem as applied to the Panama Canal.

Model studies were then conducted with the Liberty ship meeting the large naval vessel in a restricted channel with still water and with ahead and following currents of 3 knots and 5 knots. During the tests one model was towed by an endless cable in one direction while the other model was maneuvered by remote control in the opposite direction. Observations of the handling characteristics and the effect of interaction between the two vessels were limited to the maneuvered model.

With the exception of a limited number of tests at a channel width of 700 ft, all two-way traffic studies were conducted in a channel with a bottom width equivalent to 500 ft and a depth equivalent to 60 ft. It was intended to conduct further tests with a width equivalent to 600 ft but these were deferred to pursue urgent bend studies. The major part of the studies was conducted with both ships traveling at the same speed with respect to the water.

All conclusions were based on visual observations of the models by the Panama Canal pilots (who operated the models) and by the Taylor Model Basin staff. During these tests it was attempted to simulate full-scale conditions as closely as possible. However, it was not possible to satisfy all conditions. The walls of the model channel were quite smooth as compared with the probable irregularities of full-scale channels. Also, the "pilot" had to think and act much faster during the model tests than would be possible on the full-scale ship, because of the time relationship between the model and the full-scale ship. However, the pilots who observed and participated in the tests believed that full-scale conditions were simulated very well and that, where differences did exist, the model was more difficult to control than the full-scale ship.

Subject to the preceding discussion, the following general observations were made:

a. It appeared that interaction between the two vessels did not cause any serious difficulty in handling, in a channel 500 ft wide and 60 ft deep, at the ship and current speeds employed.

b. The current speed did not appear to affect the magnitude of the interaction between the two vessels, for the same ship speeds with respect to the water. However, it would probably have an effect on the handling characteristics of the vessels in the vicinity of bends or large irregularities in the walls of the channel.

c. The Liberty ship steered best when it had a speed with respect to the water of 7.5 knots. A minimum speed at which good control could be maintained was approximately 5 knots.

d. The transverse position of the naval vessel had very little effect on the maneuvering of the Liberty ship as long as the clear distance between the two vessels while passing was at least 100 ft. For more general conditions it was thought that the distance should be at least 100 ft or a distance equal to the beam of the larger vessel—whichever was the larger.

Bend Studies

The primary purpose of the bend studies was to investigate the comparative difficulty encountered in maneuvering a specified ship around variously designed bends at a 1:86 scale ratio. It was also desired to investigate the effects of variations in ship speed and current on the handling characteristics of a specified ship. Later in the investigation it was decided to conduct tests at a 1:45 scale ratio to study the maneuvering characteristics of various vessels and scale effects. Models 3769, 4018, and 3748-4 were used for the 1:45 scale-ratio studies and model 3992 was used for the 1:86 scale-ratio tests. The characteristics of the models are given in Fig. 41.

For the 1:86 scale-ratio tests, model 3992 representing a large naval vessel was selected and constructed and the movable walls were adjusted to the desired width and proper curvature for each test. A section of straight channel was constructed ahead of the bend to permit accelerating the model 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. Veteran Panama Canal pilots issued the helm and engine orders during each run. The control panel, parallel light beam, and other features were similar to those used in the two-way traffic studies and to part of the one-way traffic studies.

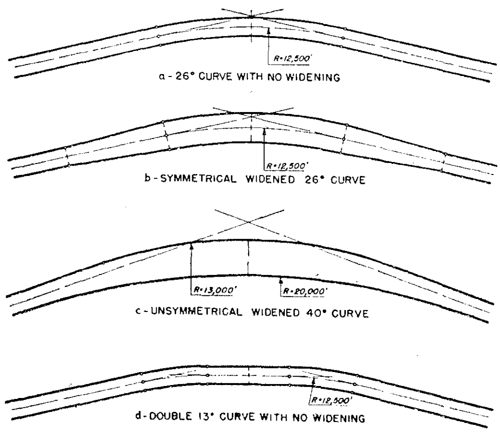


FIG. 52.—CURVES TESTED IN MODEL STUDIES

Tests were conducted on four types of bends at a 1:86 scale ratio, as shown in Fig. 52:

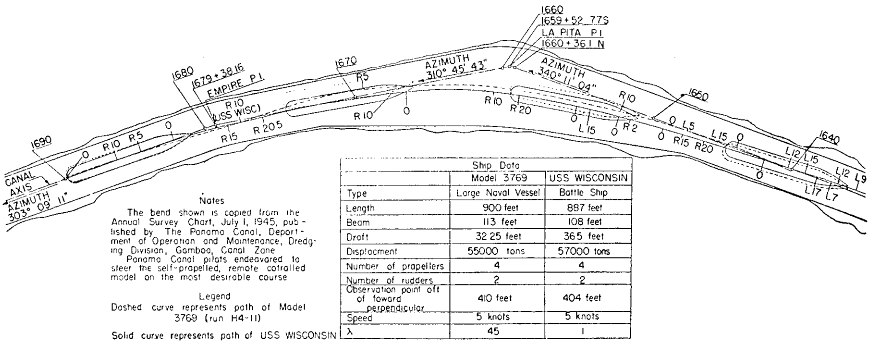
(*a*) A 26° parallel bend;
(*b*) A 26° parallel widened bend;
(*c*) A 40° widened bend; and
(*d*) A double 13° bend;

—and on two types at a 1:45 scale ratio:

(*e*) A model of La Pita bend in the Panama Canal, as generally shown in Fig. 53; and
(*f*) A 26° parallel bend, as shown in Fig. 52.

In connection with test (*e*), Fig. 53 shows a northbound transit of the *U. S. S. 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 that is 0.455% of the ship length from the forward perpendicular and is on the center line of the vessel.

The tests were conducted at ship speeds of 5 knots, 7.5 knots, and 10 knots through the water, with both ahead and following currents of 0 knot, 3 knots, and 5 knots. When the bend studies were initiated, it was planned to investigate arbitrary bend angles of 20° and 40° and to use a straight-channel section at the entrance and exit of the bend with a width of 600 ft and a depth of 60 ft. However, at the conclusion of the first 40° bend test, available information indicated that a channel width of 560 ft (600 ft wide at the 40-ft depth), a depth of 60 ft, and a maximum bend angle of 26° would be of primary interest.



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 oft of foward perpendicular	410 feet	404 feet
Speed	5 knots	5 knots
λ	45	1

Fig. 53.—Comparative Ship Performance in Model and Full-Scale La Pita Bends

At first it was felt desirable to attempt to maneuver the vessel both at the center line and at the quarter point on either side of the center line for all conditions of ship speeds and currents—in an attempt to indicate the desirability of meeting and passing a Liberty ship and a large vessel in the curved section. Although a substantial number of such tests were conducted for all the bend designs, the results indicated that such a maneuver might be dangerous if one vessel were large; but little difficulty was foreseen for Liberty ships meeting and passing in the bend. 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 may very well give a solution to this problem.

The comparisons of the 1:86 scale-ratio bends were then made for center-line transits only. Table 25 is a summary of the average maximum deviation from the center line of the channel for the various bends tested. ("Deviation" may be defined as the maximum departure of the forward or after perpendicular from the intended path of the center of gravity of the vessel. Width of path is the sum of the maximum port and starboard deviations plus the beam of the vessel for a particular test run.) Referring to Table 25, Panama Canal pilots endeavored to steer the self-propelled, remote-control models along the channel center line of the shallow water basin. Both models represented large naval vessels, with general dimensions as follows:

Dimension	Model 3769	Model 3992
Length, in feet	900	860
Beam, in feet	113	108
Draft, in feet	32.25	34.62

Model 3769 was tested in a 26° parallel bend ($\lambda = 45$); and model 3992 was tested in the other four bends ($\lambda = 86$). All measured data were taken from streak photographs of the ship's path. The average width of path in Table 25 is based on the total number of runs made under the same test conditions. The average maximum deviation of the ship's path to port or to starboard of the channel center line is based on the total number of runs made under the same test conditions. Included in Table 25 are the average widths of path for the same conditions. The width of path included the beam of the vessel. All runs that were considered as satisfactory test runs were included in the average. Some runs were excluded from the analysis because of failure of the test equipment. The average values of rudder angles or average maximum rudder angles were not used as criteria because of the variations in the techniques used by the pilots in handling the vessel. Some pilots tended to use rather large rudder angles for short periods whereas others tended to use relatively small angles for longer periods of time. Also, various pilots favored one side of the channel more than the other, which will give an even larger variation in rudder angles due to bank interaction.

The first reaction of an observer is that a widened bend would provide more room for maneuvering than would a uniform width of channel in the bend. Actually, the widened bend studies indicated that maneuvering was more difficult, the actions of the vessel were more erratic, and the widths of path were generally greater, as indicated in Table 25. It is considered that this result is principally due to the continual variations in the forces resulting from bank interaction as a vessel transits through a gradually widening section. In the normal transiting of a vessel down a straight channel, it is very difficult to keep it positioned exactly on the center line. In transiting a bend, this task is even more difficult, especially with a large vessel, because it forms a tangent or secant to the curvature of the bend. In either of the latter two cases the vessel will be positioned slightly off center and some rudder angle will be required to prevent a sheering action from developing. Some force or rudder action is usually required to turn the vessel around the bend, although in some cases the bank interaction is such as to turn the vessel around the bend without the use of rudder action. However, if the interaction is too great, the vessel may swing too fast and develop a sheer in the same direction causing the vessel to strike the inner bank. For example, if a vessel enters a right-hand bend slightly off center to the left, the bank interaction is such that the bow will tend to swing around the bend; should the vessel swing too far, a sheer would develop that would require the left rudder to keep the vessel under control. However, if the vessel enters the right-hand bend off center to the right, a larger right rudder would be required to keep the vessel under control and also to turn it around the bend. In a parallel bend the forces created by bank interaction have nearly the same values as similar forces in a straight channel. Therefore, the pilot can judge the required rudder angle for equilibrium more readily than in a widened bend where the values of the forces are changed or are continually changing during the transit. Because the vessel is swinging slightly as it traverses the bend and is not "headed" on a straight course, this maneuver can best be made by constant attention to the swing of the vessel and by the "feel" of the condition.

TABLE 25.—COMPARISO

Line No.	Bend: Angle	Bend: Description	Bend: Scale ratio	Still Water; $V_c = 0$: Total No. of center-line runs	Still Water; $V_c = 0$: Width of path[a] (ft)	Still Water: Maximum Average Deviation (Ft): Port	Still Water: Maximum Average Deviation (Ft): Starboard[b]	Ahead Current; $V_c = 3$: Total No. of center-line runs	Ahead Current: Width of path[a]	Ahead Current: Maximum Average Deviation (Ft): Port	Ahead Current: Maximum Average Deviation (Ft): Starboard
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
		(a) Velocity of Ship in Relation to Current; $V_s = 5$ Knots									
1	40°	Widened	86	2	360	59	193	2	763	468	187
2	26°	Parallel; widened	86	6	475	192	175	2	639	316	215
3	13°	Double	86	7	304	141	55	3	295	99	88
4	26°	Parallel	86	7	290	126	56	3	238	115	14
5	26°	Parallel	45	4	277	106	58	3	245	116	16
		(b) Velocity of Ship in Relation to Current; $V_s = 7.5$ Knots									
6	40°	Widened	86	6	466	166	194	5	643	439	337
7	26°	Parallel; widened	86	7	450	215	127	7	411	160	143
8	13°	Double	86	16	363	158	97	3	340	138	95
9	26°	Parallel	86	8	369	172	91	9	263	128	26
10	26°	Parallel	45	4	305	125	67	4	245	115	17
		(c) Velocity of Ship in Relation to Current; $V_s = 10$ Knots									
11	40°	Widened	86	2	723	337	278	1	401	244	49
12	26°	Parallel; widened	86	4	378	174	96	6	402	182	112
13	13°	Double	86	6	389	177	104	2	290	129	55
14	26°	Parallel	86	7	309	126	75	5	342	157	76
15	26°	Parallel	45	4	209	100	−4	4	231	124	−6

[a] Average width of path for all center-line runs. [b] A minus sign in this colum

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. In addition, the scale ratios were so small that slight motions were difficult to detect from the carriage platform in time to make the proper corrections.

By considering the foregoing factors for the analysis of the 1:86 scale-ratio studies and by comparing the performance of the model vessel in the various bends, not attempting to extrapolate the values to full-scale operation, observers felt that the 26° parallel bend provided the best solution for all conditions of testing. This decision was reached by comparing similar runs of the various bends tested. For this comparison only one ship model was used. No appreciable differences were encountered in the 1:86 scale, 26° parallel bend for still-water or moving-water conditions.

One factor that should be mentioned in the case of moving water is that of variations in time of transit through a bend. No appreciable differences were noted in the model's action for the still-water and moving-water studies, pro-

OF SHIP PERFORMANCE

Ahead Current; $V_c = 5$				Following Current; $V_c = 3$				Following Current; $V_c = 5$				
Total No. of center-line runs	Width of path[a]	Maximum Average Deviation (Ft)		Total No. of center-line runs	Width of path[a]	Maximum Average Deviation (Ft)		Total No. of center-line runs	Width of path[a]	Maximum Average Deviation (Ft)		Line No.
		Port	Starboard[b]			Port	Starboard[b]			Port	Starboard[b]	
(12)	(13)	(14)	(15)	(16)	(17)	(18)	(19)	(20)	(21)	(22)	(23)	
(a) Velocity of Ship in Relation to Current; $V_s = 5$ Knots												
....	....	....	....	4	512	193	213	2	474	170	195	1
....	....	....	....	0	....	....	....	0	....	....	....	2
....	....	....	....	0	....	....	....	0	....	....	....	3
....	....	....	....	4	229	99	22	9	269	103	57	4
....	....	....	....	4	217	93	11	6	244	118	13	5
(b) Velocity of Ship in Relation to Current; $V_s = 7.5$ Knots												
7	649	337	204	2	622	214	300	3	342	94	141	6
4	430	185	138	0	....	....	....	0	....	....	....	7
6	406	175	123	0	....	....	....	0	....	....	....	8
7	297	147	41	4	235	80	46	5	255	107	40	9
5	257	92	52	4	183	91	−21	6	190	100	−23	10
(c) Velocity of Ship in Relation to Current; $V_s = 10$ Knots												
3	568	244	217	4	486	282	98	3	380	139	133	11
4	417	223	86	0	....	....	....	0	....	....	....	12
3	392	159	123	0	....	....	....	0	....	....	....	13
7	378	159	111	4	253	102	42	5	240	108	−23	14
6	231	85	33	4	177	80	−16	6	197	101	−17	15

indicates that the center line of the ship was always to the port of the channel center line.

vided that the speed of the vessel with respect to the water remained constant. There were, of course, differences in time of transit. Appreciably fewer total rudder orders were required in transiting a bend with a following current than with an "ahead" current. However, the rudder orders necessary per unit of time were approximately equal for all conditions of testing in either still water or moving water, provided that the speed of the ship with respect to the water remained constant. Actually the vessel remains in the bend for a shorter period of time for the following current condition than for the ahead current condition. This fact usually gives the pilot the impression, from observations of the speed of the vessel over the ground rather than from observations of its speed through the water, that less time is available for adjusting his course during the transit of the bend—which evidently creates somewhat of a mental hazard for the pilots navigating through a bend in a following current. Experience proves that this condition is no more difficult than conditions of still water or ahead current.

At the conclusion of the 1:86 scale-ratio tests, it was decided to conduct two more bend studies at the larger scale ratio of 1:45:

a. The 26° parallel bend, shown in Fig. 52; and
b. The model of the La Pita bend, Panama Canal, as shown in Fig. 53.

The 1:45 scale ratio of the 26° parallel bend was tested:

a. To determine by comparison with the 1:86 scale ratio test if there were scale effect; and
b. To compare transits of models of other ships—namely, the Liberty ship and a large tanker.

The widths of path and deviations from the center line for the various test conditions are tabulated with the 1:86 scale-ratio tests in Table 25. Similar records were taken, by photographic methods, of all record runs. The results of this study indicate that some scale effect was present in the 1:86 scale-ratio studies. However, the actions of the vessel were quite similar. The scale effect was chiefly present in the additional time permitted the pilot for giving orders. Except for the poor handling quality of the large tanker, as determined in the straight-channel studies, no difficulty was experienced in transiting the 1:45 scale-ratio parallel bend with any of the models under any of the conditions as long as the transits were made on the center line. The Liberty ship model handled very well.

The model of the La Pita bend was tested at a 1:45 scale ratio in a further effort to determine scale effect by comparing model tests with a full-scale transit, as shown in Fig. 53. The model transit of the bend compares very favorably with the full-scale transit. However, studies of the Suez and Cape Cod canals indicated that bends of uniform width throughout were more desirable. In the case of the Suez Canal, a parallel bend had been widened to provide room for larger vessels. Ships which previously had had no difficulty began to experience some erratic action. Therefore, the bend was further widened in such a manner that it again became parallel.

The model studies have been limited to a small number of ships and bend designs. The comparison of widths of path for the 1:86 scale-ratio studies indicated that the 26° parallel bend would give the most satisfactory operating characteristics of the model for all conditions. This comparison was further substantiated by visual observations of the test runs, the number and magnitude of rudder orders, and the greater uniformity of results from pilot to pilot. The 1:45 scale-ratio studies of the 26° parallel bend showed improvement in the operation characteristics of the model over the 1:86 scale-ratio tests. This improvement could be attributed only to scale effect. The width of path in the bend compared quite favorably with the width of path for the straight channel when "crabbing" or "angular position" of the vessel in the channel bend is considered.

The 26° parallel bend was determined to be the most desirable bend of those studied and the test showed that currents did not produce any hazardous operating conditions. The model could be navigated as readily in moving water as in still water.

Summary

The variety of sizes, shapes, rudders, and propulsion characteristics of the many ships that will transit any channel is so great that only representative types from different general groupings could be used for the experiments. For these studies and their relation to the Panama Canal the vessels were selected because of (1) their large size, (2) their poor handling characteristics in restricted waters, or (3) their being representative of a large percentage of the present ships transiting the canal. It is felt that the models of the ships studied "bracket" these conditions and that the results obtained provide a guide for selecting the channel dimensions. Before a final selection of the channel dimensions is made, there are other factors, which could not be inserted into a laboratory investigation, to be studied and considered. Ships of the same class may not have similar steering qualities. The efficiency of operation of a vessel is measured to some extent by the age and the number of days the ship has been under way since overhaul. Seldom do two captains or pilots come to perfect agreement on the proper methods to use in maneuvering a vessel. 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.

This paper has presented the information that is available from tests conducted at the David Taylor Model Basin. A study of the maneuverability and controllability of specified ships in specified restricted waters is a multifold problem. The results of the experiments and analysis thus far made give a more complete understanding of a problem which has harassed ship operators, engineers, and pilots for more than a century. A complete solution of the general problem has not yet been obtained; however, limits and trends have been established that may serve a useful purpose in determining (*a*) the speed at which vessels may operate in restricted waters, (*b*) the practical depth and width of a restricted channel, and (*c*) the actions that produce extraneous moments on the vessels. Generally the forces and moments acting on the various ship models were explained and the rudder angle required for controllability and balancing of those moments was used as a measure of the moment.

Acknowledgments

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DESIGN OF CHANNEL

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Synopsis

Methods of design and analysis are presented in this paper for use in determining the minimum cross section of the channel and the alinement and treatment of curves in a sea-level canal at Panama, to provide safe and efficient transit of all vessels to the year 2000. The channel design is based on the operation of the canal as an open waterway with a maximum current of 4.5 knots. The design methods described in this paper utilize the marine operating experience of existing waterways and the results of ship model tests conducted at the David Taylor Model Basin, some of which have been presented in the preceding paper in this Symposium. A minimum channel section 600 ft wide, measured at a depth of 40 ft, and 60 ft deep is proposed.

Introduction

The existing Panama Canal has provided commercial and military shipping with a safe and efficient means of transiting the American Isthmus, since its opening in 1914. Almost 200,000 ships have passed through the canal and the total accident cost has been only $1,310,000—equivalent to $7.76 per transit. Any modification of the existing canal, or any new canal to provide the necessary national security, must also provide commerce with a waterway at least as safe and efficient as the existing canal. In a sea-level canal, the adequacy of the channel cross section and alinement are the primary considerations in accomplishing this objective.

This paper describes the methods of designing and selecting the sea-level canal channel. The channel of the sea-level canal referred to herein is the restricted part of the waterway as distinct from open reaches of harbors where the topography does not limit the width of the channel. Although this paper discusses primarily the sea-level canal, there is no essential difference in the method used in the design of either a sea-level or a lock canal channel except that tidal currents in the sea-level canal introduce a factor that must be weighed and compensated for in the design. A comparison of the final selection of the lock canal channel and the sea-level canal channel is included.

The importance of avoiding the construction of a channel larger than necessary is obvious when it is considered that the excavation for the sea-level canal would total more than 1,000,000,000 cu yd. On the other hand, prudent planning is required to meet all reasonable demands of navigation in the future to avoid expensive corrective work.

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Navigation Features of Existing and Sea-Level Channels

The channels of the existing canal are of three types: Those through the lake where the width and depth are unrestrictive to vessels; those through harbor or approach areas where both width and depth are restricted, but where channel banks are well below water level and interaction between ship and bank is insignificant; and those where both depth and width are fully restricted by the channel bottom and side banks. In the existing canal, the 8-mile reach north of Pedro Miguel Locks known as Gaillard Cut and a few miles of lock approach channels make up the full extent of restricted channel section. In this restricted section about 70% of all bank-striking and grounding accidents of the existing canal occur. The minimum section of the restricted channel has a bottom width of 300 ft and a minimum depth of about 42 ft. Fig. 54 shows this section with a battleship hull of the *Iowa* class in it. The

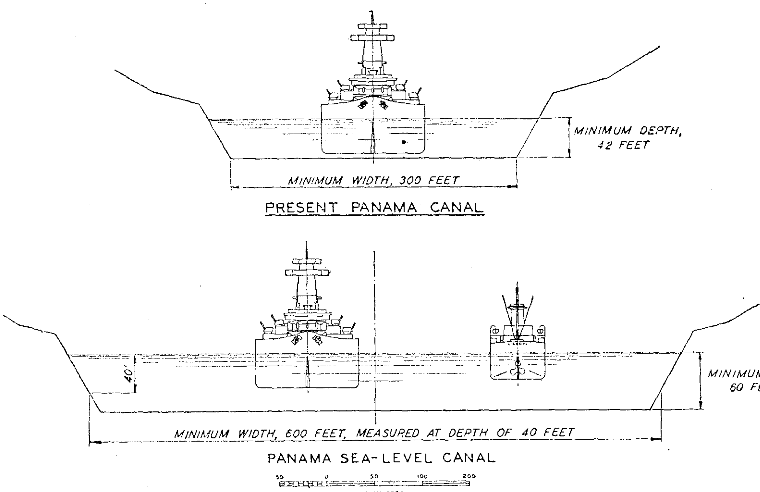


Fig. 54.—Channel Sections

sea-level canal, in comparison, would have approximately 30 miles of restricted channel section of minimum width extending from Limon Bay on the Atlantic side to the inner Balboa Harbor, Pacific side.

The existing canal is free of currents except for periodic tidal currents ranging up to a maximum of 1.5 knots in the sea approach channels. Currents in the sea-level canal would be limited by tidal regulation for the safety and convenience of shipping in the ordinary use of the canal to a maximum velocity tentatively established at 2 knots. If the tidal structures were damaged or wrecked by enemy action, the maximum current that would occur for short periods at extreme ranges of tide would be 4.5 knots. The importance of shipping in wartime requires that the channel be designed to provide safe and efficient transit when operating as an open waterway in which currents up to 4.5 knots would occur.

A survey of restricted waterways and canals in which currents are experienced discloses that currents do not significantly increase the problem of ship handling if (1) the ship is adequately powered and ruddered so that it can maintain sufficient headway for good controllability, and (2) the channel section and alinement are satisfactory for navigation under slack-water conditions. However, mechanical failures and personal errors, even if they occur rarely, are essential considerations in analyzing the safety of navigation. The loss of control in a following current would probably result in accidents of greater severity and frequency, because of the shorter time available for regaining control and the greater speed of the ship on striking the bank. To reduce the likelihood of accidents under such circumstances, additional width of channel for maneuvering is desirable.

Climatic conditions, particularly fog, play an important part in operating and scheduling transit in the existing canal; however, they do not have a major bearing on fixing the channel dimensions, alinement, or treatment of curves.

Fogs are of frequent occurrence in Gaillard Cut during the late hours of the night in the rainy season. Operations in the existing canal are scheduled so that ships do not enter the cut during fog periods. Although no exact estimate is practicable of the probable extent, frequency, and duration of fogs in a sea-level canal, some increase in each may be expected. However, no operation in fogs is planned for either an improved lock or a sea-level canal at Panama because the daytime capacity would be sufficient to meet all conceivable demands of traffic to the year 2000. Electronic navigation aids have been perfected which make navigation in fog feasible, and these will be adaptable for use in the Panama sea-level canal if and when required.

Where strong winds are present, vessels having large superstructures, or lightly-loaded vessels, may have difficulties navigating at low speeds in restricted channels. This situation holds at present for large aircraft carriers at the lock approaches and at the curves in Gaillard Cut of the Panama Canal. The difficulties are primarily attributable to the fact that the carrier must necessarily approach the lock or curve at a low speed. The effect of wind is less important in a sea-level canal as it would not be necessary for ships to transit curves at low speeds and lockages would be eliminated or reduced drastically.

Operating Criteria for the Sea-Level Canal

The general regulations under which the canal would be operated form an important part of the criteria for channel design. The essential criteria are those having to do with pilots, the meeting and passing of ships, ships' speeds, and interval between ships.

The design is based on the assumption that all transiting ships will be under the direction of experienced canal pilots. This condition exists in the present canal.

Single-direction traffic with alternating movements of traffic by direction would be feasible in a sea-level canal. This method of operation is used in the narrow and tortuous 8-mile Gaillard Cut for the transiting of large or poor-handling ships and for the transiting of all traffic in the cut after dark. Such a precaution unquestionably has been a major factor in the safety of transit through Gaillard Cut, and shipping has not been unduly delayed. The sea-level canal, by contrast, would have about 30 miles of restricted channel. Since the average time of transit through the sea-level canal would be 4.5 hours as compared to 8 hours in the present canal, it would be possible to operate the new canal by limiting traffic to one direction and causing some additional waiting without loss of efficiency over present canal operation. However, it would be highly desirable to retain the benefit of the shortened transit time in the new waterway, and the imposition of the restriction of one-direction traffic on the efficient use of the canal in wartime is clearly inadvisable. Therefore the canal should be designed for two-way traffic.

A survey by the United States Navy revealed that increases in the size of ships may be expected during the remainder of the twentieth century, and that, for a lock canal, locks 200 ft wide and 1,500 ft long would be required. Whether ships approaching these dimensions will become a reality and will require transit through the canal is quite uncertain. In any case such exceptionally large ships will be few in number, so that the channel needs to be adequate only for the single-direction passage of these ships.

Any future Panama Canal must accommodate the largest ships of the Navy now afloat without restriction or delay, particularly in times of emergency. The transit of large naval vessels would not be required in both directions at the same time, and the canal would not be required to accommodate naval ships of the largest class traveling simultaneously in opposite directions. Likewise, the meeting of the largest of the existing commercial vessels, such as the *Queen Mary*, and large naval vessels need not be considered. The incidence of their meeting would be infrequent and resultant delays to avoid such meetings would be minor.

An index to the size of ships that would transit the canal with such frequency as to make special transiting arrangements inadvisable has been developed by frequency studies of transits of various size ships based on Panama Canal records. Table 26 is based on predicted traffic in the year 2000 and on the

TABLE 26.—THEORETICAL FREQUENCY OF MEETING OF SHIPS IN THE RESTRICTED CHANNELS OF A PANAMA SEA-LEVEL CANAL, IN THE YEAR 2000

Length of vessels (ft)	NUMBER OF TIMES PER DAY THAT THE VESSELS LISTED IN COL. 1 WOULD MEET AND PASS A VESSEL HAVING A LENGTH (FT) OF:		
	500 or more	400 or more	300 or more
(1)	(2)	(3)	(4)
More than 500	1	11	15
400 to 500	10	31	48

assumption that the canal will be operating 16 hours daily. It shows that two ships more than 500 ft long would meet about once a day. It would be impractical to design a canal for the meeting and the passing of two such ships, as the passing could be avoided with little, if any, delay by proper scheduling of transits. Vessels longer than 500 ft would meet vessels from 400 ft to 500 ft long about ten times daily. Since special transit schedules to avoid those passings would cause individual delays of as much as 6 hours to 21 vessels on average days and to 31 vessels on peak-traffic days, the channel should be adequate for such passings. In using this criterion, "design ships" typical of each length group were selected. For the group, 500 ft and longer, a large loaded ore ship and a large naval vessel were selected. A loaded Liberty ship was selected to represent an average ship in the 400-ft to 500-ft class. Therefore, the channel of the sea-level canal is designed to permit a large loaded ore ship or a large naval vessel to pass a loaded Liberty ship with safety and ease. The controlling dimensions of these ships are shown in Table 27. The passing positions of a large naval vessel and a Liberty ship in the proposed sea-level canal channel are shown in Fig. 54.

TABLE 27.—CHARACTERISTICS OF DESIGN SHIPS

Description	Dimensions (Ft)				Displacement tonnage	Shaft horsepower	Horsepower per ton	Design speed (knots)	Controllability in proportion to size
	Over-all length	Water-line length	Beam	Loaded draft					
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Large naval vessel...	986	925	113	36	55,000	213,000	3.87	33+	Very good
Large ore ships......	583	574	78	35	32,450	13,000	0.40	17	Good
Liberty ship........	442	428	57	28	14,250	2,500	0.18	11	Good

Ships longer than 250 ft transiting the present Panama Canal are limited to speeds of 6 knots in the 300-ft channels, 10 knots in the 500-ft channels, 12 knots in the 800-ft channels, and 15 knots in the 1,000-ft channels, except in the case of the lock approaches or the channel through Balboa inner harbor where speeds are further reduced. Overtaking and passing is permitted only when one of the vessels is small or in the channels of Gatun Lake which are from 800 ft to 1,000 ft wide.

For the sea-level canal, a limiting speed of 10 knots was adopted for daily operation with the canal handling two-direction traffic. Naval task forces and convoys would be permitted a higher speed when not meeting opposing traffic. The minimum interval between ships would be about 1.5 miles, which is much greater than is normally required in canals. However, even at this interval, the capacity of the canal, with 16-hour daily operation, would be greatly in excess of the predicted peak-day traffic of the year 2000, so there would be no reason to reduce the interval.

Five criteria were used in the design of the sea-level canal channel, involving (*a*) pilots, (*b*) two-direction traffic, (*c*) single-direction traffic, (*d*) transit speed, and (*e*) ship interval. Specifically it was assumed that:

(*a*) All ships will carry a canal pilot.

(*b*) Naval ships up to the size of the largest existing naval vessel, and commercial vessels up to the size of a large loaded ore ship, will be permitted to meet and pass commercial vessels up to the size of a loaded Liberty ship.

(*c*) The design will be adequate for the clear channel transit of the largest ship that may be constructed to the year 2000.

(*d*) The normal speed of ships will be 10 knots; the passing speed, an average of 6 knots for both vessels.

(*e*) The average distance between ships will be 1.5 miles.

Design Methods and Investigations

Previous Methods of Design.—Available information showed that, ordinarily, one of three methods has been used in the past to desgn navigable channels:

(1) One method is to provide a cross-sectional area of channel equal to a certain multiple of the immersed hull area of the largest ship expected to transit. The channel depth is obtained by allowing about 3 ft of clearance under the hull of this ship, plus an allowance for deposition of silt between dredgings. The channel width is determined from the previously selected channel area and depth.

(2) A second common method involves comparing the channels of existing waterways and, on the basis of operating records, selecting channel widths and depths for the proposed waterway. This method has also been used in selecting the treatment of curves.

(3) The third method employs empirical formulas developed from actual experience or from studies of the maneuvering characteristics of ships.

An analysis of navigation in various major world waterways showed that many factors not taken into account by these methods had an effect on channel requirements. For this reason, none of the foregoing methods was considered satisfactory for the design of a new canal at Panama.

Investigations for Present Studies.—The magnitude and importance of the present Isthmian Canal Studies led to an investigation of all aspects of channel design including many not previously considered. An outline of the investigations follows:

a. Examination of the literature on past practices in the design of restricted waterways;

b. Review of records of ship handling in the Panama Canal and consultation with pilots and others of the marine operating staff, The Panama Canal;

c. Compilation of physical data affecting channel design on the major waterways of the world (those having the greatest similarity to a sea-level canal at Panama being the present Panama Canal, the Suez Canal, the Cape Cod Canal, and the Houston (Tex.) Ship Channel);

d. Consultations with the pilots and operating personnel of the Suez Canal, the Cape Cod Canal, and the Houston Ship Channel on navigation in their respective canals and on the channel requirements for a sea-level canal at Panama, information also being obtained from ship operators regarding the adequacy and limitations of the major world waterways being studied;

e. Operation of ship models in restricted channels of different sizes under various conditions of current, by the Navy at the David Taylor Model Basin;

f. Construction and operation of a model of a Panama sea-level canal at a scale of 1:100, to determine the magnitude of uncontrolled tidal currents and also the range of control that could be established if tidal regulation were adopted; and

g. Advice and recommendations from the Navy on features of the canal, particularly those affecting the requirements for ships operated by the Navy.

The results of these examinations and inquiries are not described in this paper except where they have an important bearing on specific problems of design.

Design of Channel Depth

Both experience and ship model tests have established the fact that depth of section is of prime importance to good navigation, and that, within reasonable limits, the required width of channel is a function of the depth. Consequently, the depth of channel is established prior to the determination of the channel width.

The channel depth must be sufficient to allow transiting of the largest naval and commercial vessels expected to be constructed to the year 2000 under conditions of good controllability and without excessive squat or sinkage of the vessel when traveling at design speeds. Insufficient depth under a ship hull retards the flow of water to the propeller and to the rudder and reduces the effectiveness of both. The Navy has advised that a 50-ft depth over the sills of any new locks should be adequate for the largest naval or commercial vessels expected to the year 2000. As ships pass through the locks at very slow speeds, it is necessary that the channel have a minimum depth greater than 50 ft.

The depth of the channel at any location along the canal is measured below the water-surface profile connecting the low water elevation at each entrance to the canal.

TABLE 28.—Relationship Between Channel Depth and Ship Draft, for Existing Waterways

Waterway	Depth channel (ft)	Transit speed (knots)	Largest Vessels Using Canal		Largest Vessel Having Good Controllability	
			Draft (ft)	Depth/Draft	Draft (ft)	Depth/Draft
Gaillard Cut (Panama Canal)	42	6	36	1.17	32	1.31
Suez Canal	43	7.5	34	1.26	28	1.54
Cape Cod Canal	40[a]	6–12	32	1.25	28	1.43

[a] Project depth is 32 ft, but scour has increased this depth to an estimated average of 40 ft.

A study was made of the relationship in certain major existing waterways between the channel depth and the draft of transiting vessels. The depth of the channels of three major waterways and the draft and the transit speeds of the largest ships normally using the waterways are given in Table 28. The draft shown for the "Largest Vessels Using Canal" is either that of the deepest draft vessel to transit the waterway or that of the maximum draft vessel that the canal authorities will permit to transit.

This study, which considered speed and channel width, indicated that for good vessel controllability the channel depth of the Panama sea-level canal should be about 1.5 times the draft of ships comprising the normal daily traffic, which in the year 2000 would probably include vessels having drafts up to about 40 ft. Consequently, a channel depth of approximately 60 ft is indicated. Study of the behavior of ships having a lesser ratio of depth to draft in existing waterways indicates that vessels of maximum size for the year 2000, with draft possibly approaching 50 ft, could safely transit a channel of 60-ft depth at the design speed of 10 knots.

The ship model tests discussed in the fifth paper of the Symposium clearly illustrated the importance of depth on the controllability of a vessel. The rudder angle required to control and hold a vessel parallel to the banks during off center-line maneuvers is the best indicator of relative controllability. Fig. 55 shows a curve, based on data obtained from the model tests, of the rudder

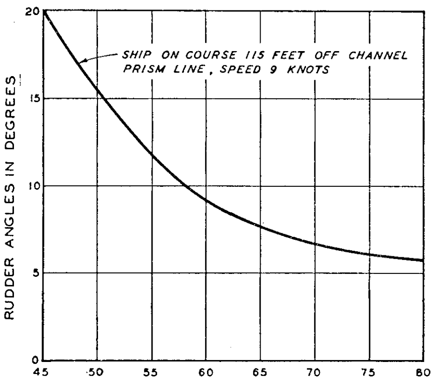


FIG. 55.—EFFECT OF CHANNEL DEPTH ON SHIP CONTROLLABILITY

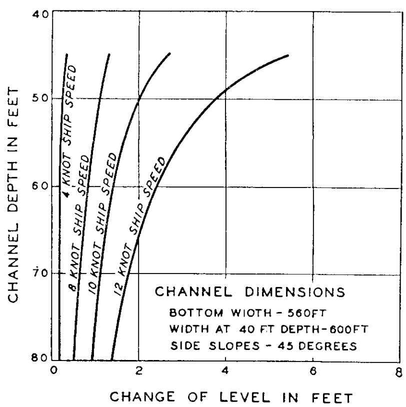


FIG. 56.—CHANNEL DEPTH VERSUS CHANGE OF LEVEL OF A SHIP

angles required to maintain a large naval vessel (length 900 ft, beam 113 ft, and draft 32.25 ft) on a course 115 ft off the prism line of a 500-ft wide channel (bottom width 500 ft with 45° bank slopes and depths ranging from 45 ft to 80 ft). A ship might be in such a position in a passing maneuver following momentary failure of equipment or wrong execution of a rudder command. At a 60-ft depth, a rudder angle of only 9° is required to control the vessel. In a 45-ft depth of channel, the angle required is 20° and the curve is rising rapidly, indicating that an unsafe condition is being approached where full available effort of the rudder would be required to control the vessel. The gain in reduction of the rudder angle as depth increased beyond 60 ft is slight and would not justify the increased construction costs.

In selecting channel depth, sufficient clearance must be provided between the ship and the channel bottom to avoid excessive sinkage or change of level of a vessel when transiting a restricted channel at the maximum allowable speed. Fig. 56 illustrates the effect of channel depth and ship speed on the change in level of the same large naval vessel as that in Fig. 55 in a channel with the same width as the proposed sea-level canal channel. The curves shown are based on data obtained from ship model tests, verified in part by measurements made on actual ships transiting the Panama Canal. It was found that, with a channel depth of 60 ft, sinkage would not be a factor so long as the channel has a width of 300 ft or more. The curves shown are for the stern only, the bow curves being similar. The ship traveled on the center line of the channel.

Based on the experience of existing waterways and experimental work at the Taylor Model Basin, with due consideration of costs, a minimum depth of 60 ft for a sea-level canal is considered adequate. For a lock canal having a shorter length of restricted channel, a lower transit speed, and no currents, a 55-ft depth is considered adequate.

Design of Channel Width

Two methods were used in designing the width of channel, one (method *A*) being based largely on the adjustments of similar existing waterways, and the other (method *B*) being based primarily on observations of the behavior of ships in existing waterways and in ship model experiments.

Method A.—The existing waterways used in the application of method A should have characteristics somewhat similar to the waterway for which the channel width is to be determined. A study is then made to ascertain the sizes of the largest ship or ships of average maneuverability that can easily navigate each of the existing waterways under normal conditions with the degree of safety and efficiency of transit desired in the proposed waterway. The selection of these ships may be on the basis of either single-direction or two-direction traffic. In those waterways where single-direction traffic is used as the basis of analysis, the ship selected is called the "representative ship." In those where two-direction traffic is the basis of analysis, the larger of the two passing ships is called "representative ship No. 1," and the smaller, "representative ship No. 2." The ships that are adopted as the maximum size for which the proposed canal should be adequate to provide two-direction traffic are designated "design ships" and the notations "No. 1" and "No. 2" apply to the larger and smaller ones, respectively. The channel section of each waterway is then adjusted to be adequate for the "design ships" transiting the adjusted waterway under the conditions that would exist in a sea-level canal. This procedure requires four steps, as follows:

1. The channel dimensions of each existing waterway are multiplied by the ratio of the dimensions of design ship No. 1 to those of representative ship No. 1. On the premise that the required channel section is directly proportional to ship size, the resulting channels are then adequate for design ship No. 1.

2. The adjusted channel sections of the existing waterways are now converted to a common selected depth and to the same side slopes. This is done by holding the cross-sectional areas of the channel sections constant and by adjusting the channel width. The adjustment is based on the premise that the navigational characteristics of a channel within reasonable limits are a function of its cross-sectional area.

3. The third step is an adjustment for design ship No. 2. Those channels which in the previous steps were based on single-direction traffic are increased in width by an amount equal to three times the beam of design ship No. 2. Channels based on two-direction traffic are increased (or decreased, if the first step resulted in representative ship No. 2 being larger than design ship No. 2) by an amount equal to five times the difference between the beam of design ship No. 2 and the beam of representative ship No. 2 after the latter has been multiplied by the ratio used in step 1. The ratios of three and five are empirical and were developed from an analysis of the relationship of channel width to ships' beams.

4. The navigating and physical characteristics of each of the existing waterways are compared with those of the proposed sea-level canal and a final adjustment is made in the channel widths obtained in step 3. The characteristics compared are traffic speed, currents, alinement, bank material, and length of restricted channel.

Application of Method *A*.—Channel studies using method *A* included the Cape Cod Canal, the Suez Canal, and the Houston Ship Channel, and Gaillard Cut of the Panama Canal. The procedure followed in adjusting the Gaillard Cut channel of the present Panama Canal is described in detail.

The study of navigation in Gaillard Cut showed that for single-direction traffic the representative ship is a T-2 tanker, and for two-direction traffic representative ship No. 1 is a Liberty ship and representative ship No. 2 is a small ocean-going cargo vessel. The *S. S. Pereira,* a vessel of good controllability with a beam of 32.7 ft and a draft of 15.1 ft, was selected as typical of small ocean-going cargo vessels. Both cases are shown in Fig. 57 which illustrates the step-by-step procedure used in determining channel widths for Panama lock and sea-level canals. The two-direction traffic condition which is shown as case 2 in Fig. 57 will be developed for a Panama sea-level canal in the following paragraphs. In this application the large loaded ore ship (Table 27) is used as design ship No. 1 and the Liberty ship as design ship No .2. One of the requirements of this method is that design ship No. 1 and representative ship No. 1 be of the same controllability classification, thus the large naval vessel (Table 27) could not be used. The ratio of the beam of design ship No. 1 (78 ft) to the beam of representative ship No. 1 (57 ft) is 1.37 and the ratio of of drafts (35 to 28) is 1.25. The average of the two ratios is 1.31 which, for purposes of conservatism, is increased to 1.35. The actual minimum channel dimensions of Gaillard Cut and the dimensions after being multiplied by 1.35 in the first step are shown in Fig. 57.

Step 2 is a conversion of the Gaillard Cut adjusted section to the selected 60-ft depth and to 1-on-1 side slopes, which are approximately average bank slopes. The bottom width is decreased to 363 ft as shown in Fig. 57.

Step 3 adjusts for design ship No. 2. When the adjustment in step 1 was made, not only was the size of the channel increased, but representative ship No. 2 was also increased in size from a beam of 32.7 ft and a draft of 15.1 ft, to a beam of 44 ft and a draft of 20.5 ft, respectively. The difference between the beam of design ship No. 2 and that of representative ship No. 2, after ad-

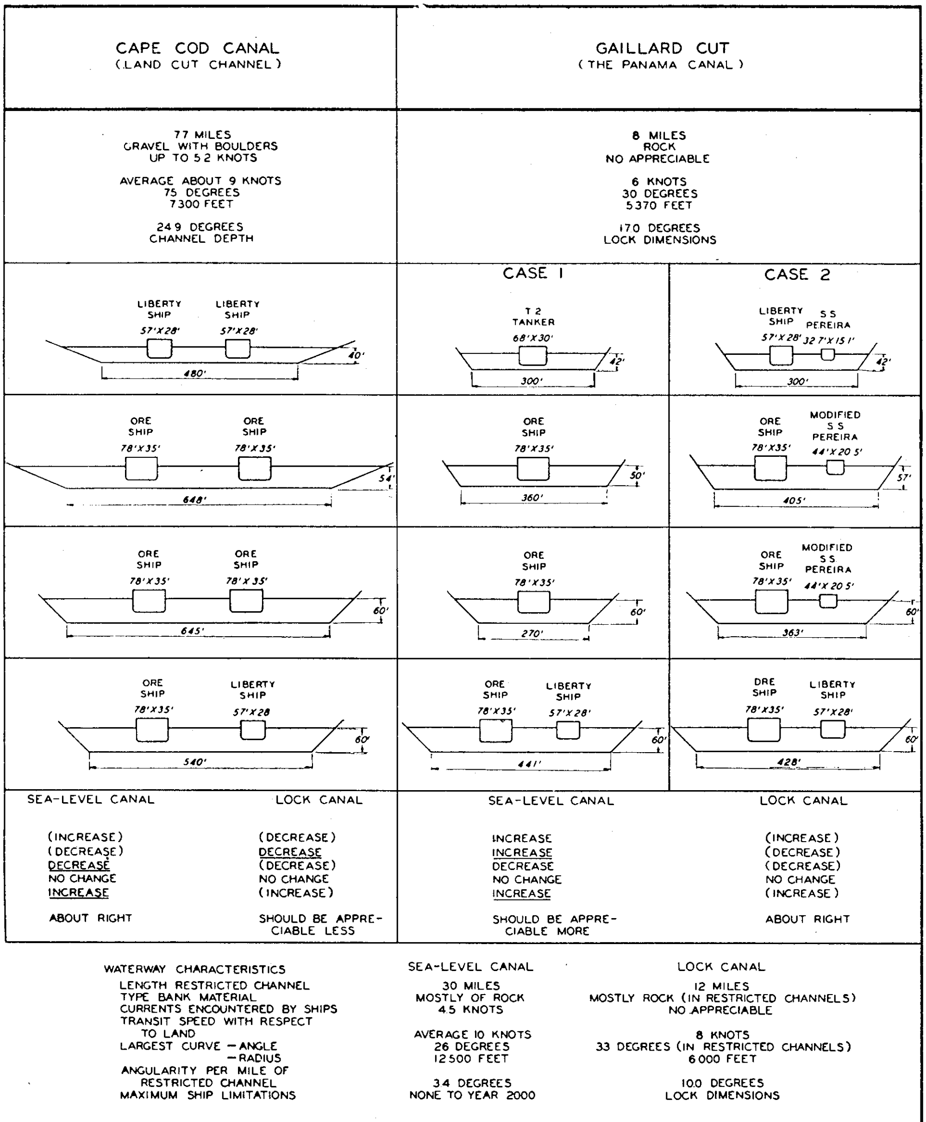
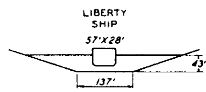
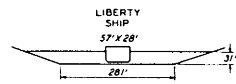
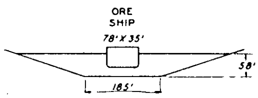
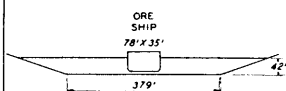
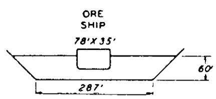
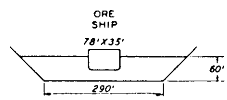
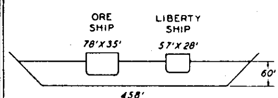
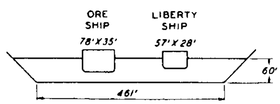
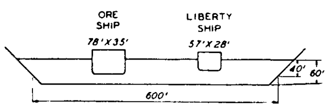


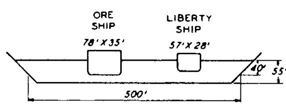
FIG. 57.—DIAGRAM OF PROCEDURE FOR

STEP NO	DESCRIPTION OF STEPS	SUEZ CANAL (LAND CUT CHANNEL)	HOUSTON SHIP CHANNEL (250 FOOT PROJECT WIDTH CHANNEL)
	WATERWAY CHARACTERISTICS		
	LENGTH RESTRICTED CHANNEL	75 MILES	12.5 MILES
	TYPE BANK MATERIAL	SAND	EARTH
	CURRENTS ENCOUNTERED BY SHIPS	UP TO 3 KNOTS	NO APPRECIABLE
	TRANSIT SPEED WITH RESPECT TO LAND	7.5 KNOTS	4-8 KNOTS
	LARGEST CURVE — ANGLE	63 DEGREES	109 DEGREES
	— RADIUS	9966 FEET	3000 FEET
	ANGULARITY PER MILE OF RESTRICTED CHANNEL	3.3 DEGREES	61.7 DEGREES
	MAXIMUM SHIP LIMITATIONS	CURVES	CHANNEL DEPTH
	REPRESENTATIVE SHIPS IN THE SELECTED WATERWAYS		
1	ENLARGEMENT OF WATERWAY FOR DESIGN SHIP NO 1		
2	ADJUSTMENT TO 60 FOOT DEPTH AND 1/1 SIDE SLOPES		
3	ADJUSTMENT FOR DESIGN SHIP NO 2		

STEP NO 4 — WATERWAY CHARACTERISTICS AND INDICATED ADJUSTMENTS	SUEZ: SEA-LEVEL CANAL	SUEZ: LOCK CANAL	HOUSTON: SEA-LEVEL CANAL	HOUSTON: LOCK CANAL
TRAFFIC SPEED	INCREASE	NO CHANGE	(INCREASE)	DECREASE
CURRENT	INCREASE	(DECREASE)	INCREASE	NO CHANGE
ALIGNMENT	(DECREASE)	(INCREASE)	DECREASE	DECREASE
BANK MATERIAL	INCREASE	INCREASE	INCREASE	INCREASE
LENGTH RESTRICTED CHANNEL	DECREASE	DECREASE	INCREASE	NO CHANGE
GENERAL ADJUSTMENT	SHOULD BE APPRECIABLE MORE	SHOULD BE SLIGHTLY LESS	SHOULD BE APPRECIABLE MORE	SHOULD BE LESS



PANAMA SEA-LEVEL CANAL



IMPROVED PANAMA LOCK CANAL

SELECTED CHANNEL SECTIONS FOR PROPOSED PANAMA CANALS

SELECTION OF CHANNEL SECTIONS

justment by step 1, is 57 − 44 = 13 ft. To adjust for design ship No. 2, the channel width is then increased by 5 × 13 = 65 ft. Thus, the bottom width of the Gaillard Cut channel section is changed from 363 ft to 428 ft.

Step 4 takes into account the difference in the navigating and physical characteristics of the waterways. Traffic speed in Gaillard Cut is 6 knots, but 10 knots is to be allowed in the Panama sea-level canal; therefore, an increase in the width of the Gaillard Cut section, as adjusted by step 3, is indicated. There are no appreciable currents in Gaillard Cut, but currents up to 4.5 knots would obtain in the proposed canal; therefore, an appreciable increase in width is indicated. The alinement of the proposed canal would be an improvement over the existing alinement through Gaillard Cut, so a decrease in width is indicated. Bank material would be the same for both waterways, so no change in width is indicated because of this factor. Gaillard Cut is about 8 miles long, and the proposed canal would have about 30 miles of restricted channel of minimum width; therefore, an appreciable increase in channel width is indicated. These indicated adjustments, which apply to both case 1 and case 2, Fig. 57, for the Gaillard Cut, and the indicated adjustments as developed for the Cape Cod Canal, the Houston Ship Channel, and the Suez Canal, are shown in Fig. 57 for

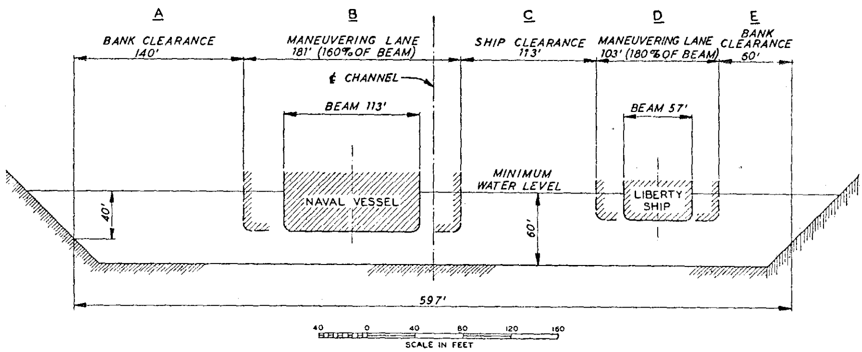


FIG. 58.—ELEMENTS OF CHANNEL DESIGN; SEA-LEVEL CANAL

both lock and sea-level canals at Panama. The characteristics are listed in the order of their importance to channel width. The general indicated adjustment for each of the four waterways and the bottom widths of each after adjustment by the first three steps are shown in Fig. 57, slight adjustments being indicated in parentheses and appreciable ones being underlined. The bottom width for the Panama sea-level canal as indicated by this method is 560 ft. However, because of variable slope conditions that would prevail throughout the canal, it is considered desirable to reference the channel width to a depth corresponding to the draft of the larger vessels, which is approximately 40 ft. On the basis of 1-on-1 side slopes used in this method, the indicated desirable width at the 40-ft depth is 600 ft. The indicated width at the 40-ft depth for an improved Panama lock canal is 500 ft.

Method B.—In this method the channel is divided into five parts (Fig. 58) and each part is analyzed separately. The combined widths of the parts then determine the width of the channel. The parts are titled "bank clearance"

(A and E), "maneuvering lanes" (B and D), and "ship clearance" (C). In this method of analysis, use is made of experience at Panama, pilot opinion, and the results of the ship model tests as presented in the fifth paper of this Symposium. The passing of the large naval vessel and the Liberty ship is used in this application since test data are not available for the ore ship.

The bank clearances A and E are considered as the space from the rail of the ship to the bank at a depth corresponding to the draft of the vessel in question. This space must provide sufficient water area between ship and bank so that the ship will retain good controllability when transiting at this distance off the bank. This distance is selected from Fig. 59, which gives the rudder angles required to hold a ship on a course parallel to the bank for various offsets from the bank of a channel 60 ft deep and 600 ft wide at the 40-ft depth. The angularity of the rudder that had to be carried to hold or to maintain the vessel on its course under a particular set of conditions is considered the best measure of controllability. The maximum angle to which a ship's rudder can be set is normally about 35°. The difference between this angle and that required to accomplish a particular maneuver is a measure of the reserve controllability available in the event of an emergency. Thus, a large rudder angle indicates a low safety factor, and a small angle, a high safety factor. The selection of the maximum rudder angle considered safe for approaching the bank or for passing an opposing ship must, therefore, be made primarily on the basis of navigational safety. Also, the selection must take into consideration the discrepancies in model tests as compared to actual navigation, and the factors affecting the channel dimensions which are not fully considered in operating the model. The bank clearance selected is based on a rudder angle of 5°, considered to be a very conservative value but selected to provide an excess of safety to cover conditions that exist in an actual waterway that cannot be reproduced in the model. From Fig. 59, the bank clearance for the large naval vessel is 140 ft, and for the Liberty type ship it is 60 ft—both clearances being measured at the 40-ft depth. The curves in Fig. 59 are based on a 9-knot speed rather than on a 6-knot speed—to take account of head currents.

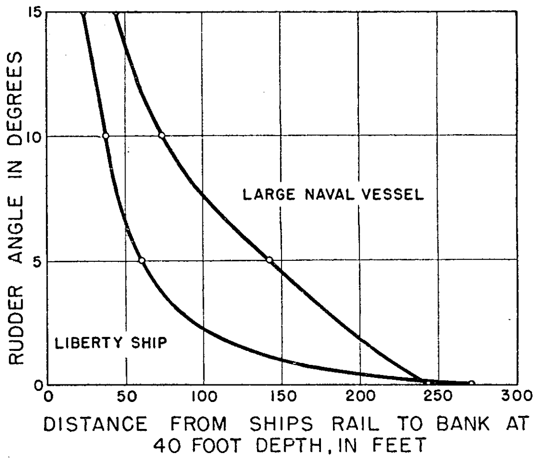


FIG. 59.—BANK CLEARANCE VERSUS RUDDER ANGLE

The maneuvering lanes are indicated as B and D, Figs. 58 and 60. These lanes represent the part of the channel in which each ship may maneuver without encroaching on the safe bank clearance or without approaching the other ship so closely that dangerous interference between ships will occur. The ship model tests in themselves did not give sufficient data for fixing the widths of the maneuvering lanes because time and funds did not permit the running of a sufficient number of tests on the wide range of ship sizes and types that would be necessary to establish the possible variations of a ship's position when meeting. Based on pilots' opinions and observation of ship courses, the width

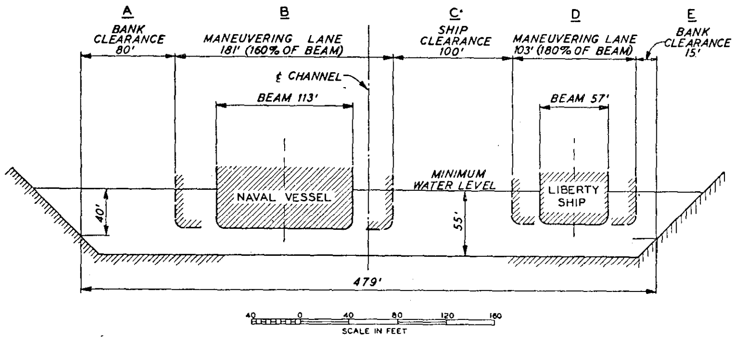


FIG. 60.—ELEMENTS OF CHANNEL DESIGN; LOCK CANAL

of the maneuvering lane has been established as ranging from 160% to 200% of the beam of the ship, depending on the characteristics of the ship. The limited observations taken on transits of actual ships through certain reaches of the Panama Canal indicate that these allowances are entirely adequate. Plots of ship courses in the model tests confirm the allowances. Neither experience nor tests indicate that currents have an appreciable effect on the required maneuvering lane if sufficient depth of channel is provided to assure proper response to the rudder. Ships having "very good," "good," and "poor" controllability are considered to require maneuvering lanes of 160%, 180%, and 200% of their beams, respectively. The large naval ship with a beam of 113 ft, therefore, would require a lane width of 181 ft; and the Liberty ship, one of 103 ft.

The ship clearance indicated as lane C in Fig. 58 is the minimum space between two ships in passing that will assure good controllability for both ships during and following the passing maneuver. As both ships approach the inner limits of their maneuvering lanes, the effects of the channel banks decrease, and the interaction between the two ships becomes controlling. With ships at the inner limit of the maneuvering lane, bank action is insignificant. The ship model tests indicate that, if rudder angles of from 10° to 15° are not to be exceeded when two such ships pass in a channel with a current up to 4.5 knots, the distance between ships must be at least 100 ft or equal to the beam of the larger ship, whichever value is greater. Pilot opinion is consistent with this criterion in establishing ship clearance. A larger rudder angle for passing than that used for bank clearance is justified because of the much shorter time that the interaction between ships exists as compared to the time bank action may affect the ship. The minimum clearance required for the passing of the large naval vessel and the Liberty ship is 113 ft.

With a computation based on this method of analysis, the required width of the sea-level canal, measured at a depth of 40 ft, would be 597 ft. The values for each part of the channel are shown in Fig. 58. A similar analysis for the minimum section of a lock canal resulted in the values shown in Fig. 60.

The Panama Canal pilots assisting in the ship model tests were of the opinion that the effect of the proximity of channel banks and channel bottom, the currents, and the interaction between passing ships were clearly and accurately indicated in the ship model tests. A limited series of prototype tests at Panama has generally confirmed qualitative results of the model tests. However, there are certain discrepancies between model and prototype which must be considered in adapting the test data to channel design. The factors favoring the test results included the following:

(*a*) Uniformity of channel section,
(*b*) Weather conditions; and
(*c*) Freedom from mechanical (rudder and engine) breakdowns.

Those factors not favoring the test results included the following:

(*a*) Time scale requiring pilots to act seven to ten times as fast;

(*b*) Stability of ship models about a vertical axis not being comparable with prototype ships (particularly evident in the test run using the 1:86 scale ratio); and

(*c*) The fact that the pilot is not actually aboard the vessel and thus loses the viewpoint and the "feel" of an actual ship.

Pilots were in agreement that navigation under prototype conditions would show some over-all improvement over the action observed in the model. The model tests, although limited in their capabilities to reproduce and take into consideration all factors affecting the safety and security of transiting ships in an actual waterway, have performed an invaluable service in enabling the pilots, technicians, engineers, and consultants to reach a common understanding of the operation of ships in restricted channels.

Final Selection of Channel Dimensions

Pilots and marine operating officials at the Cape Cod Canal, the Houston Ship Channel, and the Suez Canal were polled informally by Panama Canal representatives on their views with respect to the required channel width and depth for two-way traffic in the Panama sea-level canal. The Cape Cod personnel considered that a channel from 500 ft to 600 ft wide, and of adequate depth, would afford easy navigation for the largest commercial and military ships. At the Houston Ship Channel it was considered that for a channel with rocky banks the channel should have a minimum width of 600 ft and a minimum depth of 60 ft. The Suez Canal personnel were of the opinion that a channel from 500 ft to 600 ft wide and from 50 ft to 60 ft deep would be ample for two-direction traffic of the largest commercial vessels operating in currents up to 4.5 knots.

The Marine Division of The Panama Canal and its pilots have been closely associated with all navigation studies made as a part of "Isthmian Canal

Studies—1947," and they are in general agreement that a channel 60 ft deep and 600 ft wide at the 40-ft depth would be satisfactory for the sea-level canal and that 55-ft by 500-ft dimensions would be adequate for the restricted channels of the lock canal.

As a result of the design studies and opinions of marine operating personnel, it was concluded that the Panama sea-level canal should have a minimum channel depth of 60 ft and a minimum channel width of 600 ft at the 40-ft depth, and that corresponding dimensions for an improved Panama lock canal should be 55 ft and 500 ft.

Curves

Navigation around curves is generally more difficult than in a straight channel, particularly if currents exist. The alinement as tentatively accepted for a sea-level canal has a maximum deflection angle of 26°. This value corresponds to maximum deflection angles of 30° for the Gaillard Cut of the present Panama Canal, 63° for the Suez Canal, 75° for the Cape Cod Canal, and 109° for the Houston Ship Channel.

Experience in Existing Waterways.—Analysis of the different types of curves on existing waterways, although illustrating the weaknesses of much of the treatment, has not resulted in the development of a satisfactory method of treatment for a sea-level canal. There are so many differences in operating technique and physical conditions of the different waterways that comparison of curve treatment to establish the best method is not possible. The marine opinion at Suez, where the original curves were widened and modified, is that unwidened long-radius curves are the most desirable. However, this opinion is based on single-direction traffic on curves with no passing even of ships tied up to the bank.

The Cape Cod Canal is a good example of a channel having curves of adequate radius (7,000 ft or more) and channel width (480 ft) to permit two-direction traffic and practically unrestricted operation by all ships that may transit the waterway. There are no straight sections in the land-cut channel of the Cape Cod Canal of sufficient length to establish any relationship between the difficulties of navigating on a curve as compared to a straight channel.

At the existing Panama Canal a true curve is not used. In most cases the outside prism lines are extended to intersection. The inside prism lines are stopped short of the point of intersection and connected by a chord. This treatment, although reasonably satisfactory for a channel without currents, would be unsatisfactory with currents because of poor flow and eddy conditions.

Ship Model Tests of Curves.—Ship model tests of various types of curve treatment were performed at the Taylor Model Basin. Time and funds did not permit the continuation of these tests to the point where finally conclusive results could be established. Most of the tests were conducted at a scale of 1:86 rather than at the scale of 1:45 used in straight-channel tests. Outlines of the various curve treatments tested are shown in Fig. 52. The 1:86 scale tests indicated that the curve with no widening (Fig. 52 (*a*)) was superior to all the others for single-direction traffic and that two-direction traffic would not be acceptable for any of the curves. The results of the 1:86 scale tests were very erratic and definitely not consistent with actual experience at either Cape Cod or Suez. It was believed that the instabilities of the 1:86 scale model and of the 9:1 time ratio were the principal causes of the unsatisfactory results. Therefore, tests were made using a scale ratio of 1:45, of a single unwidened curve, 600 ft wide at a 40-ft depth and 60 ft deep, with 1-on-1 side slopes, a 12,500-ft radius, and a 26° intersection angle. These tests clearly demonstrated that complete dependence could not be placed on the results of the 1:86 model tests. The tests to a 1:45 scale demonstrated that single-direction navigation around a prototype of the curve tested is entirely practicable and safe with controllability characteristics similar to those for operation in straight channels. Time did not permit two-way navigation tests in the 1:45 scale curve. The limited number of off-center runs, although showing some improvement in conditions over the 1:86 scale tests, did not indicate that two-direction traffic of "design ships" would be a safe operation.

Whether a practicable method of widening can be developed to permit passing of the large ore carrier or naval vessel and a loaded Liberty ship (design criteria for straight channel) has not been established. It is considered that model tests to scales of 1:20 or of 1:30 should be used in any further tests to determine the best methods of curve treatment.

Should it develop that satisfactory curve treatment for two-direction traffic is unattainable, operating restrictions would have to be placed on the passing of the larger ships on curves. These restrictions would not noticeably affect the transit time or increase delays to shipping but would necessitate more detailed dispatching.

ALINEMENT

The alinement of the present canal contains twenty-three angles with a total angularity of 598°. The largest of the angles is 67°, and four of the angles are larger than 50°. Use of this alinement and a center-line radius of 12,500

TABLE 29.—COMPARISON OF SELECTED ALINEMENT FOR SEA-LEVEL CANAL WITH PRESENT CANAL ALINEMENT

Canal	No. of Angles		Angularity (Degrees)			Length (Miles)		Restricted Channel	
	<20°	>20°	Maximum angle	Total	Per mile	Minimum length of straight reach	Total length of canal	Length (miles)	In-curves (%)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Sea level......	6	2	26	117	2.54	2.94	46.02	30	14
Present lock...	11	12	67	598	11.68	0.07	51.20	12	33

ft on the curves would result in almost 50% of the restricted channel of a sea-level canal being in curves, and was considered unsatisfactory for a sea-level canal having a restricted channel for the major part of its length in which currents up to 4.5 knots might exist.

An investigation was made of possible alinements for a sea-level canal at Panama ranging from the present canal alinement to an absolutely straight alinement from shore line to shore line. The proposed alinement is shown in Fig. 7. The maximum angle in this alinement is 26° and the total angularity is 117°. It was found that any reasonable increase in the size of the maximum angle or in the total angularity would not decrease the excavation cost. A comparison of the characteristics of this alinement with that of the present canal is shown in Table 29.

Summary of Sea-Level Channel Design

A summary of the tentative channel design of a sea-level channel resulting from these studies and investigation is as follows:

Physical Dimensions—	
Total length of restricted section of minimum channel width, in miles	30
Minimum Channel Section—	
Depth, in feet	60
Width, in feet, at 40-ft depth	600
Side slopes (steepest)	3 on 2
Number of angles in restricted section	6
Maximum angle, in degrees	26
Radius of curves, in feet	12,500
Widening at curves (dependent upon further study)	...
Minimum distance between points of intersection, in miles	4.21
Minimum sight distance, in miles	1.52
Qualifying Operation Criteria—	
Pilots required for all ships	...
Maximum transit speed (water speed), in knots	10
Normal passing speed of large ships, in knots	6
Two-direction traffic with maximum limitation of largest existing naval vessels or a large commercial cargo vessel passing an average size commercial cargo vessel	...
Passing on curves limited to average size ships (subject to additional curve study)	...
Maximum length of ships, in feet, that can pass in same direction	300

The design is liberal in physical dimensions and should provide a safe and efficient waterway for all shipping, both commercial and military, that may be expected to use it to the year 2000.

The adequacy of the proposed sea-level canal channel is affirmed by Panama Canal pilots as presented in a review of the Governor's Report to Congress by a pilot committee consisting of four senior pilots whose total experience at the Panama Canal totals 87 years:

> "From a piloting point of view, we feel that this canal [sea level] will have a greater safety factor than the other three plans [lock canal] outlined and will not contain any difficulties or hazards of any importance. The most important safety factors inherent in the proposed sea-level canal are

the dimensions, alignment, and tidal-control structures, as shown and described in the draft [of the report]. We are of the opinion that in the event the tidal-control structure should be badly damaged or destroyed, it would be feasible to operate the canal as an uncontrolled waterway."

Further Tests and Investigations.—The channel dimensions for the Panama sea-level canal, as developed in this paper, are considered to be satisfactory. However, in the event that construction is authorized, the magnitude of the project and the necessity for more information on curve treatment would make it essential that additional studies be made. These studies would consist of further investigations of navigation in existing waterways and continuance of the ship model tests. Particular emphasis would be placed on the development of data to confirm the width of maneuvering lane and passing clearance and the best method of treating curves. Model studies would be conducted at a larger scale than used previously to reduce the scale effects apparent in former studies.

EXCAVATION SLOPES

By Wilson V. Binger,[43] Assoc. M. ASCE and Thomas F. Thompson,[44] Affiliate, ASCE

Synopsis

The geologic and soil mechanic studies conducted to establish stable slopes for the formations that would be excavated for a sea-level canal at Panama are described in this paper. The authors discuss the early and current geological investigations, the geological features of the area, the difficulties experienced in the slides that occurred during construction of the present canal, and the development of slope standards used in the preliminary design of a sea-level canal.

The paper concludes that adequate exploration and testing to develop the strength properties and distribution of the materials to be excavated, combined with present understanding of the mechanics of slide development, allow design of slopes that would be secure from major slides.

Introduction

The construction of a sea-level canal across the Isthmus of Panama would require the excavation of more than 1,000,000,000 cu yd of material, or about three times the volume of material removed in the construction of the existing canal. Almost 30% of the new excavation would be concentrated in a 4-mile section through the Continental Divide north of Pedro Miguel, where cuts deeper than 600 ft would be required.

Experience with the great slides that developed during the excavation of the present canal indicates the design of stable slopes for a sea-level canal to be a problem of unprecedented magnitude in engineering geology and soil mechanics. The renowned slides of the Panama Canal occurred in the Continental Divide area, the greatest troublemakers being limited to the 1-mile length of deepest cut where the weak Cucaracha formation in the East Culebra, West Culebra, and Cucaracha slides (Fig. 61) increased by about 20% the amount of excavation required for building the canal. These slides are object lessons for the design of slopes.

There can be little question of the importance of designing the canal banks for stability. If permitted to occur, slides might block the canal during or following construction. Interruption of traffic by slides at any time would penalize commerce, and in wartime such delays would be intolerable. Furthermore, if slides occur, the total amount of material to be removed would be greater than the excavation required if the canal banks were excavated initially to stable slopes.

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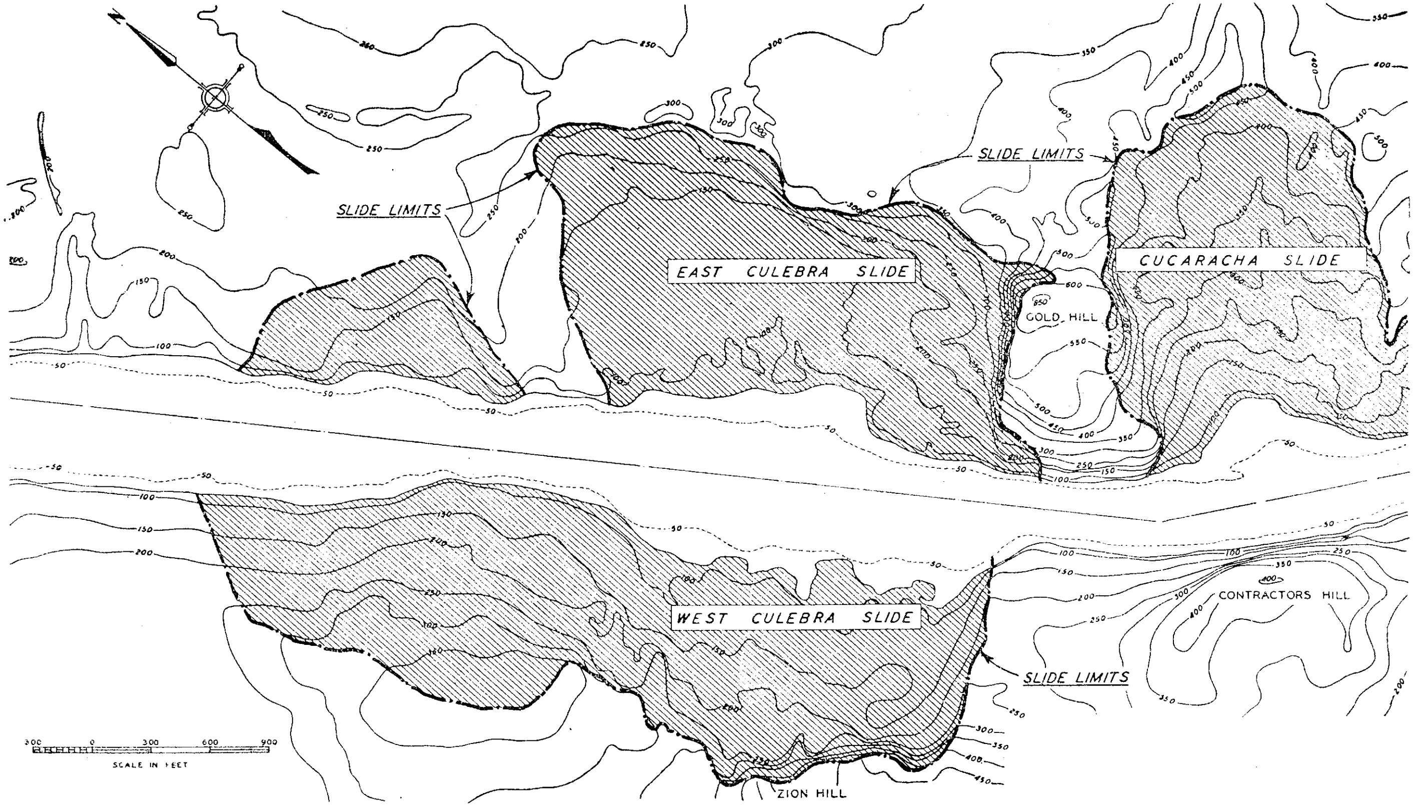


FIG. 61.—LOCATION OF MAJOR SLIDE AREAS, PANAMA CANAL

The current studies for Public Law No. 280 have been greatly facilitated by the extensive slope studies made from 1939 to 1942 during the Third Locks Project, particularly those of the areas containing the materials most critical with respect to sliding. Despite the extent of the past and current studies, additional geologic exploration would be required prior to excavation to locate the contacts between rock formations more accurately, as well as to define the location and character of the various weak and strong strata within each formation. More extensive testing and more detailed analysis would also be employed in the design of final excavation slopes. It is believed, however, that the studies of slopes reported herein have been conservative enough that the estimates of excavation cost will more than cover the adjustments in slope design that may result from more extensive studies.

History of Geologic Exploration

The geology of the Canal Zone has been studied intermittently for many years, but such study prior to the arrival of the French was not conducted for engineering purposes and, moreover, was neither systematic nor thorough. By present standards, the geologic investigations by the French during the periods of the first and second canal companies were very inadequate. Explorations were conducted in some detail to determine foundation conditions at dam, lock, and harbor-facility sites by both the early French and early American investigators prior to commencing construction, but only a minimum of information for establishing proper slopes was assembled for the regions of heavy cut through the Continental Divide area where disastrous slides later developed.

TABLE 30.—Subsurface Explorations, Panama Canal, 1881 to 1947

Line	Agency	Years	Total number of holes	Holes in Gaillard Cut	
				No.	Average depth (ft)
(1)	(2)	(3)	(4)	(5)	(6)
1	Old French Company	1881–1894	605	63	(42 holes) 120
2	New French Company	1894–1903	60	27 pits, 2 borings	No records available
3	Isthmian Canal Commission	1904–1914	5,073	81	160
4	Third Locks Project[a]	1938–1943	1,968	242	151
5	Studies under Public Law No. 280[a]	1946–1947	230[b]	87[c]	335

[a] The Panama Canal. [b] Includes twenty-three holes on adjacent Panama routes. [c] For purposes of estimating sea-level canal slopes, these holes are of more value than all previous borings combined. They are the only borings completed for that specific purpose—that is, spotted at critical locations, carried down to sufficient depth (El. −100 or deeper), with cores carefully logged by a geologist, and with samples of weakest materials tested in the laboratory.

The principles of slope design to forestall the "deep deformation," shear-type slides were not known at the time of the early studies. It was not until near the end of the American construction period, after serious sliding was well advanced, that the studies of the late D. F. MacDonald, then resident geologist, led to an appreciation of causes and prevention of this type of failure.

Studies for the design of the Third Locks Project between 1939 and 1942 resulted in a thorough understanding of the geologic nature of the relatively small areas in which excavation was to be made for the locks and approach channels. In addition to determining the foundation adequacy of the rock at the sites selected for locks and appurtenant structures, investigations were sufficiently detailed to permit the establishment of slopes that would be secure against major slide development. In this work great benefit was derived from the services of Mr. MacDonald, who had returned to the Canal Zone as consulting geologist.

Table 30 presents the quantities of subsurface exploration performed during each of the several periods of major design or construction at Panama.

Field and Laboratory Investigations

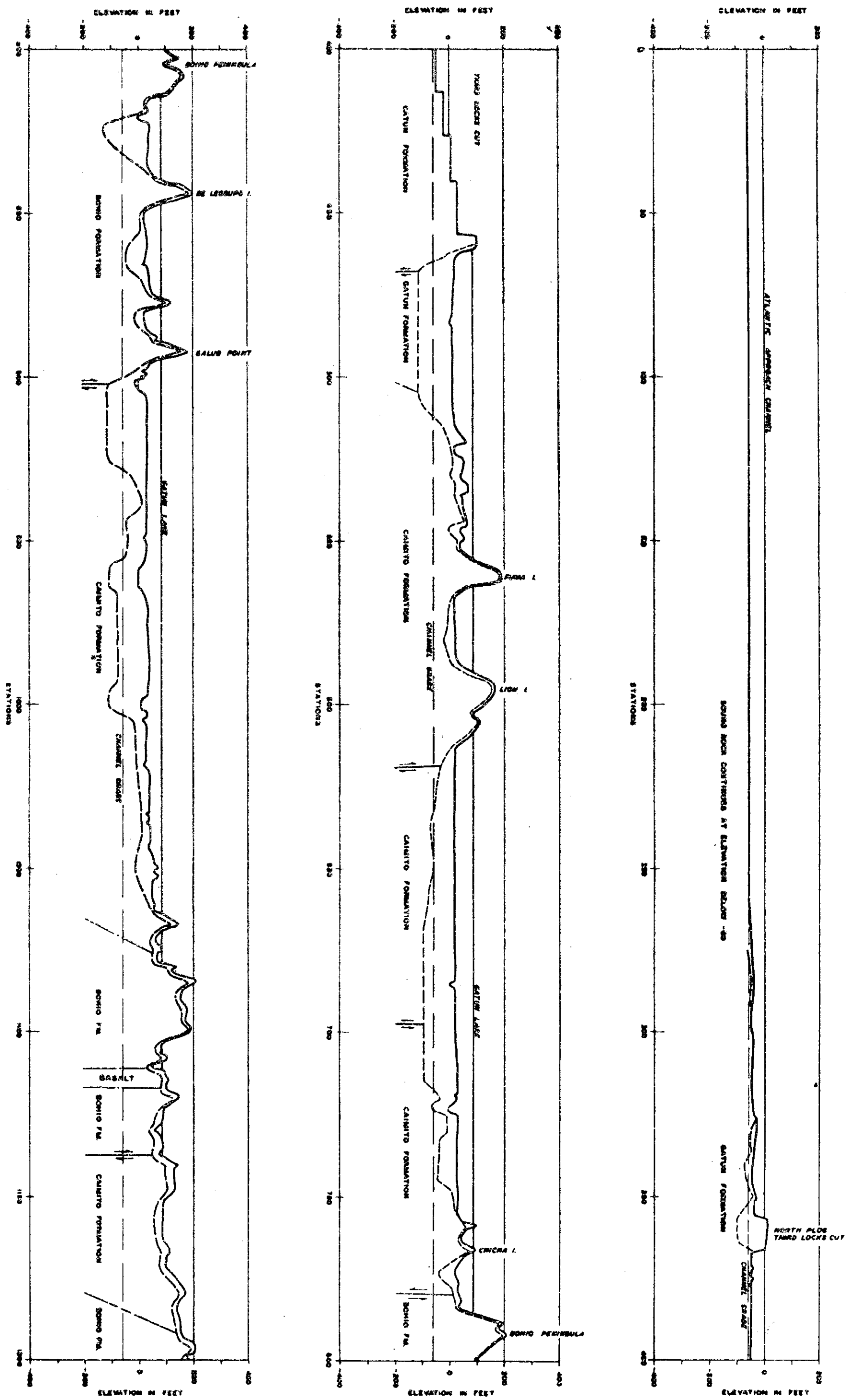
The investigations of the geology of the region traversed by the alinement of the Panama sea-level canal included: (1) Mapping on 1:20,000 scale base maps of all outcrops to be found along the line of the present canal, roads, and natural exposures such as stream channels that have removed the deep soil overburden; and (2) core borings at selected locations to develop further the character, distribution, and structural relationships of the underlying rock formations. Both methods of investigation benefited from stereoscopic examination of aerial photographs, which permitted characteristic topographic expressions to be used in tracing faults and contacts and in establishing the areal extent of certain formations. A large proportion of the borings was located near the Continental Divide where the sliding of oversteep slopes in the original canal excavation attested to the need for careful study in setting of slopes required by the greater depths of cut for the new canal.

The deepest boring made during the present investigations, near the Continental Divide, was 825 ft deep. The average depth of all holes drilled was 236 ft, and the total footage drilled for the 230 holes completed up to July 1, 1947, was 54,376 ft. Drill accessories employed were of "NX" size and yielded $2\frac{1}{8}$-in. diameter cores. Tungsten-carbide hand-set bits were found to be most efficient for the soft and medium rock types, whereas diamond bits proved best for the hardest igneous rocks.

Core-boring operations were inspected by a qualified geologist assigned to each drill rig. Samples of rock were obtained with standard core barrels and samples of the softer types of plastic overburden with 3-in.-diameter brass tubes. Samples were subjected to standard laboratory tests to determine their engieering properties, of which the strength characteristics were the most important and were determined principally by unconfined and triaxial compression tests.

Geology

Geologic History and Physiography.—The datable geologic history of the Canal Zone commences in late Eocene time, some 50,000,000 years ago, when the local Isthmian region was depressed to the extent that a seaway extended diagonally across it and covered at least part of the present Canal Zone. During the succeeding ages, the land surface was repeatedly raised and lowered by diastrophism, resulting in changes in base level that are reflected in the character and distribution of bedded formations deposited on the lands or in the seas of each period. Recurrent volcanic activity ejected vast quantities of



ELEVATION IN FEET
STATIONS
BOHIO PENINSULA
DE LESSEPS I.
BOHIO FORMATION
SALUS POINT
GATUN LAKE
CAIMITO FORMATION
CHANNEL GRADE
BOHIO FM.
BASALT
THIRD LOCKS CUT
GATUN FORMATION
FLAM I.
LION I.
CHICHA I.
ATLANTIC APPROACH CHANNEL
BOHIO ROCK CONTINUOUS AT ELEVATION BELOW -80
NORTH PLUG
THIRD LOCKS CUT

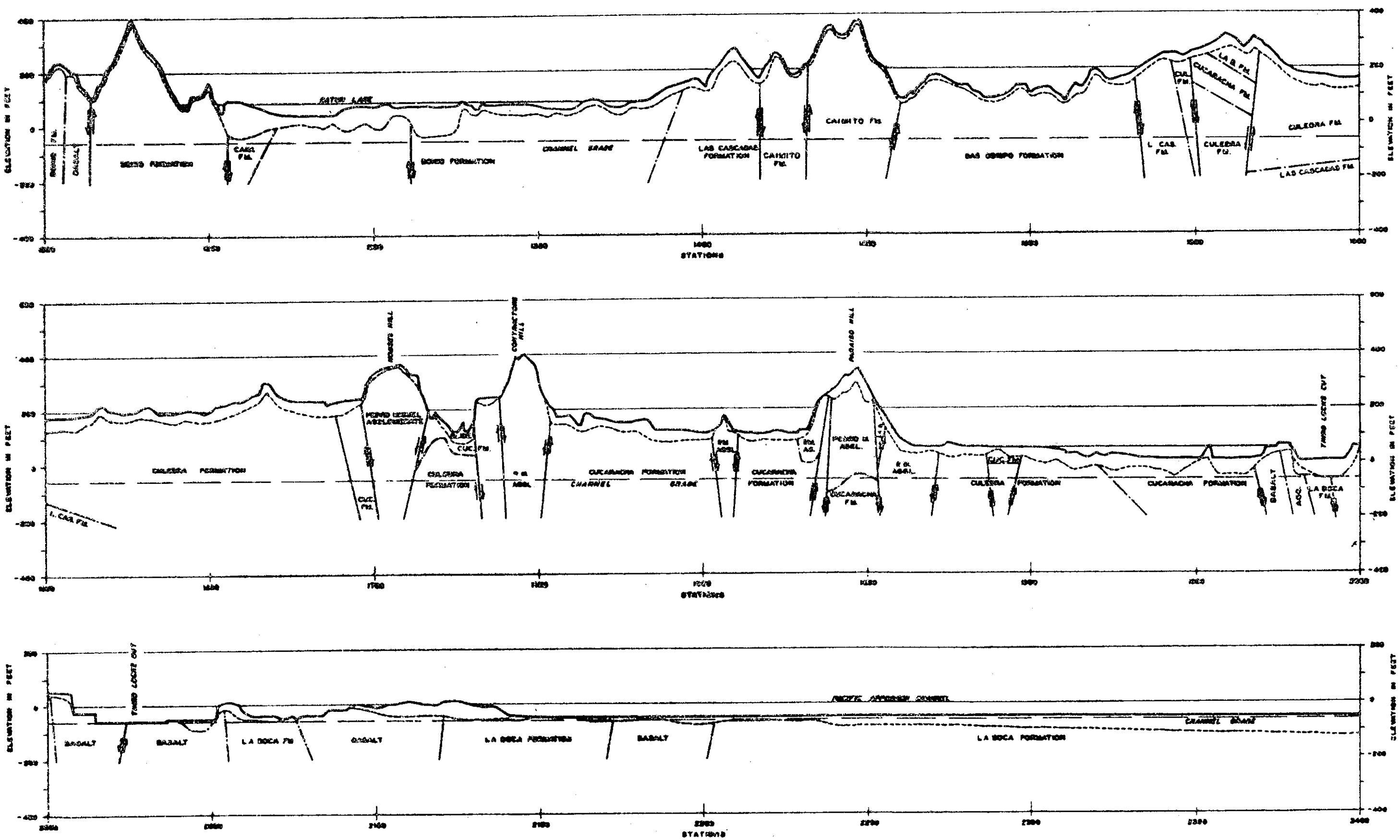


FIG. 62.—GEOLOGIC SECTION ALONG CENTER LINE, PANAMA SEA-LEVEL CONVERSION ROUTE

materials over then-existing lands and seas or intruded igneous rocks into the pre-existing materials. This period is reflected today by widespread distribution of pyroclastic flow, and intrusive rock types intimately associated with those resulting from normal sedimentation processes.

The topography of the Canal Zone is the result of stream erosion in a humid climate acting on a land surface, composed of rocks with very different resistances to erosion, which periodically has been elevated and depressed with respect to sea level. The region is one of unique topographic diversity, characterized by conical, irregularly spaced hills and by unsystematic drainages that give a chaotic appearance to the terrain. Sizes and shapes developed by the land forms are controlled principally by their relative resistances to erosion. Structural features, such as faults and folds, play a secondary and relatively minor role in configuration of the landscape. Drainage patterns are well developed and sharply defined despite their comparatively recent geologic age. Areas underlain by soft rocks are marked by broad valleys within which the larger streams have beveled the strata and deposited on them a blanket of alluvial material. Along both coasts, extensive swamps are present in the lower reaches of the main streams.

Rock Formations.—Only the formations that would be cut through by construction of a new canal are described in this paper. Their distribution along the proposed sea-level canal route is indicated in the center line geological profiles, in Fig. 62, to which the following condensed descriptions apply:

Formation	Explanation
Overburden	Poorly consolidated mucks, clays, silts, gravels, etc.
Gatun	Fine-grained argillaceous and calcareous sandstones with interbedded tuffs and conglomerates
Caimito	Medium-hard, medium to fine-grained, coarsely bedded, limy sandstones and tuff
Bohio	Volcanic pebbles, cobbles, and boulders in a tuffaceous sand matrix
Basalt	Flows and intrusives
Cucaracha	Largely soft clay shales with minor intercalations of sandstones and conglomerates
Culebra	Medium-hard sandstones and soft carbonaceous and sandy shales
La Boca	Largely soft silty and sandy shales with sandstone, tuff, and agglomerate interbeds
Las Cascadas	Medium-hard agglomerate tuffs and tuff-breccias
Bas Obispo agglomerate	Largely angular fragments of andesite and basalt in hard sandy matrix of same composition
Pedro Miguel agglomerate	Hard, fine to coarse textured agglomerates and tuffs

In succeeding paragraphs each formation is taken in order of geologic age, beginning with the oldest and progressing to the youngest materials.

Bas Obispo Formation.—The Bas Obispo formation is a massively jointed agglomerate formed from angular rock fragments and ash that was blown from an old volcanic vent and cemented into a strong dark-gray rock of concrete-like appearance on freshly exposed surfaces. The Bas Obispo is hard and tenacious except where broken or sheared and softened by faulting. Only small slides have developed in the section exposed along the existing canal, and these are related to fault-broken zones. Where undisturbed by faulting, the formation represents one of the strongest rock types involved in new canal construction. About 2.5% of the total excavation for a sea-level canal at Panama would be through this strong formation.

Las Cascadas Formation.—The Las Cascadas formation originated in much the same manner as the Bas Obispo and directly overlies it, but its subsequent history has been dissimilar and it is much more heterogeneous. The Las Cascadas is mostly composed of scattered hard angular fragments of basalt and andesite that are embedded unsystematically in a fine, soft to medium-hard, altered tuff. Some sections are composed entirely of well-bedded tuffs without the hard inclusions. The fines are variably clayey and locally somewhat bentonitic. The formation contains interbedded and random sheets and dikes of fine-grained, hard, igneous rock, mostly either basalt or andesite. During and after the original construction of the canal, numerous small bank failures developed in this formation where the banks had been weakened by faulting. One of the weaker rock units within the Canal Zone series, it would comprise only 1.5% of the excavation for a sea-level canal.

Bohio Formation.—The Bohio formation is composed of heavy beds of conglomerate and sandstone with infrequent shale or tuff layers. The conglomerates are most prevalent and consist of subangular to well-rounded pebbles, cobbles, and boulders in a basaltic sand matrix. The Bohio, in general, is well-cemented, moderately hard, and has widely spaced joints. This formation would comprise roughly 12.5% of the total excavation for a sea-level canal at Panama.

Culebra Formation.—The Culebra formation overlies, unconformably, the Las Cascadas formation and is in turn overlain by the Cucaracha formation. The Culebra can be divided into an upper calcareous and a lower argillaceous member. Its component beds are mainly soft to medium-hard sandstones, shales, limestones, tuffs, and thin conglomerate seams. Carbonaceous shales and a few impure lignite beds are found frequently in the upper and middle parts, and it is highly fossiliferous throughout. This is one of the weaker formations found in the Canal Zone. About 15% of the sea-level canal excavation would be rock of this formation.

Cucaracha Formation.—Strata of this formation were involved largely in the historic huge Gaillard Cut slides that developed during and continued for some time after the original digging of the canal. The maximum known thickness of the formation is 625 ft. Its composition is dominated by weak, poorly bedded, variably bentonitic, slickensided, soapy-textured clay shales (altered impure tuffs) interbedded with soft to medium-hard, fine, tuffaceous siltstones; medium to coarse, cross-bedded sandstones; pebble conglomerates; thinly bedded, often lenticular, soft clayey lignitic beds; and one hard bed of agglomeratic, indurated tuff. The formation largely represents an accumulation of fine volcanic detritus that has been reworked by stream action and subjected to a partial chemical decomposition of its component ash particles with resulting creation of hydrous clay minerals of the montmorillonite-beidellite group. It is the weakest rock formation encountered along the Panama sea-level canal alinement and would represent 14.5% of the total volume of excavation for sea-level construction.

La Boca Formation.—The La Boca formation consists of medium-hard, silty or sandy, variably calcareous shales, tuffs, sandstones, and limy concretion beds, with scattered heavy agglomerate layers. It is similar in most essential respects to the Culebra formation but represents only 2% of the material to be excavated for sea-level canal construction.

Pedro Miguel Agglomerate.—This formation occurs near Pedro Miguel, where it overlies and is in intimate association with the Cucaracha formation. Thick beds of agglomerate also are found interspersed within the lower part of of the La Boca formation. The dominant constituents range from small angular fragments to huge blocks of basalt enclosed in a strong, dense tuff matrix, locally cemented by secondary calcite. Beds of hard, black, indurated tuff are found through its section. It is massively jointed and frequently shows crude bedding. It is one of the stronger types of material to be found locally. Only 4% of the materials that would be removed for a sea-level canal are from this formation.

Caimito Formation.—The Caimito formation is widely distributed in the Gatun Lake area, where it overlies the Bohio formation. It has been divided into three recognizable units. Its basal phase is a tuffaceous sandstone conglomerate of spotty, localized outcrop distribution containing abundant igneous pebbles, cobbles, and boulders. The middle phase, slightly fossiliferous tuffs, limestones, and sandstones, is also localized in extent. The upper phase is a widely distributed series of tuffs, tuff-breccias, and sandstones, with occasional sandy or fairly pure limestone beds. It is moderately strong throughout. Of the total sea-level canal excavation, 13.5% would be through its members.

Gatun Formation.—This formation is composed essentially of variably calcareous or argillaceous fine-grained sandstones, tuffs, and a few conglomerate beds that were deposited in a shallow sea in middle Miocene time. Stratification and jointing are massive and tight. As encountered at the site for the Gatun Third Locks, it was easily excavated with a minimum of blasting, and the deep cuts made for this project in 1941 and 1942 show no sliding after 5 years. Rock of this formation would comprise 2% of the material to be removed in sea-level canal construction at Panama.

Atlantic and Pacific Mucks.—These deposits are the combined accumulation of stream-deposited and ocean-deposited fines that were laid down as a result of a general land submergence in late Pleistocene time that drowned the then-existing stream-carved topography. Soft clays, silts, sands, organic swamp deposits (mostly decayed leaves and wood), and layers of sea shells are found intimately intermixed and to highly variable depths. Near Gatun Dam, muck-buried channels locally extend to below El. − 200. The mucks have very high natural water contents and are of low shear strength. They can be removed economically by hydraulic dredging methods.

Igneous, Intrusive, and Flow Rocks.—All formations of the Canal Zone older than the Gatun (Middle Miocene) have been intruded by volcanic dikes, sills, or plugs, and have interlayered flow rocks. These are mostly basalt, but andesites, rhyolites, and dacites are occasionally present. Rocks of this group in their unweathered occurrences are hard crystalline types and are characterized by a high shear resistance, but their other properties are extremely variable. They are found in greatest development in the central and Pacific regions. About 8.5% of the total volume of sea-level excavation would consist of igneous rocks.

Soils and Weathered Rock.—Depth and character of the soil and weathered rock cover are much diversified and are usually related to the type of underlying rock and topography. In many instances, weathering is known to extend to depths of 50 ft or more, but the average depth is in the order of from 20 ft to 30 ft. Clay soils predominate throughout but are usually rather stiff and only moderately plastic. This material and the mucks previously described represent together 24.5% of the total volume of materials requiring removal for new canal construction.

Geologic Structure.—Geologic features cut by the center line of the proposed new canal alinement are shown in profile in Fig. 62. Particular geologic study has been devoted to a number of basalt-capped or agglomerate-capped hills in the section between the Continental Divide and Pedro Miguel. The structural relationships of these hill-forming, hard basalts and agglomerates to adjacent or underlying softer materials of relatively low shear resistance, as typified by the weak Cucaracha beds, are of great importance. Certain hills have been determined to be deep-seated, stable masses of agglomerate or basalt that present no unusual problem in the design of excavation slopes for a canal, but others involve basalt or agglomerate, as either a cap or an overhang, resting on the Cucaracha formation. Experience in the construction of the existing canal has demonstrated that severe slides may result in cases where a deep cut is opened in a competent mass underlain by weak material if the contact between the two materials is above the bottom of the cut or within limited distances below. The potential slide hazard of this condition can be eliminated only by special slope-design treatment involving a removal of at least a part, if not all, of the overlying hard rock mass above the line defining the stable slope of the weaker formation.

Panama Canal Slides

Types of Slides.—The slides of the Panama Canal were divided by Mr. MacDonald into four types. His description of these follows:

"(1) Deep-deformation Slides. These began where the canal channel was cut deep into weak, somewhat plastic rocks. The weight of the high steep banks caused the rocks to deform very slowly and eventually to shear more than a score of yards below the bottom of the excavation. (2) Structural Slides. These took place where sheared zones, joints, bedding planes, or other structural weaknesses dipped fairly steeply toward the excavation. (3) Mudflow Slides. These formed where mud or moist clay slipped off or flowed down an inclined surface. (4) Combination Slides. A combination of any of the above types."

The deep-deformation slides were by far the largest and most troublesome. They practically all originated in the Cucaracha formation and, in the area of principal occurrence, are represented by the two slides of greatest magnitude, the East and West Culebra. Slides of this kind began to develop when the cut reached a depth of about 100 ft and increased in size and frequency as the excavation was deepened. The next largest slide was the Cucaracha slide, of the mudflow type. The structural and combination slides were not nearly as large or as troublesome as those of the deep-deformation type. The brief slide history which follows is confined to the East and West Culebra slides and the Cucaracha slide, because they were not only the largest, but also the only slides that actually blocked the channel. The locations of these three slides are shown in Fig. 61.

Slide History.—Shortly after the start of excavation by the first French canal company in 1884, the Cucaracha slide became active. It appeared at first to involve only the surface materials—soil and highly weathered rock from 20 ft to 30 ft thick—and took the form of mudflows down the steep slopes of the cut. This slide was intermittently active between 1885 and 1889, while the first French company was in operation. From 1889, when this company failed, until 1905, the slide was small or inactive, there being practically no excavation in the Cucaracha area by the second French company.

The first French company attempted to reduce the water in the slide material by surface drainage and tunneling. Surface drainage was reasonably successful in diverting the water, but neither method was successful in preventing the reoccurrence of slides.

American excavation for the Panama Canal began in 1905. The Board of Consulting Engineers established canal slopes approximating 3 vertical on 2 horizontal for all cuts in rock through the region of the Continental Divide.

The Cucaracha slide resumed activity in January, 1907, and in October of that year a large mass flowed into the bottom of the cut and caused extensive damage. The slide involved some 500,000 cu yd of material and for 2 weeks moved at the rate of 14 ft per day.

Another slide developed in January, 1907, on the east bank of the canal opposite the village of Culebra, and in October a crack developed 50 ft or more back of the top of the west bank near Culebra. This cracking was followed by bulging of the bottom of the cut. These movements marked the beginning of the East and West Culebra slides. The activity of the slides increased in 1911, and large quantities of material moved into the cut during the years from 1911 to 1913. During this period, excavation operations were delayed as railroad tracks and shovels were overturned. The disruptive effect of these slides is illustrated in Fig. 63.

In 1911 a project was undertaken to stabilize the banks by terracing to flatten the excavation slopes. This work was stopped in December, 1913, when it appeared that the Culebra slides were finally stable.

The Cucaracha slide started anew in January, 1913, and by February it was estimated that from 2,000,000 cu yd to 3,000,000 cu yd of clay and rock were in motion. By October, 1913, the channel was completely obstructed for 90 ft near Gold Hill, and partly blocked for 100 ft south. For the remainder of 1913 and during the first half of 1914, the slide continued to move while failed material was removed from the toe. By August 15, 1914, a channel 150 ft wide and 35 ft deep had been excavated through the Cucaracha slide, and the canal was opened to commerce.

FIG. 63.—EAST CULEBRA SLIDE SHOWING UPHEAVED MATERIAL BETWEEN STATIONS 1746 AND 1758, FACING SOUTH, FEBRUARY 6, 1913

Two months later, on October 14–15, a section of the east bank of the cut, north of Gold Hill, extending over 2,000 ft along the face of the cut and about 1,000 ft back from the center line of the channel, settled almost vertically, and about 725,000 cu yd of rock and earth were squeezed out or heaved up into the channel prism. The channel had 45 ft of water when the movement started. An hour later the bottom of the channel had been forced upward in some places to within 9 in. of the water surface. The dredges were able to clear the obstructions and keep the channel open until August 7, 1915, when slides closed the canal for 4 days. The canal was again closed to shipping for 6 days beginning September 4, 1915.

On September 15, 1915, a section of the face of Zion Hill (directly opposite the East Culebra slide) broke away and settled down. Both the East Culebra and West Culebra slides then began to move rapidly toward the channel. An