MISCELLANEOUS PAPER H-69-12

A STATISTICAL MODEL TO PREDICT THE TRANSIT CAPACITY OF SEA-LEVEL CANALS

by

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13. ABSTRACT The large first cost and subsequent operation and maintenance costs of sea-level canals demand that all economic and technical alternatives be thoroughly investigated before construction is begun. The vast number of variables to be considered for any given set of alternative canals requires study in an orderly and meaningful manner. The derivation and application of a statistical model in the form of an algebraic equation which predicts yearly transit capacities of sea-level canals are presented in this paper. The equation considers only the following significant variables: canal geometry, ship mix, ship stopping distances, length and number of convoys, a desired maximum waiting time, and an overall canal efficiency (to predict transiting at less than maximum capacity). A simple algebraic representation is particularly useful because it can be used for preliminary canal transit studies without the need for either sophisticated mathematics or digital computer facilities. After narrowing the number of technically and economically feasible alternatives with the canal transit equation, the remaining alternatives can be studied in more detail by other means. Because of time limitations on the study, the canal transit equation has not been tested against either known solutions or solutions given by the digital computer simulation derived as part of this study and described in U. S. Army Engineer Waterways Experiment Station Miscellaneous Paper H-69-10 entitled "An Analytical Model to Predict Ship Transit Capacities of Sea-Level Canals."

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FOREWORD

The study described herein was requested by COL J. H. Tormey, Office, Chief of Engineers (ENGCW-Z), in a telephone call to the Director, U. S. Army Engineer Waterways Experiment Station, on 4 August 1969; authority to perform the investigation was granted by ENGCW-Z, in a subsequent telephone conversation of 4 August 1969. The investigation was conducted in the Hydraulics Division of the Waterways Experiment Station during the period 4 August 1969 to 15 September 1969.

The research work reported herein was sponsored by the Atlantic-Pacific Interoceanic Canal Study Commission, and this paper is designated IOCS Jax 87-1833.10 in the IOCS report series. This is the second report in a series of two reporting the results of the study; the first, Miscellaneous Paper H-69-10, entitled "An Analytical Model to Predict Ship Transit Capacities of Sea-Level Canals" is designated IOCS Jax 88-1834.10 in the IOCS report series.

The study was conducted under the general supervision of Mr. E. P. Fortson, Jr., Chief of the Hydraulics Division, with the assistance of Mr. W. G. Shockley, Chief of the Mobility and Environmental Division, and Mr. Guy L. Arbuthnot, Jr., Chief of the Nuclear Weapons Effects Division.

This investigation was conducted by Mr. B. G. Stinson, Vehicle Studies Branch, Mobility and Environmental Division, with the assistance of Mr. J. W. Brown, Analytical Research Group, Nuclear Weapons Effects Division. Others making contributions were LTC F. M. Anklam, Deputy Director, and Dr. John Harrison, Mathematical Hydraulics Group, Hydraulics Division. This report was prepared by Dr. Harrison, with the assistance of Messrs. Stinson and Brown and LTC Anklam.

Director of the Waterways Experiment Station during the conduct of this investigation and preparation and publication of this report was COL Levi A. Brown, CE. Technical Director was Mr. F. R. Brown.

CONTENTS

NOTATION

B	Number of ships that can be stored in the two-way sections
d	Stopping distance of first ship in a convoy, ft
E	Efficiency factor for canal (decimal fraction)
i	Summation index
K	Number of groups of ships into which the convoys are divided
ℓ	Sum of lengths of two-way canal sections, ft
ℓ_i	Length of i^{th} ship in a convoy, ft
L	Center-line length of the canal, ft
N	Number of ships in a convoy
P_1	Percentage of ships that must travel in one-way mode
P_2	Percentage of ships that can travel in a two-way mode
P_3	Percentage of ships that can travel in a two-lane mode
q_i	Following or stopping distance of i^{th} ship in a convoy, ft
Q	Average length plus stopping distance for ships in convoy, ft
Q_i	Length plus stopping distance for ships in group i, ft
S	Total number of ships that can transit the canal
t	Maximum waiting time for ships to enter the canal, sec
T	Time required for all ships to transit a given canal under optimum operation, sec
T_B	Time to transit all ships with canal bypass capability, sec
T_o	Time required for one convoy to transit under full one-way operation with no bypass, sec
T_S	Time to transit all ships under full one-way operation without bypass, sec
T_1	Time to transit those ships that must travel in one-way mode, sec
T_2	Time to transit those ships that may travel in two-way mode, sec
T_3	Time to transit those ships that may travel in two-lane mode, sec
U	Total number of ships that will be considered for transit
V	Average ship speed in canal, ft/sec

CONVERSION FACTORS, BRITISH TO METRIC UNITS OF MEASUREMENT

British units of measurement used in this report can be converted to metric units as follows:

Multiply	By	To Obtain
feet	0.3048	meters
miles	1.609344	kilometers
tons	907.185	kilograms
	0.907185	metric tons
feet per second	0.3048	meters per second

SUMMARY

The large first cost and subsequent operation and maintenance costs of sea-level canals demand that all economic and technical alternatives be thoroughly investigated before construction is begun. The vast number of variables to be considered for any given set of alternative canals requires study in an orderly and meaningful manner.

The derivation and application of a statistical model in the form of an algebraic equation which predicts yearly transit capacities of sea-level canals are presented in this report. The equation considers only the following significant variables: canal geometry, ship mix, ship stopping distances, length and number of convoys, desired maximum waiting time, and overall canal efficiency (to predict transiting at less than maximum capacity).

A simple algebraic representation is particularly useful because it can be used for preliminary canal transit studies without the need for either sophisticated mathematics or digital computer facilities. After narrowing the number of technically and economically feasible alternatives with the canal transit equation, the remaining alternatives can be studied in more detail by other means.

Because of time limitations on the study, the canal transit equation has not been tested against either known solutions or solutions given by the digital computer simulation derived as part of this study and described in U. S. Army Engineer Waterways Experiment Station Miscellaneous Paper H-69-10 entitled "An Analytical Model to Predict Ship Transit Capacities of Sea-Level Canals."

A STATISTICAL MODEL TO PREDICT THE TRANSIT CAPACITY OF SEA-LEVEL CANALS

PART I: INTRODUCTION

1. The large first cost and subsequent operation and maintenance costs of sea-level canals demand that all economic and technical alternatives be thoroughly investigated before construction is begun. It is of primary importance that the canal serve its intended purposes economically and safely. The vast number of variables to be considered for any given set of alternative canals requires study in an orderly and meaningful manner. The prediction of ship transit capacities during some period of time is a basic tool for evaluating the various proposed designs. The proper use of such predictions will allow the designer not only to select the optimum route from an economic and technical standpoint, but also to set firm rules on the use of the canal by both canal and ship personnel.

2. This report is the second of a series of two generated by the same study. The first report, "An Analytical Model to Predict Ship Transit Capacities of Sea-Level Canals,"[1] was concerned with the development and application of a digital computer program to predict transit capacities of sea-level canals. The objective of this report is to present a concise and relatively simple algebraic equation for calculating ship transit capacities of sea-level canals. While the digital computer program accurately describes the interactions of the many variables of this highly complex problem, this report presents the development and application of an approximate method that requires neither sophisticated mathematics nor access to a digital computer. It is hoped that the researcher who must make preliminary decisions as to the relative cost and effectiveness of various canal geometries and modes of operation will find use for this algebraic relation.

3. Background information for both reports was obtained from both the open literature and private conferences. Because of the short duration of the study, an extensive literature review was not undertaken. Information gleaned from the literature was supplemented strongly by four one-day

conferences with people considered expert in this area. These persons included Messrs. E. W. Eden and L. E. Miller of the U. S. Army Engineer District, Jacksonville; Drs. D. Savitsky, C. Henry, and H. Edo of the Stevens Institute of Technology, Hoboken, N. J.; Messrs. C. G. Moody and B. Gertler of the Naval Ship Research and Development Laboratory, Carderock, Md.; and Mr. C. F. Wicker, Consultant, Philadelphia, Pa. It is realized that this listing does not include all those who have knowledge in this field; rather it is limited only to those experts who were most readily available during the study period. The individuals listed above provided both excellent verbal advice and unpublished written material on the subject. Brief descriptive write-ups of these conferences and, where possible, the literature so obtained are presented in Appendix C of reference 1. The transit capacity study was divided into three interrelated parts, each of which is discussed in detail in reference 1. These parts are:

a. Physical characteristics of the canal.

b. Flow conditions in the canal.

c. Ships that use the canal.

It will be recognized that each of these areas contains many subareas which are themselves significant topics.

4. This report is devoted entirely to the development and usage of a statistical model in the form of an algebraic equation that predicts ship transit capacities of sea-level canals.

PART II: DERIVATION OF CANAL TRANSIT EQUATION

5. A complete description of all variables and their relative importance to the overall transit capacity is a very complex problem. The approach taken here is that the major variables are (a) canal geometry; (b) desired maximum waiting time; (c) types of ships that will use the canal; (d) mode of canal operation, i.e., one-way, two-way, or two-lane;[2*] and (e) desired average speed for ships in the canal. Other variables that affect the total canal operation (tidal heights and currents, canal bank and bedding materials, canal roughness, weather, accidents, maintenance, etc.) are considered to be parameters that change one or more of the selected major variables. This approach allows major emphasis to be placed on major variables, and allows simplicity in choice of variables and their dimensions. No dimensions except length and time appear in the final equation.

6. In the derivation of the equations herein it was assumed that the canal would always be operating at peak efficiency and that there would always be ships waiting to use the canal. In this sense the equations are means of predicting maximum transit capability of the canal. An efficiency factor appears in the final equation if for any reason one might like to consider operations other than maximum.

7. If one desires to calculate the transit time for a given number of ships, U , he must first determine if the physical characteristics of the canal and the ships (ship beam and draft compared with canal width and depth) allow the vessels to transit at all. For most ship mixes it is logical to assume that some ships could not transit. The remaining number, S ,

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* a. One-way traffic. Ships travel on canal center line, pass no other ships, and require a minimum channel width of three times the beam of the ship.

b. Two-way traffic. Ships travel on canal center line; when two ships meet they each swing off the center line to pass and then return to the center line after passing. Two-way traffic requires a minimum channel width of five times the beam of the larger ship.

c. Two-lane traffic. Ships travel in two separate, opposite direction lanes, each off the center line of the channel. The minimum channel width required for two-lane operation is 7.6 times the beam of the larger ship.

will be used as the number for which transit time will be calculated.

8. Assuming that the S ships can be divided into convoys containing N ships in each convoy, the time for one convoy of N ships to transit the canal in one-way operation can be approximated by

$$T_o = \frac{1}{V}\left[L + \ell_1 + \sum_{i=2}^{N} (q_i + \ell_i)\right] \tag{1}$$

where

T_o = time for one-way passage, sec

V = average convoy speed, ft/sec*

L = length of center line of canal, ft

N = number of ships in convoy

q_i = following or stopping distance of i^{th} ship, ft

ℓ_i = length of i^{th} ship, ft

The entire number of ships S could then transit in approximately

$$T_S = \frac{S}{N}\left(\frac{1}{V}\right)\left[L + \ell_1 + \sum_{i=2}^{N} (q_i + \ell_i)\right] \tag{2}$$

9. I[illegible] had sections of two-lane width, then a number of ships could be stored, B (approximated by equation 11), in the two-lane sections and bypassed with each cycle change. This would effectively increase the number of ships in a convoy by B and the time to transit all S ships would become

$$T_B = \frac{S}{N + B}\left(\frac{1}{V}\right)\left[L + \ell_1 + \sum_{i=2}^{N} (q_i + \ell_i)\right] \tag{3}$$

10. Assuming that the canal would not operate in a one-way mode at all times but would, in addition, use two-way and two-lane operations, the amount of time required to transit those ships that must travel in the one-way mode can be calculated by:

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* A table of factors for converting British units of measurement to metric units is presented on page ix.

$$T_1 = \frac{P_1 S}{N + B} \left(\frac{1}{V}\right) \left[L + \ell_1 + \sum_{i=2}^{N} (q_i + \ell_i)\right] \qquad (4)$$

where P_1 = percentage of S ships that must travel in the one-way mode.

11. Analogously, the time required to transit those ships that can travel in a two-way mode can be calculated by:

$$T_2 = \frac{P_2 S}{1.5N} \left(\frac{1}{V}\right) \left[L + \ell_1 + \sum_{i=2}^{N} (q_i + \ell_i)\right] \qquad (5)$$

where P_2 = percentage of S ships that travel in the two-way mode. The factor 1.5 appears in this equation because the efficiency of two-way operation over one-way operation is estimated to be approximately 1.5:1. The value B does not appear because there would be no storage or bypass capability during two-way operation.

12. The time required to transit those ships that may travel in a two-lane mode is

$$T_3 = \frac{P_3 S}{2N} \left(\frac{1}{V}\right) \left[L + \ell_1 + \sum_{i=2}^{N} (q_i + \ell_i)\right] \qquad (6)$$

where P_3 is the percentage of S ships that travel in a two-lane mode. Two-lane operation is considered twice as efficient as one-way operation.

13. The time required to transit all S ships using one-way, two-way, and two-lane modes is then

$$T = T_1 + T_2 + T_3 \qquad (7)$$

$$T = \frac{S}{V} \left[L + \ell_1 + \sum_{i=2}^{N} (q_i + \ell_i)\right] \left(\frac{P_1}{N + B} + \frac{P_2}{1.5N} + \frac{P_3}{2N}\right) \qquad (8)$$

14. In order to facilitate use of the formula it is suggested that the ships in each convoy be divided into groups so that one length and one

stopping distance can be used for each group. This allows the number of summations to be significantly reduced. In addition to this change, a factor may be added to account for less than maximum canal use. Incorporating these into equation 8 yields

$$T = \frac{S}{V}\left(L - d + \frac{N}{K}\sum_{i=1}^{K} Q_i\right)\left(\frac{P_1}{N + B} + \frac{P_2}{1.5N} + \frac{P_3}{2N}\right)\frac{1}{E} \qquad (9)$$

where

T = time for S ships to transit the canal, sec

S = number of ships from the sample U that can transit

where $S = S$ (draft, beam, minimum canal depth, minimum canal width)

V = mean ship speed in the canal, ft/sec

where $V = V$ (maneuverability, canal curvature, bank and bed materials, canal roughness, tidal currents, weather)

L = center-line distance through the canal, ft

d = stopping distance of first ship in the convoy, ft

N = number of ships in one convoy

where $N = N$ (average ship speed, maximum waiting time to enter canal, canal length, ship length plus stopping distance)

K = desired number of groups into which the ship sample is divided

Q_i = stopping distance plus length of ship in group i, ft

P_1 = percentage of ships that must travel in a one-way mode

where $P_1 = P_1$ (beam distribution, width of minimum canal section)

P_2 = percentage of ships that can travel in a two-way mode

P_3 = percentage of ships that can travel in a two-lane mode

B = total number of ships that can be placed in one lane of the two-lane section

E = efficiency factor for the canal at a given time

where $E = E$ (accident possibilities, weather conditions, entrance conditions, ship availability, etc.)

PART III: USE OF CANAL TRANSIT EQUATION

15. In order to use equation 9, one must first construct table 1 and the corresponding graphs shown in fig. 1. The graphs in fig. 1 describe

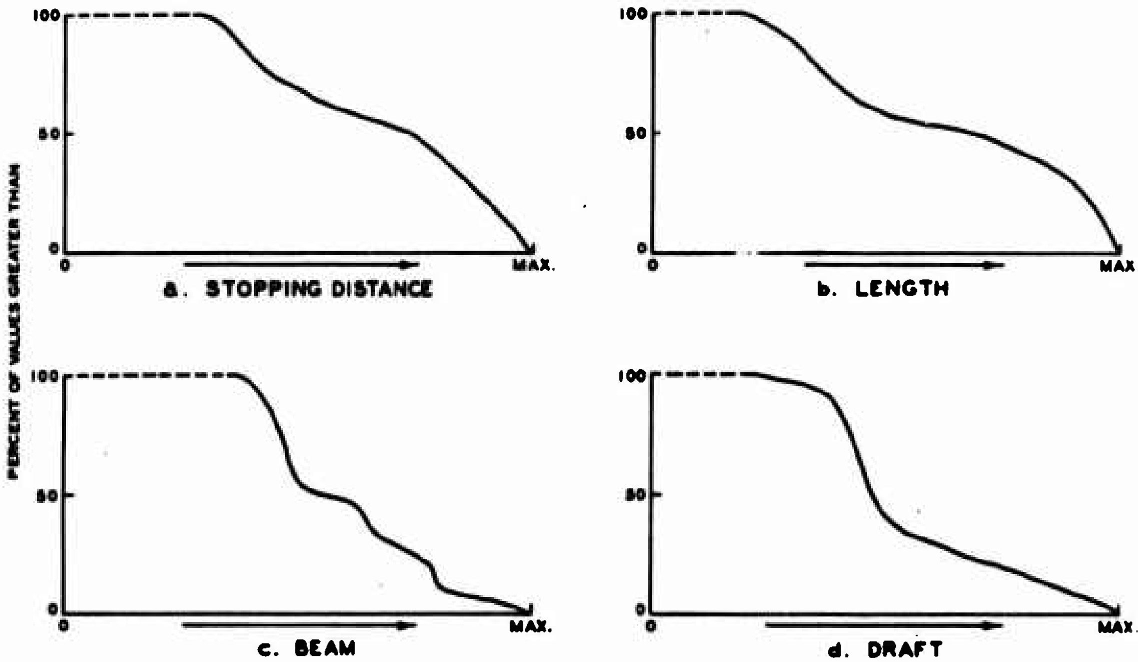

Fig. 1. Distributions of ship parameters

the various physical characteristics of the sample ship mix and table 1 provides the necessary canal description.

16. For a general ship mix it is probable that some of the ships can never transit the canal due to excessive beam and/or draft. The percentage of ships that can transit can be found from the graphs and table. The number in the sample ship mix is then reduced by this percent. The resulting number is S in equation 9. For ships that can travel only at certain times (e.g. high tide conditions) no reduction is made in equation 9 as the ships will be sent through under the required conditions and hence be a part of the number of transits. If much waiting time is anticipated for ships because of such conditions, the efficiency factor E can be adjusted as described below.

17. The average speed, V , of ships in the canal will be affected by canal roughness, current, weather, canal curvature, bank and bedding

materials, and safety limitations of the various vessels. This factor must be selected based on experience and conditions at time of transit.

18. The number of ships, N , in one convoy can be arbitrarily selected, but the maximum value can be approximated by

$$N \approx \frac{tV - L}{Q} \tag{10}$$

where

t = maximum waiting time for a ship to enter canal (an assigned value, sec)

Q = average value of ship length plus stopping distance for ships in the convoy, ft

If the proposed waiting time t produces a negative value for N , then the time is unrealistic and must be increased.

19. The value for K can be selected based on the ship mix of the sample. Usually the number of distinct groups of ships in a sample will be clear, but any number can be used. Once the value of K has been selected, Q_i can be found directly from the graphs. One divides the distribution curves for stopping distance and length into K parts along the ordinates and then reads a length and stopping distance from the middle of the group band. The sum of length plus stopping distance for the i^{th} group is Q_i for that group.

20. The canal section of minimum width will determine the calculation of the percentage values P_1 , P_2 , and P_3 . Dividing the width of the minimum width section by 7.6 will give the beam of the largest ship that can transit the canal in a two-lane mode. This number is used in graph c, fig. 1, to established what percentage of the ship mix can travel in this mode. The percentage value so obtained is used as P_3 in equation 9. P_2 is calculated by dividing the width of the minimum width section by 5 and finding the corresponding percentage value from graph c. Subtracting $P_2 + P_3$ from 1.00 (100 percent) establishes the percentage of ships that must travel in a one-way mode, P_1 . All percentages enter equation 9 as decimal fractions.

21. When parts of the canal are being used in a one-way mode it is

possible to place ships in two-way sections and bypass them. The number of ships B that may be so bypassed can be approximated by

$$B \approx \frac{\ell}{Q} \qquad (11)$$

where ℓ is the sum of the lengths of the two-way sections.

22. The value E is a factor that will usually be taken as 100 percent. However, it is possible that canal transit efficiency might be reduced by inclement weather, accidents, lack of available ships, restricted one-way operation, etc. In this case the value of E may range from 0 to 100 percent. For example, if the canal were of sufficient width to permit use as a two-lane canal and one lane of the canal were unusable (e.g. a ship burning in it) then E could be taken as 50 percent for the time that the lane was out of operation. Note that E will enter equation 9 as a decimal fraction.

PART IV: EXAMPLE PROBLEM

23. The ship mix sample used in this example problem is given in table 2. The percentage distribution curves for ship stopping distance, length, beam, and draft are shown in figs. 2a, b, c, and d, respectively.

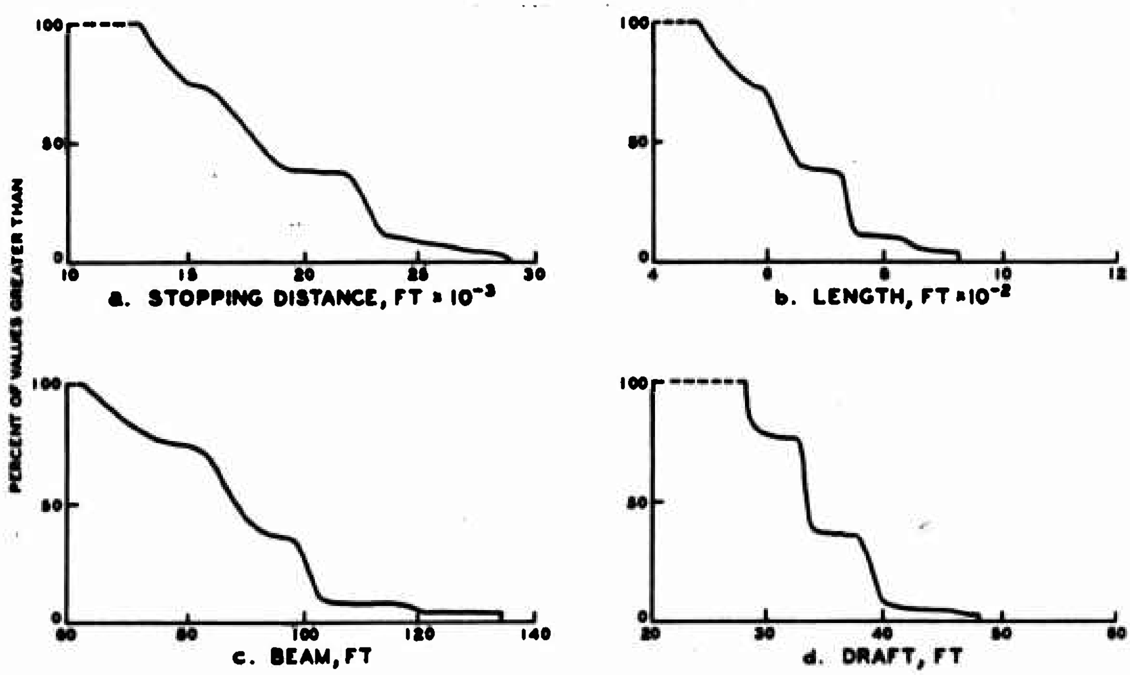

Fig. 2. Distribution of ship parameters for the example problem

A plan view and the cross-section geometry of the canal used for the example problem are shown in fig. 3. The canal geometry, ship mix, and ship parameter data are taken from the second example problem (without tugs) discussed in reference 1. The physical characteristics of the canal necessary for solution of the example problem are given in the following tabulation.

Canal Physical Characteristics

Section No.	Length - ft	Width ft	Minimum Depth, ft
1	52,800	600	60
2	52,800	600	60
3	39,600	600	60
4	13,200	600-1200*	60
5	105,600	1200	60
6	13,200	1200-600*	60
7	92,400	600	60

* These values used as 600.

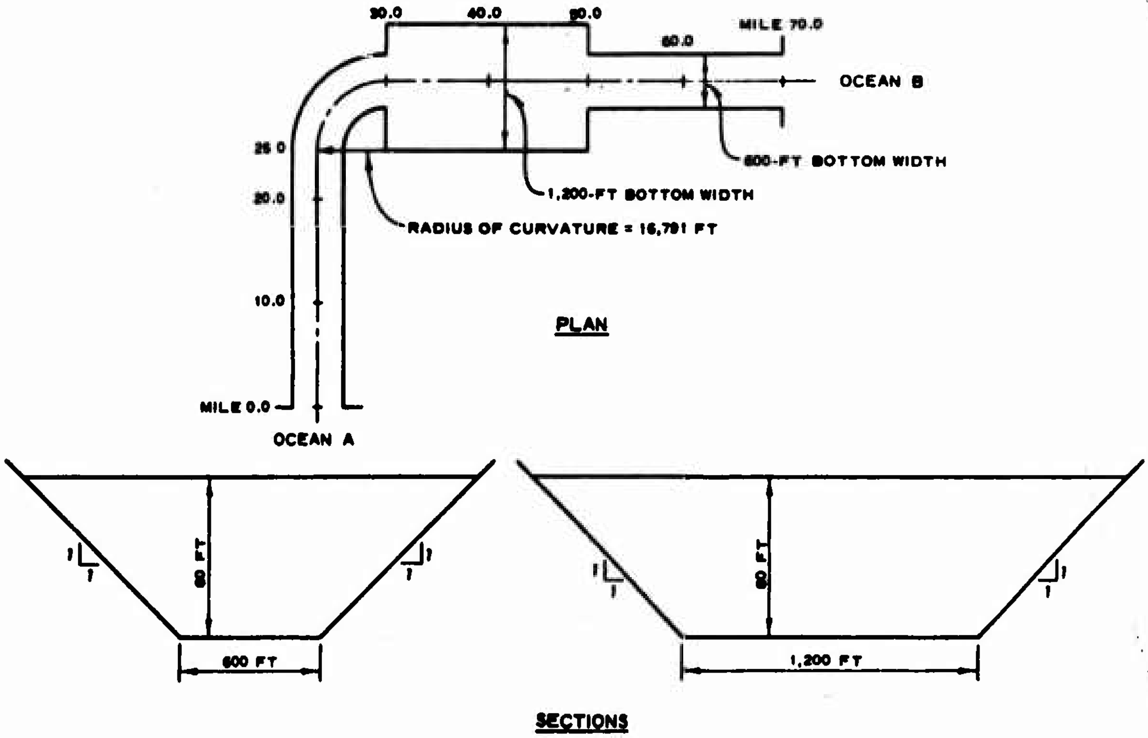

Fig. 3. Canal geometry used in example problem

24. The total number of ships in the sample is 1000 and S is, by definition, the number out of 1000 that can transit the sample canal. The minimum depth of the sample canal is 60 ft and the maximum draft of any ship in the sample is 48 ft; therefore by a depth-draft comparison all 1000 ships can transit the canal. It is also necessary to compare the beam of the ship with the canal width. If the canal width is equal to or greater than three times the beam of the ship then the ship can transit the canal; otherwise the ship cannot transit. The maximum beam of any ship in the sample is 138 ft, and the minimum canal width is 600 ft; therefore 600 is greater than (3 × 138 = 414) 414 and S is, therefore, 1000.

25. After considering the overall structure of the canal and the ship sample, it was decided that the ships should maintain an average velocity V of 7 knots or 11.8 ft/sec. The total length of the sample canal L is 70 miles or 369,600 ft.

26. The number of ships in one convoy N might be arbitrarily selected; however, for this example N was determined by use of equation 10:

$$N \approx \frac{tV - L}{Q} \qquad (10\ bis)$$

where

t = the maximum time any ship should wait to enter the canal. For the example problem it was decided this maximum waiting time should be 12 hr or 43,200 sec

V = 11.8 ft/sec

L = 369,600 ft

Q = average length plus stopping distance for ships in convoy, determined by reading stopping distance and ship length at the 50 percent value from graphs a and b of fig. 2 and adding. Fifty percent of the ships can stop in 18,000 ft and 50 percent of the ships are 630 ft long; therefore Q = 18,630 ft

Now

$$N = \frac{43{,}200 \times 11.8 - 369{,}600}{18{,}630} = 7 \text{ ships/convoy}$$

27. The ship sample was divided into 10 groups for the sample problem. Therefore, K equals 10. The values of Q_i were determined by reading stopping distance q_i and ship length ℓ_i from the curves in figs. 2a and b at 10 percent intervals, beginning at 5 percent. The values for Q_i are:

Percent Value	i	q_i	ℓ_i	$Q_i (= q_i + \ell_i)$
5	1	26,500	860	Q_1 = 27,360
15	2	25,750	750	Q_2 = 26,500
25	3	22,700	740	Q_3 = 23,440
35	4	22,000	730	Q_4 = 22,730
45	5	18,200	645	Q_5 = 18,845
55	6	17,300	630	Q_6 = 17,930
65	7	16,500	605	Q_7 = 17,105
75	8	14,750	565	Q_8 = 15,315
85	9	13,800	520	Q_9 = 14,320
95	10	13,200	490	Q_{10} = 13,690

Hence

$$\sum_{i=1}^{K} Q_i = 197,235$$

28. The stopping distance of the first ship d in the convoy will be taken at the 50 percent value of graph in fig. 2a; thus, $d = 18,000$ ft.

29. The values of P_1, P_2, and P_3 are the percentages of the total ship sample that can transit the narrowest section of the given canal in one-way, two-way, and two-lane modes, respectively. P_3 is determined by dividing the minimum canal width (600 ft) by 7.6 (which equals 79 ft). Therefore only those ships having beams less than 79 ft can transit all of the sample canal in the two-lane mode. Now reading from the curve given in graph in fig. 2c it is determined that 72 percent of the ships in the sample have beams greater than 79 ft; therefore 28 percent of the ships can transit the entire canal in the two-lane mode.

$$P_3 = 0.28$$

P_2 is determined in the same way except that 5 is used instead of 7.6.

$$P_2 = 0.67$$

30. P_1 is now determined by the formula

$$P_1 = 1.00 - (P_2 + P_3)$$

$$P_1 = 1.00 - (0.67 + 0.28) = 0.05$$

31. The total number of ships that can be placed in one lane of a two-lane section of the sample canal is estimated by equation 11

$$B \approx \frac{\ell}{Q} \qquad \text{(11 bis)}$$

where

ℓ = the total length of all bypass sections in the sample canal. A bypass section is defined as a section of the canal in which 100 percent of the ship sample can travel in two lanes. The sample canal has one bypass section (section No. 5), which is 105,600 ft long; therefore ℓ = 105,600 ft

Q = 18,630 ft (determined in paragraph 26)

Therefore,

$$B = \frac{105,600}{18,630} = 6$$

32. It was arbitrarily assumed that the operations of the sample canal would be 85 percent efficient.

33. Using equation 9

$$T = \frac{S}{V}\left(L - d + \frac{N}{K}\sum_{i=1}^{K} Q_i\right)\left(\frac{P_1}{N + B} + \frac{P_2}{1.5N} + \frac{P_3}{2N}\right)\frac{1}{E} \qquad \text{(9 bis)}$$

where

S = 1000

V = 11.8 ft/sec

L = 369,600

d = 18,000

N = 7

$\sum_{i=1}^{K} Q_i$ = 197,235

P_1 = 0.05

P_2 = 0.67

P_3 = 0.28

B = 6

E = 0.85

$$T = \frac{1000}{11.8}\left[369,600 - 18,000 + \frac{7}{10}(197,235)\right]\left(\frac{0.05}{13} + \frac{0.67}{10.5} + \frac{0.28}{14}\right)\frac{1}{0.85}$$

$$= 4,274,882 \text{ sec}$$

Converting time-sec to time-days yields

Time in days = 49.5

34. This means that 1000 ships can transit the canal in 49.5 days. When projected to a yearly figure, we get 7374 transits per year. Although this figure is close to that given by the digital computer simulation in reference 1 (6845 transits per year), it would not be proper to assume, without more testing and comparison of the two solution methods, that this is anything but coincidence.

PART V: CONCLUSIONS AND RECOMMENDATIONS

35. An algebraic equation has been derived to predict ship transit capacities of sea-level canals. The equation represents an attempt to formulate a simple design tool which contains the significant problem variables in their proper perspective. The equation can be changed to incorporate future developments with relative ease.

36. Based on the results of conferences, a review of the literature, and the development presented in this report, it is concluded that:

a. An algebraic equation which considers all the variables of this complex problem cannot be derived.

b. Some of the factors which have an appreciable effect on instantaneous ship operation (e.g. tidal conditions and stopping distances) can be either averaged or neglected over an entire year of operation and thus probably have little effect on yearly transit capacities.

c. While the algebraic equation does not provide any means of studying the transiting of any individual ship or the operation of the canal-ship system for a fraction of a year, it will provide approximate yearly transit capacities.

d. Time limitations on the present study permitted only one comparative calculation with the digital computer simulation and none with known solutions to specific problems.

e. Additional comparisons should be made by either one, or both, of two methods:

(1) By comparison with presently existing situations, for which answers are known.

(2) By comparison with results obtained by solutions of the digital computer simulation.[1]

f. A variable analysis (or parameter analysis) using the digital computer program would permit an investigator to selectively change a single variable, or combination of variables, and study the influence of such changes on canal transit capacity. This would allow the investigator to determine analytically the relative importance of the many variables.

g. The development and usage of an algebraic expression are desirable for two reasons:

(1) This type of solution requires neither sophisticated mathematics nor high-speed digital computers, and is thus easy to use.

(2) If proven satisfactory, an algebraic representation could

be used to reduce the number of technically and economically feasible alternatives in a systematic, economic manner. A more comprehensive method, such as the digital computer simulation, could then be used to study this reduced number of feasible alternatives in great detail.

The present short-term study has been a thorough first effort toward solving the canal transit capacity prediction problem by both a digital computer simulation and a simple algebraic representation. A more comprehensive, better tested solution by either method depends upon further work on this subject. Detailed recommendations concerning the general canal transit capacity problem and the digital computer simulation program are outlined in reference 1. The following recommendations deal with the further development and application of the canal transit equation derived in this paper:

a. Some additional programming should be performed on the digital computer simulation so that the equation derived herein can be effectively compared with the digital computer results.

b. A thorough sensitivity analysis should be performed using the computer program to determine whether the variables and parameters assumed to be basic for the development of the algebraic equation are, indeed, those most important to the problem.

c. A number of comparative solutions should be made with both the computer program and the algebraic equation. The results should be presented in a manner that will facilitate comparison, and the reasons for significant differences should be determined.

d. Since the canal efficiency E is the only factor presently without firm foundation, it is desirable to determine its approximate values under various conditions of canal and ship operation.

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Table 1

Canal Physical Characteristics

Section No.	Length ft	Width ft	Minimum Depth, ft
1	L_1	W_1	D_1
2	L_2	W_2	D_2
⋮	⋮	⋮	⋮
n	L_n	W_n	D_n

Table 2

Ship Mix Used in Example Problem

Ship Type	Length ft	Beam ft	Draft ft	Deadweight tons	Percentage of Total No. of Ships
Freighter	600	83	29	12,000	25.2
Freighter	750	98	33	18,000	33.6
Freighter	930	117	40	34,000	25.2
Bulk carrier	480	62	28	16,500	3.0
Bulk carrier	660	92	38	44,000	4.0
Bulk carrier	840	121	48	93,000	3.0
Tanker	570	77	34	21,000	1.8
Tanker	730	103	40	55,000	2.4
Tanker	860	134	48	97,000	1.8