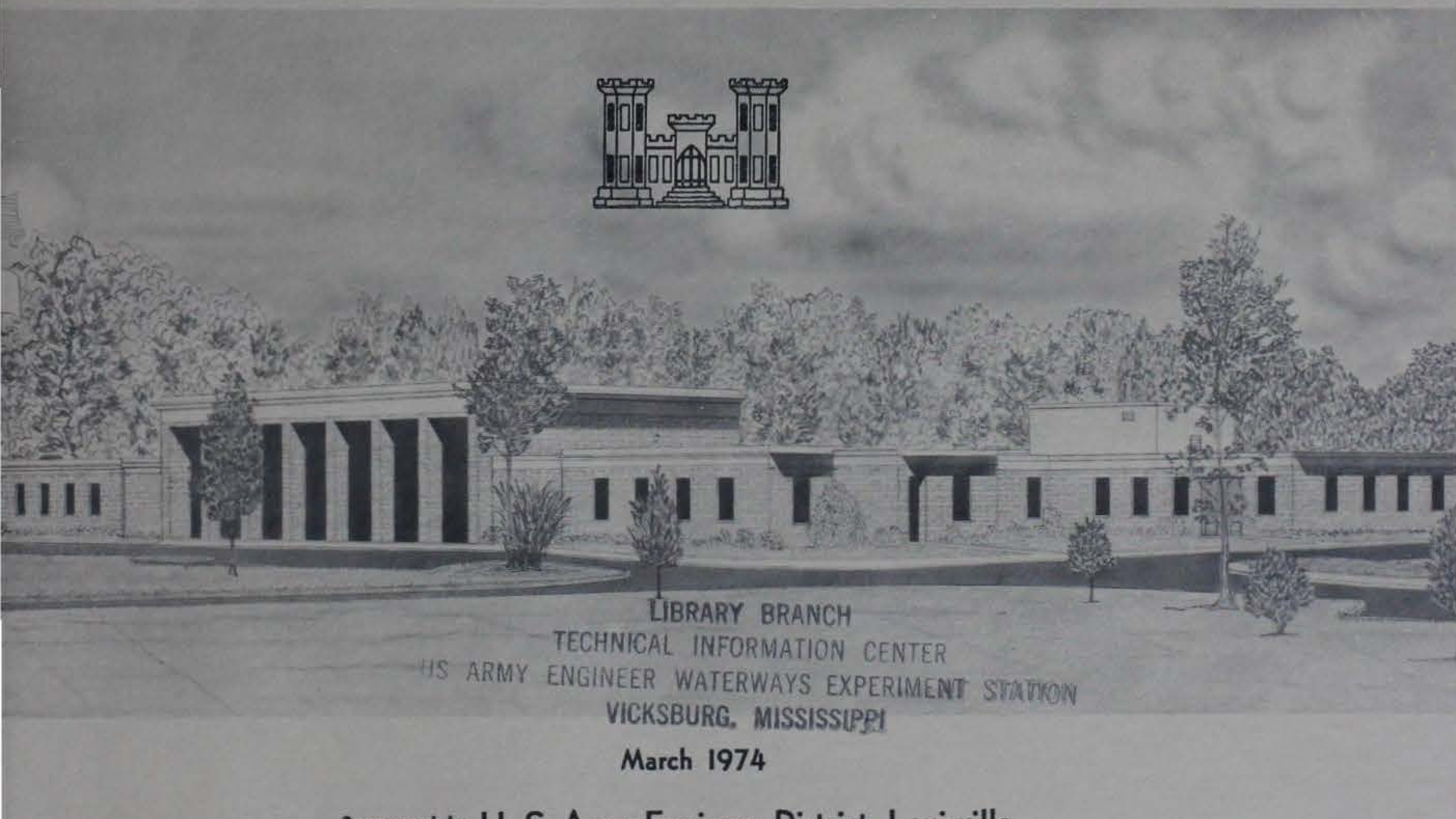
MISCELLANEOUS PAPER H-74-4

ANALYSIS OF TOW ENTRY, LOCKING, AND EXIT TIMES AT LOCK AND DAM 51 OHIO RIVER

by

L. L. Daggett, R. W. McCarley, J. E. Stinehour



March 1974

Sponsored by U. S. Army Engineer District, Louisville

Conducted by U. S. Army Engineer Waterways Experiment Station
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FOREWORD

This study of lock traffic data was performed by the U. S. Army Engineer Waterways Experiment Station (WES) for the U. S. Army Engineer District, Louisville. The data used in this study were recorded at Lock and Dam 51 on the Ohio River during 1969. The analysis of these data was made in conjunction with a study to optimize the operation of Lock 51 through improved tow sequencing procedures. The results of the lock optimization study will be reported in a future WES report. Most of the work on the analysis of the data was performed by WES during the period 15 April-15 August 1972. Additional limited data analyses were conducted throughout the lock optimization investigation.

This study was conducted by personnel of the Mathematical Hydraulics Division (MHD) under the general supervision of Mr. H. B. Simmons, Chief of the Hydraulics Laboratory, and Mr. M. B. Boyd, Chief, MHD, and under the direct supervision of Dr. L. L. Daggett, MHD. Mr. R. W. McCarley, MHD, was project engineer. Mrs. J. E. Stinehour of the Automatic Data Processing Center assisted by developing the required computer programs for the desired data analyses. This report was prepared by Mr. McCarley with guidance from Dr. Daggett and Mrs. Stinehour.

Acknowledgement is made to Messrs. A. R. Chandler, C. R. Smith, and D. D. Pattison of the Ohio River Division; Messrs. J. R. Bleidt, W. N. Whitlock, and L. P. Dickson of the Louisville District; and the operations personnel at Lock and Dam 51 for their cooperation and assistance at various times throughout the investigation.

Directors of WES during the conduct of this investigation and preparation and publication of this report were BG E. D. Peixotto, CE, and COL G. H. Hilt, CE. Technical Director was Mr. F. R. Brown.

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NOTATION

H	Null hypothesis for test statistic t' stating that two sample means are equal
L_B	Length of towboat in feet
L_L	Length of lock in feet
L_T	Length of tow in feet (towboat plus barges)
n_x	Number of observations in sampling x
n_y	Number of observations in sampling y
NLB/TB	Ratio of the number of loaded barges in a tow to the total number of barges in that tow
S_x^2	Variance of data sampling x
S_y^2	Variance of data sampling y
t'	Test statistic to test equality of the means of two population distributions given that the standard deviations are unknown and not necessarily equal
$t_{\alpha,\nu}$	Standard table value at the α level of significance and ν degrees of freedom
T_{Ai}	Arrival time of the i^{th} tow
T_{Bi}	Bow-over-sill time of the i^{th} tow on entrance to the chamber
T_{Ci}	Clear-approach-point time on exit of the i^{th} tow
T/HP	Ratio of tonnage carried by tow to the horsepower rating of the towboat
T_{Ni}	Callup time of the i^{th} tow to begin lockage
T_{Si}	Stern-over-sill time of the i^{th} tow on exit from the chamber
W_L	Width of lock in feet
W_T	Width of tow in feet at widest point
X	Set of sample values from population X
$\overline{X}$	Mean of data sampling x

Y	Set of sample values from population Y
$\overline{Y}$	Mean of data sampling y
α	Level of significance associated with t' test
μ_x	Mean value of population x
μ_y	Mean value of population y
ν	Degrees of freedom associated with t' test

SUMMARY

An analysis of a large sampling of the tow traffic data taken in 1969 at Lock and Dam 51 (L&D 51) on the Ohio River was needed primarily to provide a data base for the development of an improved standardized method for sequencing tows waiting in queue. Traffic congestion at L&D 51 has become an increasingly serious problem in recent months, as has been the case at a number of other locks. This situation has intensified interest in low-cost operational improvements which can help alleviate the congestion at such locks without the necessity for expending large sums for structural improvements.

Through an analysis of available tow traffic data, literature reviews, and discussions with knowledgeable Corps personnel, it was attempted in this investigation to determine easily identifiable and recordable physical parameters that, as a rule, have a recurring positive influence on the steps of the lockage procedure, i.e., tow entry, locking, and exit. The quality and scope of the available data did not permit as comprehensive an analysis of all significant parameters as desired, but, for the first time, the effects of certain parameters were isolated and quantified to a usable degree of accuracy. Parameters for which an acceptable degree of meaningful information was obtained were (a) entry type (long and short), (b) lockage type (single, double, knockout, and setover), (c) direction of travel (upstream and downstream), and (d) commodity loading (empty and loaded). Other less successful attempts were made to analyze the combined effects of towboat horsepower and commodity loading on tow entry and locking times. An unsuccessful attempt was also made to analyze the degree of loading as a function of the ratio of number of loaded barges to total number of barges in order to quantify the influence of this parameter on entry and locking times. This report is limited primarily to a discussion of those parameters that could be satisfactorily analyzed.

Very little information could be gleaned from an analysis of the tow exit times. Unfortunately, the exit time of most tows was recorded only to the nearest 5 min regardless of size, power, or other such factors that contribute to tow speed and maneuverability. The collection of additional data recorded to the nearest minute would undoubtedly provide the necessary data for a more accurate analysis of this and other steps of the lockage procedure.

ANALYSIS OF TOW ENTRY, LOCKING, AND EXIT TIMES AT LOCK AND DAM 51, OHIO RIVER

PART I: INTRODUCTION

Statement of the Problem

1. An urgent need exists for increasing the ability of our inland waterways to handle a greater volume of commercial tow traffic. Since locks are often the primary capacity restraints on waterways, any improvement in their operation would increase the overall capability of the waterway to provide a higher level of service to the towing industry and other users. One proposed method of improving the operation of existing locks is to schedule waiting tows for callup according to certain predetermined vessel characteristics and other factors that correlate with probable lockage time requirements. This study specifically addresses the problem of determining easily definable tow characteristics that could be used in developing an improved method for sequencing tows waiting to use a lock facility.

2. There is another aspect of this study that bears mentioning. In recent years, studies of traffic problems on inland waterways have centered around the simulation of locking processes and other waterway functions through the use of electronic computers. The data and assumptions used in these simulation models are often not adequate or accurate enough to provide meaningful predictions of vessel movements. In addition, important tow characteristics and other contributing factors that significantly influence tow movements are often not included in the simulation models.

3. Finally, in recent years, the Corps of Engineers has become concerned with the application of the systems approach to the management of inland waterways. To assist in developing the required management techniques, the Corps has acquired the services of the firm Peat, Marwick, Mitchell, and Company (PMM&C), Washington, D. C. One of the

primary objectives of PMM&C's efforts is to design a new and improved performance monitoring system (PMS) for the Nation's system of inland waterways.* The information and data analysis reported herein should provide new insights relative to certain parameters which perhaps should be included in the PMS.

Background

4. The lock traffic data collected on the Ohio, Illinois, and Upper Mississippi Rivers have been routinely analyzed by Corps personnel for several years. Most of these studies consist of unpublished analyses that simply partition tow entry and locking times according to lockage type and direction of travel. The results are sometimes limited to a simple display of frequency diagrams showing the relationship between the number of tows in the sampling and their respective entry or locking times. Even though a comprehensive literature search was conducted throughout the duration of this study, nothing that sufficiently explained the effects of other parameters on lockage times could be found. Other parameters, such as commodity loading and entry type, obviously influence the time required to lock a given tow; but the available reference material was void of information that reflected the degree of this influence. Thus, a quantitative analysis of such parameters was conducted to provide data essential to the development of improved lock operating procedures.

Purpose

5. The purpose of this further analysis of lock traffic data was severalfold. First and most important, a meaningful data base had to be established for use in developing a computerized tow sequencing

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* Peat, Marwick, Mitchell, and Company, "Inland Waterway Systems Analysis," Final Report, May 1971, prepared for Task Group for Inland Waterway Systems Analyses, Office, Chief of Engineers, U. S. Army Corps of Engineers, Washington, D. C.

system. To this end, easily identifiable and measurable tow characteristics that correlate with lockage times had to be defined and quantified. A secondary but related purpose of the study was to develop the basic information for the formulation of a few simplified tow sequencing rules that could be employed by the Corps on an interim basis pending the procurement of the necessary electronic computer equipment.

6. Another noteworthy purpose of this study was to generate more reliable information for use in waterway simulation models. Such models are being used to a greater extent to analyze the capacity of waterway systems to move waterborne commerce and to solve waterway transport problems. Use of the most reliable information available in the design of these models is essential.

7. In addition, though not one of its primary purposes, this study supplements the work of PMM&C in developing an improved PMS for the inland waterway system.

Scope and Approach

8. This study was limited to an analysis of lock traffic data collected in 1969 at Lock and Dam 51 (L&D 51), Ohio River, by the lock operators. The 1969 data were the most recent detailed data available on magnetic tape for computer analysis.

9. After elimination of certain undesirable data, the approach used in the analysis was as follows. First, the group of parameters that probably have the most significant influence on tow lockage times was determined. Next, this group was narrowed down to include only those parameters amenable to analysis through the use of the available data. Each selected parameter was then divided into two or more meaningful categories. For example, there were four types of lockages (singles, doubles, knockouts, and setovers) and two directions of travel (upstream and downstream) considered. Finally, the tows represented by the data were grouped by parameter category in order to analyze statistically the effects of each parameter on the times required to execute the three steps of the lockage procedure, i.e., entry, locking, and exit.

PART II: DESCRIPTION OF THE STUDY

Data Base for the Analysis

10. L&D 51 (fig. 1) was selected for this investigation because it is a typical, congested lock on the Ohio River. It is a 600- by 110-ft (183- by 234-m), single-chambered lock that was constructed in the 1930's by the Corps of Engineers and is now scheduled to be replaced by the Smithland Locks and Dam in about 1976. Traffic congestion has become a serious problem at this lock and is expected to worsen each year.

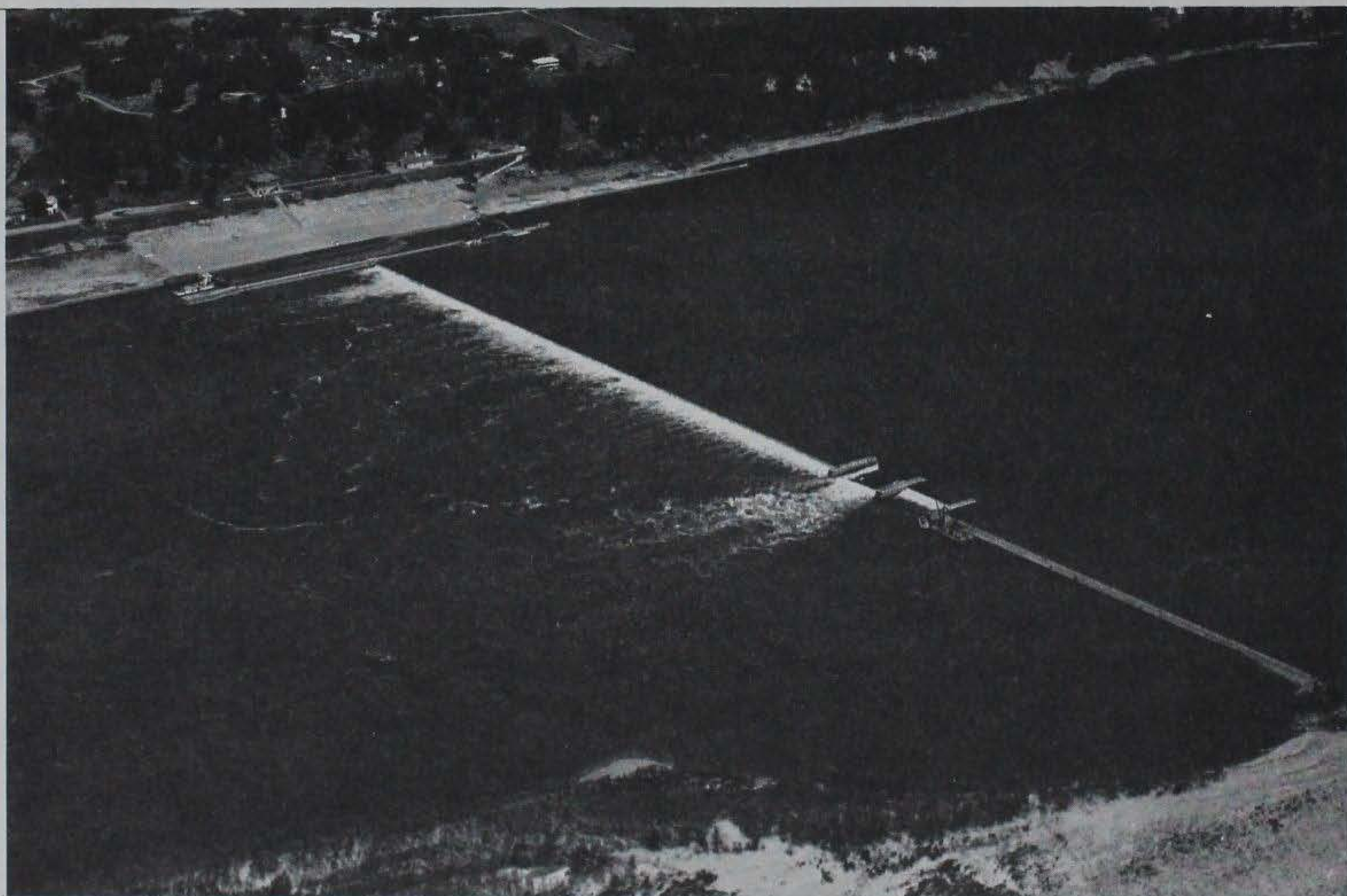

Fig. 1. Lock and Dam 51 on the Ohio River near Golconda, Illinois

11. In recent years, a massive volume of vessel traffic data has been recorded at L&D 51 on ORD Form 886 by operations personnel of the U. S. Army Engineer District, Louisville. ORD Form 886 is shown in Appendix A to indicate the nature and scope of the data collected. The horsepower of tows locked during 1969 was obtained from the Waterborne

Commerce Statistics Center, New Orleans, Louisiana. During early discussions of this investigation, personnel of the Ohio River Division, the Louisville District, and the U. S. Army Engineer Waterways Experiment Station (WES) mutually agreed upon the use of readily available data for the analysis, rather than collecting additional data. The large volume of available data suggested that an adequate sampling would remain even after elimination of the unusable portions. Unfortunately, however, these data were not adequate in scope or quality to make possible the analysis of the effects of all significant parameters on tow lockage times.

12. Lock traffic data for the years 1967-69 were furnished by the Louisville District. These data were the most recent available on magnetic tapes for computer analysis. The data for more recent years have not been transcribed from the data forms to a computer-compatible form. The 1967-69 data were recorded during both open- and closed-pass conditions at the lock and were quite voluminous. Due to storage limitations and excessive processing times required to analyze data from all three years, the decision was made to use only the 1969 data taken during locking operations, i.e., closed-pass conditions. This provided sufficient data to perform the desired analyses. No locking problems exist at the lock during open-pass conditions since the wicket dams are down to permit unimpeded passage of all river vessels. This condition occurs when the river flow is adequate for maintaining the required navigable depths.

Data Eliminated

13. Of the river-going vessels locked during 1969, only tows with one or more barges were retained for analysis. According to the lockmaster at L&D 51, other craft, such as pleasure boats and passenger vessels, do not significantly contribute to the traffic problem.

14. With the massive volume of data taken annually at L&D 51, recording errors and omissions were anticipated. Apparent errors, omissions, or illogical recordings which resulted in the exclusion of

one or more line items of lockage data included the following:

a. The omission of vessel number, tow length or width, commodity tonnage, direction of travel, or other such pertinent data.

b. The appearance of unrealistic clock times for two succeeding tows. The computer was programmed to filter out any two succeeding tows if $T_{Ni} \leq T_{Ni-1}$, $T_{Bi} \leq T_{Bi-1}$, $T_{Si} \leq T_{Si-1}$, and/or $T_{Ci} \leq T_{Ci-1}$,
where

T_{Ni-1} and T_{Ni} = Callup clock times of the first and immediately following tows, respectively, and similarly,

T_{Bi-1} and T_{Bi} = Bow-over-sill clock times

T_{Si-1} and T_{Si} = Stern-over-sill clock times

T_{Ci-1} and T_{Ci} = Clear-approach-point clock times

Appropriate provisions were made in comparing all times throughout this study for times recorded on different days.

c. The recording of clock times for a given tow in some order other than chronological. Tow data were eliminated if $T_{Ni} \geq T_{Bi}$, $T_{Bi} \geq T_{Si}$, or $T_{Si} \geq T_{Ci}$.

d. The appearance of identical vessel numbers in succession. While a particular tow could pass through the lock and later return before the lockage of an intervening tow, such data were eliminated simply as a result of the several illogical recordings observed. Identical vessel numbers were recorded in succession only a few times in the 1969 data.

15. Tows which could be placed in the following categories were also excluded from the data analyzed:

a. Any tow arriving when the lock was apparently empty. The entry of these tows is commonly referred to as "on-the-fly" since they are permitted to enter directly into the lock chamber without delay. Data for tows entering on-the-fly were excluded to ensure consideration of only the true short and long entry times (to be discussed later). Tows on-the-fly do not have to begin moving from a stopped position, and hence their entry times are shorter. They are also not relevant to the sequencing of a queue.

b. A tow arriving at exactly the same time that a previous tow cleared the approach point (AP) on exit. This somewhat unlikely circumstance was recorded numerous times throughout the data. The entry type of these tows was assumed to have been on-the-fly.

c. Any tow with a computed short entry time greater than 20 min or a long entry time greater than 70 min. These times were considered as maximum extremes under normal operating conditions at L&D 51.

Data Observations and Parameter Groupings

General data observations

16. Following the elimination of the unusable lockage data, the remaining data were visually inspected to develop a thorough understanding of the overall content. Significant findings resulting from this preliminary review were as follows:

a. Tows were listed in order of callup rather than arrival order. This proved to be an advantage in the analysis. If the tows had been listed in some other order, a computer program would have been required to place them in the order of callup.

b. Single lockage tows were totally empty of commodities more often than other lockage types. Tows requiring setover lockages were, in almost all cases, transporting a hazardous commodity, e.g., crude petroleum, oil and gasoline, or chemicals. Also, almost all setover tows were traveling upstream.

c. In many instances, the arrival time of a tow was identical with the time that the stern of the previous tow cleared the AP. It seems unlikely that this coincidence would have occurred in practice nearly as often as recorded.

d. The wrong arrival day was recorded by error several times.

e. The recorded waiting time did not always agree with the apparent waiting time calculated by determining the number of minutes between arrival and callup clock times.

f. As a rule, the recorded stern-clear-AP clock time of an exiting tow was identical with or later than the depart-AP clock time of the next tow called. In some cases when the next tow to be serviced departed before the stern of the previous tow cleared the AP, relatively long computed entry times occurred. This may have distorted the computed average entry times to some degree.

g. Almost all clock times were recorded to the nearest 5 min.

h. The duration of an exit, regardless of tow characteristics, was almost always 5 min. For this reason, a meaningful analysis of the factors that influence exit times was not practical.

Computation of entry,
locking, and exit times

17. This investigation has contributed additional information regarding the effects of various tow characteristics on the average times required by tows to execute each of the three major lockage steps, i.e., entering, locking (or chambering), and exiting. A program was written to compute entry, locking, and exit times in the following manner:

a. Entry time equals the bow-over-sill clock time minus the depart-AP clock times (data elements 61 through 64 and 57 through 60, respectively, on ORD Form 886 in Appendix A).

b. Locking time equals the clear-lock clock time (data elements 65 through 68) minus the bow-over-sill clock time.

c. Exit time equals the stern-clear-AP clock time (data elements 69 through 72) minus the clear-lock clock time.

The total of these three times defines the lockage time. The lockage time plus the waiting time before callup is the total transit time of a tow.

Tow entry types

18. Calculated entry times were partitioned into three major groupings: (a) on-the-fly, (b) short, and (c) long. An on-the-fly entry occurred when a tow arrived when the lock was not in use, thereby making a direct entry into the lock chamber. For this type of entry, the clock time at which an entering tow arrived (T_{Ai}) had to be later than the clock time at which the stern of the previous tow cleared the AP (T_{Ci-1}), i.e., $T_{Ai} \geq T_{Ci-1}$. Since a queueing condition did not exist at the time of their arrival, tows entering on-the-fly were not considered to be within the scope of this investigation. If $T_{Ai} < T_{Ci-1}$, the entering tow had to wait, and its entry was then considered to have been either a short or long one.

19. An entering tow made a short entry when it could be locked immediately following an exiting tow traveling in the same direction and $T_{Ai} < T_{Si-1}$, where T_{Si} is the clock time recorded when the stern of an exiting tow passes over the lock sill. While the chamber was occupied, the second tow was permitted to approach the lock and tie to the guide wall with its bow near the lock gates. Thus, a short travel distance free from river current effects was possible after callup.

20. A tow made a long entry when it could be locked immediately following an exiting tow traveling in the opposite direction and $T_{Ai} < T_{Ci-1}$. In this situation, the entering tow had to wait far back from the lock to insure that adequate room was provided for safe passage of the exiting tow. Thus, a tow facing a long entry situation had to transit a much longer distance and was subjected to the effects of the river current. In this situation, the tow required a much longer time

to enter the lock than in the short entry situation, resulting in a separate classification.

Analysis of short entry times

21. One aspect of the entry time computed in the manner described in paragraph 17a requires further explanation. As indicated above, ORD Form 886 required the lock operators to record clock times for depart-AP and bow-over-sill. These two data elements were used to compute the entry time (in minutes) of the selected tows. However, the entry time of a tow should ideally begin when the lock is available for use (i.e., the time when the lock operator signals or calls up the tow for entry) and end when the bow of the tow crosses the gate sill. ORN Form 398, dated October 1971, provides a column for the gate-opening clock time, which would closely approximate the callup time for a short entry. In many cases, the entry time of a particular tow is significantly influenced by operations performed by the immediately preceding tow. As an example, consider a small tow following a very long double-lockage tow, both traveling in the same direction. The small single-lockage tow could normally depart the designated AP about the time the gate is opened to receive the second cut of the double tow and align itself along the guide wall of the lock, if one is available. But before the lock can receive the entering small tow, the following activities would have to be completed:

a. Entry of the second cut of the double tow into the lock.

b. Tying off this cut on the lock wall.

c. Filling or emptying of the lock.

d. Rejoining the two sections of the double tow.

e. Exit of the double tow to allow closure of the lock gates.

f. Closing of the lock gates.

g. Lock swingaround, i.e., emptying or filling of the lock.

h. Opening of the lock gates to receive the small tow.

The entering tow would normally have completed its approach to the lock and would have been waiting on the guide wall for some time. However, based on the available data, the time required to complete some of the above-listed activities would be included in the computed short entry time. Times computed in these situations would, therefore, not appear to be typical of a short entry time.

22. The visual analysis of the 1969 tow traffic data revealed that the lock operators quite often did not record the exact depart-AP times of many tows. Rather, the time recorded in the depart-AP column for entering tows was, in many cases, identical with the stern-clear-AP time for exiting tows. Since average computed swingaround time was approximately the same (within about 2 min) as tow exit time, the computed short entry times more closely approximated those that would have resulted if entry times commenced at callup. To eliminate unreasonably long computed entry times resulting from use of the available data, only those short entry times less than or equal to 20 min in duration were considered.

Tow lockage types

23. Tow size and configuration were considered in the analysis of entry, locking, and exit times by partitioning the tows locked in 1969 according to lockage type as follows:

a. Single. $L_T < L_L$; $W_T < W_L$

b. Double. $L_T - L_B > L_L$; $L_T < 2L_L$; $1/2\ W_L < W_T < W_L$

c. Knockout. $L_T > L_L$; $L_T - L_B < L_L$; $W_T < W_L$

d. Setover. $L_T - L_B > L_L$; $L_T < 2L_L$; $W_T < 1/2\ W_L$

where

L_T = length of the tow (towboat plus barges), ft

L_L = length of the lock, ft

L_B = length of the boat, ft

W_T = width of the tow at widest point, ft

W_L = width of the lock, ft

24. The tow dimensions were used in determining lockage type rather than using the recorded lockage type because in many cases the lockage type recorded could not have possibly been accomplished with a tow of the recorded dimensions. In general, tow dimensions appeared to be recorded more accurately than the codes for individual lockage types.

Direction of travel

25. Upbound and downbound tows were separated for a more accurate

analysis of long entry times. Tows making a short entry are partially protected from river currents by the lock structure and do not have as far to travel. Direction of travel, therefore, did not have very much influence on short entry times. In addition, locking times were essentially the same for both filling and emptying.

Ratio of commodity tonnage to towboat horsepower

26. This parameter was considered to be a relative indication of a tow's capability to travel the required entry and exit distances under load of the commodity tonnage in transit. The objective of the analysis was to determine the adverse effects on speed, momentum, and maneuverability of increasing a tow's payload without comparably increasing boat power. The following eight ranges of tonnage-to-horsepower (T/HP) ratio were considered: (1) $T/HP = 0$, (2) $0 < T/HP \leq 2$, (3) $2 < T/HP \leq 4$, (4) $4 < T/HP \leq 6$, (5) $6 < T/HP \leq 8$, (6) $8 < T/HP \leq 10$, (7) $10 < T/HP \leq 16$, (8) $T/HP > 16$. The results of the data analysis did not indicate that relatively underpowered tows, based on the T/HP ratio, averaged longer entrance or locking times than adequately powered tows. To the contrary, some of the average entry and locking times for adequately powered tows were longer than those of underpowered tows. However, a significant difference did exist between average entrance and locking times of empty tows of a given lockage type and those of the loaded tows. Since an overwhelming majority of the computed exit times for all tows was 5 min, an analysis of the effects of the T/HP relationship on exit times would obviously not be very fruitful. Accordingly, only the effects of this parameter, i.e., empty versus loaded tows, on entrance and locking times were included in the analysis.

Ratio of number of loaded barges to total barges

27. This parameter was assumed to be an indication of commodity loading. The tows were divided into the following six categories according to the ratio of their respective number of loaded barges to total number of barges (NLB/TB): (1) $NLB/TB = 0$, (2) $0 < NLB/TB \leq 0.25$, (3) $0.25 < NLB/TB \leq 0.50$, (4) $0.50 < NLB/TB \leq 0.75$,

(5) $0.75 < NLB/TB < 1.00$, (6) $NLB/TB = 1.00$. This analysis did not prove to be meaningful; however, it did indicate that a high percentage of the tows were transporting either all empty barges or all loaded barges. This further strengthened the justification for a detailed analysis of the simple parameter, empty versus loaded tows, as will be explained later.

Visibility at the lock

28. A study of the adverse effects of poor visibility at the lock was considered desirable. The thought was to compare the daylight entry times with the entry times at night and to compare entry times of tows operating on clear days with those of tows operating on foggy days.

River currents

29. Strong river currents undoubtedly affect tow entry and exit times. Therefore, an analysis of lockage data was considered desirable to quantify the effects of river currents on the speed and maneuverability of various tows.

Wind conditions

30. Tows transporting empty barges, whose sides ride high above the water surface, are hindered in their approach to or exit from a lock during periods of high winds. Therefore, it was considered desirable to study entry and exit times during windy as well as calm conditions for the purpose of developing accurate probable times for use in the lock optimization program.

Crew capability

31. Crew capability has an important influence on lockage times, but is undoubtedly the most difficult of all parameters to analyze properly and accurately. This parameter is listed here because it is one that must be considered in any complete optimizing procedure for sequencing tows through a lock. However, due to the difficulty of identifying and measuring crew capabilities and due to the potential favoritism that could develop, a decision was made not to analyze this parameter during this study.

Scope of the Analysis

32. Use of the available data limited the data analysis to only the following parameters:

- a. Entry type.
- b. Lockage type.
- c. T/HP. (Meaningful information was not obtained. See paragraph 26.)
- d. Direction of travel.
- e. NLB/TB. (Meaningful information was not obtained. See paragraph 27.)
- f. Commodity loading (empty versus loaded tows).

33. There were a number of reasons for limiting the scope of the analysis, the most important being the limited scope of the data furnished. For example, river current conditions were not recorded. Some thought was given to relating the current conditions on a given day to available river stage and discharge data. This thought was dismissed after learning that such a correlation would require an excessive effort. A study of the daily river bulletins for the year 1969 together with the lock log book would be required to reconstruct the approximate current conditions on selected dates. It was felt that the need for a large volume of data (and hence, high cost) coupled with the potential inaccuracies inherent in the improvised river current data would practically nullify potential benefits to be derived from the proposed analysis.

34. The effects of poor visibility and wind on tow movements were not analyzed in detail for basically the same reasons that the river current data were not analyzed. Further study is necessary before analysis of crew capability can be attempted with any confidence in obtaining meaningful information.

35. Both visual and statistical analyses were made to assess quantitatively the influence of the selected parameters on tow entry, locking, and, in some cases, exit times. The number of samples in each parameter grouping, together with the mean and standard deviation of

each sample set, was calculated and is presented in Appendix B. The distribution of each sample was also determined for evaluation. An unsuccessful attempt was made to develop functional relations of apparent increases in entry and locking times with increases in the T/HP or the NLB/TB ratio. These two parameters did not appear to have a strong enough influence to allow such a relationship to be developed.

PART III: ANALYSIS AND RESULTS

General

36. This part of the report presents detailed descriptions of the data analysis, a summary of the results obtained, and a discussion of the statistical tests employed. Based on conversations with Corps operations personnel, on-site observations of lock operations, and a literature search, a number of potentially important parameters were initially selected for consideration. Several of these parameters were eliminated during the investigation for reasons given earlier. The remainder of this report is, therefore, limited to a discussion of only those parameters recommended for inclusion in the initial optimal tow sequencing program.*

Summary of Significant Findings

General

37. For clarity and reference throughout the following discussions, mean lockage times are reported in table 1 in terms of the steps of the lockage procedure (i.e., tow entry, locking, and exit) and as a function of those parameters found to be statistically significant in affecting these steps. Table 1 represents a summary of the usable data gleaned from the analysis. Rationale for choosing the entry, locking, and exit times given in table 1 is discussed in paragraphs 38-51.

Average entry times for empty tows on short entry

38. An empty tow is defined as a tow transporting no commodities, only empty barges. A loaded tow is defined as a tow that is composed of a towboat and one or more loaded barges, i.e., a commodity tonnage was

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* To be discussed in detail in the following report: L. L. Daggett, R. W. McCarley, and J. E. Stinehour, "Use of Tow Sequencing Procedures to Increase the Capacity of Existing Lock Facilities," (in preparation), U. S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Miss.

recorded in the lock traffic data. The 1969 lock traffic data taken at L&D 51 revealed that in an overwhelming majority of the cases at least half of the barges associated with a given tow were loaded or else all of the barges were empty. Therefore, only the classifications "loaded" and "empty" were considered. Other attempts to analyze the effects of commodity loading, e.g., T/HP and NLB/TB, did not prove to be meaningful.

39. Tows composed solely of empty barges executed the short entry slightly faster than those tows loaded with many tons of commodities in transit. An entering tow made a short entry when it was locked immediately following a tow traveling in the same direction. The entering tow was thus allowed to align itself on the guide wall with its bow very near the gates of the lock chamber. During the short entry, a tow was, of course, delayed somewhat during lock swingaround (filling or emptying without a tow in the chamber), but this time was generally less than the long entry time.

40. The direction of travel for short entry was found to be unimportant; therefore, only the combined averages of the short entry times of tows traveling in both directions are given in table 1. It might be expected that tows traveling upstream (against the current) would require more time in reaching the lock. This is not necessarily true for the short entry because a tow aligned on the guide wall is somewhat protected from the river currents. Thus, the current's effect is minimized.

41. In computing average short entry times for both empty and loaded tows, only those entry times less than 20 min were considered. Since a short entry, by definition, dictates that the bow of a tow would be only a short distance (say, no more than about 100 ft (30.5 m)) from the lock gate sill, entry times exceeding 20 min would be uncommon. The recording of the time of departure from the AP rather than the time that the tow was signaled to begin its approach was probably the cause of most excessively long short entry times found in the data.

Average entry times for
loaded tows on short entry

42. Towboats transporting loaded barges must first overcome the added inertia imposed by their loads before developing the necessary forward motion for entry into a lock chamber. As a result, slightly longer average entry times were indicated for loaded tows of various sizes, based on the analysis of entry times for all such tows locked in 1969. For the same reasons given in paragraph 41, only entry times less than 20 min were used to compute the averages, and only the combined averages of the entry times for the two directions of travel are given in table 1.

Average entry times for
empty tows on long entry

43. A tow must enter a lock under the provisions dictated by the definition of a long entry if, after formation of the queue, the tow immediately follows an exiting tow traveling in the opposite direction. That is, in order for the exiting tow to clear the lock and safely pass the entering tow in the approach channel, the entering tow must remain a considerably longer distance from the lock than would normally be required when two sequentially locked tows are traveling in the same direction, i.e., the short entry.

44. Empty tows traversed the relatively long distance from the AP to the lock gates in considerably less time, on the average, than loaded tows.

45. For the long entry, there was a marked difference between average times of tows traveling upstream and those traveling downstream; upbound tows traveling a distance of from 1/2 to 1 mile (0.8 to 1.6 km) against the river currents were expected to take longer to enter the lock. An exception to this might occur during periods of brisk winds when the sides of the empty barges, riding high above the water surface, act as wind sails, thereby reducing the maneuverability of the tow and increasing the entry time, regardless of the direction of travel.

Average entry times for
loaded tows on long entry

46. Greatly increased water resistance and inertia associated with the loaded tows resulted in correspondingly greater long entry times, as compared with those for empty tows.

47. Due to a paucity of data, the average entry times for both empty and loaded downbound tows requiring setover lockages could not be determined. An estimate which probably approximates the actual entry time for a tow requiring a setover lockage was based on a comparison with the entry times required by other lockage types, together with a cursory analysis of the available setover lockage data. Enough data were available for calculating the average entry times for loaded setover tows traveling upstream.

Average locking
times for empty tows

48. Average locking times, in minutes, were calculated for tows with all empty barges for the four lockage types. The locking time is defined as the time that the tow is actually occupying all or part of the lock chamber. It is computed by subtracting the clock time (24-hr clock) at which the tow's stern clears the gate sill on exit from the clock time at which the tow's bow crosses the opposite gate sill on entry. Direction of travel was not considered in calculating the locking times since there did not appear to be a significant difference in locking times for tows locked up and those locked down.

Average locking
times for loaded tows

49. Average locking times, in minutes, for tows composed of a towboat and one or more loaded barges are presented in table 1 for all four lockage types. Average locking times for various size loaded tows were significantly greater than those for empty tows. This difference was primarily due to the greater inertial forces associated with stopping an entering loaded tow and getting it under way again following lockage. These inertial effects are included in the locking time period due to the manner in which the locking or chambering time is computed.

The time between bow-over-sill time and when the tow is tied off on the lock wall; the time between the opening of the gates and the stern-over-sill time; and the time between the exit of the first cut and the entry of the second cut of double lockages are included in the locking time calculations and involve acceleration and deceleration of the tow. The effects of the added momentum during these operations were clearly observed.

Average exit times

50. Visual analysis of tow exit times for 1969 indicated a high predominance of 5- and 10-min recordings. In fact, the exit time recorded for most tows regardless of size, load, horsepower, configuration, etc., was 5 min. Consequently, the factors that significantly influence exit times were difficult, if not impossible, to isolate using the available data. The average of all tow exit times by lockage type, regardless of the direction of travel or commodity loading, is recommended for use in the optimization program. The average exit times given in table 1 are considered to be rough estimates at best and were selected on a temporary basis for possible revision at a later date.

Swingaround correction factor

51. This factor is defined as the lock swingaround time minus the tow exit time and was required in the optimization program to compute more accurately the probable departure time of a tow making a short entry. Analysis of L&D 51 data indicated the average swingaround time to be approximately 8 min, which was longer than the average tow exit time. The lock presumably starts its swingaround when the stern of the exiting tow crosses the gate sill on exit and ends it when a waiting tow traveling in the same direction begins its entry. The next tow cannot begin a short entry until the swingaround is completed. In the optimization program,* the swingaround correction factor must be added to the clock time at which a departing tow passes the AP on exit in order to establish the probable clock time at which an entering tow begins a short entry. The necessity for this stems from the inclusion

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* L. L. Daggett, R. W. McCarley, and J. E. Stinehour, op. cit.

of composite average lockage times in the optimization program rather than the individual average entry, locking, and exit times.

Statistical Analysis Procedures

52. The basic determination required during the analysis of parameter effects on lockage step times was whether two sample mean times associated with different parameter values were significantly different. The normal procedure for making this determination is to use a Student's t test* to verify the hypothesis that the mean of population X, μ_x, is equal to the mean of population Y, μ_y, at a given level of significance. If this test indicates that the hypothesis is not true, then it has been determined only that the sample means may not be equal. It can then be assumed that the parameter that varied might have caused inequity. If the test indicates that the hypothesis is true, then it can be assumed that the parameter has no effect at the level of significance tested.

53. The type of test required to test statistically the tow traffic data at L&D 51 was a test of the hypothesis that the population means of two normal distributions are equal, given that their standard deviations are unknown and not necessarily equal. According to Bowker and Lieberman,*

> ...an exact procedure based on a t statistic is unavailable to cover this situation. However, a procedure exists, based on a test statistic t', which has the property that, when $\mu_x = \mu_y$, t' has an approximate t distribution. The statistic t' is given by

$$t' = \frac{\bar{X} - \bar{Y}}{\sqrt{\dfrac{s_x^2}{n_x} + \dfrac{s_y^2}{n_y}}} \qquad (1)$$

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* Albert H. Bowker and Gerald J. Lieberman, Engineering Statistics, 2d ed., Prentice Hall, Inc., Jan 1972.

and the associated degrees of freedom are

$$\nu = \frac{\left(S_x^2/n_x + S_y^2/n_y\right)^2}{\frac{\left(S_x^2/n_x\right)^2}{(n_x + 1)} + \frac{\left(S_y^2/n_y\right)^2}{(n_y + 1)}} - 2 \qquad (2)$$

The symbols used in the above equations are defined as follows:

$\bar{X}$ = mean of data sampling x

$\bar{Y}$ = mean of data sampling y

S_x^2 = variance of data sampling x

S_y^2 = variance of data sampling y

n_x = number of observations in sampling x

n_y = number of observations in sampling y

A standardized statistical computer program was used to determine the values of t' and ν for the required significance tests.

54. The mean times, number of sample observations, and standard deviations from the means (square root of the variances) used in the statistical analysis are tabulated in Appendix B. The data shown in table 1 are included as an integral part of Appendix B. Appendix C presents the computed t' and ν values, the t' values and degrees of freedom obtained from standard tables for comparison, and the corresponding levels of significance for rejecting the null hypothesis, H_o.

55. A one-tail t' test was used to determine if significant differences existed between the mean entry times or the mean locking times corresponding to the extreme cases for type of entry (short versus long), commodity loading (empty versus loaded), and direction of travel (downbound versus upbound).

56. The decision to use a one-tail t' test was based primarily on the strong evidence that varying a given parameter undoubtedly caused a consistent and predictable change in the average time required for a tow to enter or lock. This was apparent from the consistent trend of

the mean entry and locking times from one given lockage type (single, double, etc.) to another. For example, empty tows, regardless of lockage type, consistently took less time to make a short or long entry than loaded tows. Similarly, the average locking times of empty tows were always less than the average locking times of loaded tows for each lockage type, as would be expected. The objective of the one-tail t' test was to determine to what degree of certainty the means of one parameter value would differ significantly from those of another (e.g., up versus down, empty versus loaded, or long entry versus short entry), relative to their respective influences on entry and locking times. A paucity of quality data precluded the analysis of exit times in this manner.

57. A separate one-tail t' test of the two parameter extremes in each set was made for each lockage type (see Appendix C). For example, a separate t' test was used to determine if mean short entry times of empty tows requiring single lockages were significantly less than the mean short entry times of loaded tows also requiring single lockages. Similar t' tests of significance were made for tows requiring double and knockout lockages. A t' test to compare the average entry and locking times of tows requiring setover lockages could not be made in most instances because of insufficient data.

58. For both the one- and two-tail t' tests, H was $\mu_x = \mu_y$ where μ_x and μ_y represent the values of the population means associated with the two values of a single parameter. In this study, the population mean was the mean time required by the tows of a predetermined category to complete a given step of the lockage procedure, i.e., enter, lock, or exit. The alternate hypothesis for the one-tail t' test was $\mu_x < \mu_y$. The test was set up to reject H when $t' \leq -t_{\alpha,\nu}$, where t' was calculated from the L&D 51 tow traffic data according to equation 1 and $t_{\alpha,\nu}$ was the standard table value at the α level of significance and ν degrees of freedom. For example, if $t' \leq -t_{0.10,\nu}$, then the hypothesis that $\mu_x = \mu_y$ could be rejected with a level of confidence that this rejection would be correct 90 percent of the time.

59. In analyzing the results of the one-tail t' test, it was necessary to assume that if μ_x were significantly less (at the 10 percent

level of significance) than μ_y for at least one lockage type, then μ_x could also be considered as significantly less than μ_y for the other three lockage types. In other words, μ_x could be considered significantly less than μ_y for <u>all</u> tows (regardless of size and configuration) in a set of two parameter extremes. As shown in Appendix C, the minimum level of significance for rejecting H for each set of paired parameter extremes in the one-tail t' test was in no case greater than 10.0 percent. Therefore, for each pair of parameter extremes tested, the statistical analysis indicated that the mean value associated with one parameter value was significantly less than the mean value associated with the other at a level of probability no greater than 10 percent.

60. The two-tail t' test was used to compare the effects of the various lockage types (another separate parameter) on the mean time required to complete each step of the lockage procedure. The test statistic, $|t| \geq t_{\alpha/2,\nu}$, was used to reject the hypothesis that $\mu_x = \mu_y$ and to prove that $\mu_x \neq \mu_y$. The nature of the two-tail t' test dictates that the levels of significance for rejecting H are double those of the one-tail test. Appendix C shows the higher significance levels obtained for the two-tail t' test. The decision to use the two-tail t' test for the lockage type parameter in lieu of the one-tail test was based on the results of the data analysis. The analysis did not indicate a consistent trend in average lockage-step times relative to variations in lockage type. For example, a tow requiring a double lockage, even though larger than a tow requiring knockout lockage, did not always take longer on the average to complete a short entry. Double lockage tows may, in fact, be more adequately powered than knockouts, though this particular aspect was not specifically analyzed. The two-tail t' test was more appropriate for use in the statistical analysis of this parameter to determine if two given mean times were really different and, if so, to determine the significance level for obtaining that difference.

61. An assumption similar to the one used for the one-tail t' test was also employed for the two-tail t' test to determine if a

significant difference existed between the mean times associated with the four lockage types. Here, it was assumed that if a significant difference existed between the mean entry (short or long), locking, or exit times of two given lockage types, then a significant difference also existed between the mean times associated with the other paired lockage types. The high significance levels shown in Appendix C indicate that little difference existed between lockage types in the comparison of mean short entry times of both empty and loaded tows, regardless of travel direction. Differences in long entry times for the various lockage types were also not significant for loaded tows traveling in the upbound direction. For upbound empty tows, as well as both empty and loaded tows traveling downstream, the differences between mean entry times of the lockage types compared with one another were significant in most cases. As expected, differences in locking times were very significant. Mean exit times were also analyzed using the two-tail t' test and found to be significantly different in four out of six paired lockage types.

62. The statistical analysis did not attempt to include all the parameter combinations considered but rather was limited primarily to those mean times recommended for the lock optimization program.* Other parameter sets were omitted from the analysis because of unexplainable inconsistencies in mean entry, locking, or exit times among the lockage types. For example, in a comparison of the average long entry times for underpowered tows ($T/HP > 4$) with those of adequately powered tows ($T/HP \leq 4$), the underpowered tows of some lockage types took longer to enter than the adequately powered tows of the same lockage type, as would be expected. For other lockage types, however, the reverse was true. Parameters with such inconsistent results were eliminated from further consideration and therefore not discussed.

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* L. L. Daggett, R. W. McCarley, and J. E. Stinehour, op. cit.

PART IV: CONCLUSIONS AND RECOMMENDATIONS

Conclusions

63. This study has broadened the Corps' knowledge of several factors that influence tow lockage times and has opened new avenues for future endeavors. Certain characteristics of the tows themselves, together with other considerations such as river currents and wind, obviously influence tow entry, locking, and exit times. This study sought to quantify the effects of as many such characteristics as possible, using the available vessel traffic data taken at L&D 51, Ohio River. If selected additional lockage data had been available, an analysis of other parameters that apparently have an influence on lockage times would have been included in the study. The analytical techniques used were governed by the primary problem that generated this data analysis, i.e., the need for developing an improved technique for sequencing tows waiting in queue at a lock. The system developed by WES for scheduling tows for lockage was referred to several times in the report as the optimization program. A description of the optimization program is given in a WES report now in preparation.*

64. The primary conclusions from this study were utilized in the development of an initial data base for the optimization program. In summary, the average tow entry, locking, and exit times were determined to be functions of the following parameters, as shown in table 1 of this report:

a. Entry types (short and long).

b. Lockage types (single, double, knockout, and setover).

c. Directions of travel (upstream and downstream).

d. Commodity loadings (empty and loaded).

These parameters indicate the extent to which meaningful information could be gleaned from the available data. Attempts were made to analyze several other parameters that were considered to have a significant

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* L. L. Daggett, R. W. McCarley, and J. E. Stinehour, op. cit.

influence on the lockage times. However, these parameters failed to demonstrate the level of significance required.

Recommendations

65. Several points in the form of recommendations are noteworthy. First, a standard means of recording information relative to weather, river current, and visibility conditions should be formulated. Based on discussions with operations personnel at L&D 51, tow crew capability also plays an extremely important part in the time required to process a given tow through a lock. Some equitable procedures for measuring crew capability should, therefore, be established. Simple, easily obtainable data would be required so as not to burden the assigned lock operators. Examples of simple recordings that would be helpful in analyzing tow movements would include the following:

- a. Weather (good or poor).
- b. River currents (normal or adverse).
- c. Visibility (good or poor).
- d. Crew capability (outstanding, average, or below average).

Such recordings are considered to be necessary to obtain a better understanding of the primary parameters that influence lockage time requirements.

66. Another recommendation involves the need for more appropriate time data for the calculation of short entry times. The depart-AP and bow-over-sill clock times had to be used in this study to compute tow entry times. More accurate short entry times would have been obtained if the actual callup time of each tow had been available. As a supplement to the clock times currently recorded, the callup time of each tow should be recorded in addition to the depart-AP time. All clock times should be recorded to the nearest minute. Use of a digital clock would be most helpful.

67. Finally, waterway and lock simulation models should be improved by incorporating more accurate descriptions of tow processing times. Most lock processing models do not use the most significant parameters to describe the lockage times.

Table 1

Results of Analysis of 1969 Tow Lockage Data for Lock and Dam 51, Ohio River, Illinois

Lockage Type	Direction of Tow Travel	Average Entry Times, min: Short Entry* Empty	Short Entry* Loaded	Long Entry Empty	Long Entry Loaded	Average Locking Times, min: Empty	Loaded	Average Exit Times min	Swingaround Correction Factor, min** (Short Entry)	Average Lockage Times, min†: Short Entry Empty	Short Entry Loaded	Long Entry Empty	Long Entry Loaded
Single	Upstream	8.1	9.1	10.5	17.4	18.8	21.2	5.7	2.3	32.6	36.0	35.0	44.3
	Downstream			9.0	13.4							33.5	40.3
Double	Upstream	8.3	9.9	17.4	20.0	67.3	82.8	6.6	1.4	82.2	99.3	91.3	109.4
	Downstream			14.8	18.3							88.7	107.7
Knockout	Upstream	7.7	9.7	13.5	21.6	31.2	37.8	6.0	2.0	44.9	53.5	50.7	65.4
	Downstream			9.4	15.0							46.6	58.8
Setover	Upstream	7.0††	8.0	12.0††	17.8	58.2‡	58.2	6.3	1.7	71.5	72.5	76.5	82.3
	Downstream			10.0††	14.0††							74.5	78.5

* Average of entry times less than 20 min in duration.
** Average lock swingaround time (8 min) minus tow exit time (see paragraph 51 in main text).
† Average entry time plus average locking time plus average exit time.
†† Estimated because of paucity of data.
‡ Average locking time for loaded tows requiring setover lockage due to a paucity of data for empty tows requiring setover lockage.

APPENDIX A: SUMMARY LOCK SHEET (ORD FORM 886)

PART V LOCK TRAFFIC STUDY
SUMMARY LOG SHEET

LOCK NO ______
(1-2)

PAGE NO ______

RECORDER'S NAME(S) ______

VESSEL NAME	VESSEL NUMBER	ARR DAY	YR.	ARR TIME	DIRECTION	CLASS	QUAN	CHAMBER	TYPE	NO. PEOPLE	BARGES: TOTAL	BARGES: LOADS	BARGES: EMPTY		TOW SIZE: LGTH.	TOW SIZE: WIDTH	TOW SIZE: MAX DRAFT	COMMODITY: CODE	COMMODITY: TONS	WAIT TIME (MIN.)	CLOCK TIMES (0001 - 2400): DEPART A.P.	CLOCK TIMES: BOW OVER SILL	CLOCK TIMES: CLEAR LOCK	CLOCK TIMES: STERN CLEAR A.P.	DAY CLEAR	LOCK CODE		R.C.
	3-7	8-10	11-12	13-16	17	18	19	20	21	22-24	25-26	27-28	29-30	31-32	33-36	37-40	41-43	44-47	48-52	53-56	57-60	61-64	65-68	69-72	73-75	76-78	79	80
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DIRECTION (17)
U Upstream
D Downstream
O Other (Explain)

QUAN. (19) OF PLEASURE CRAFT
Number of each type of pleasure craft in lock chamber Max. of 9 per line

TYPE (20) OF PLEASURE CRAFT
1 Outboard 4 Sail
2 Inboard 5 Row
3 Out/In 6 Other

CLASS (18) OF VESSEL
COMMERCIAL
1 Towboat
2 Tow With Barges
3 Passenger
4 Other (Explain)
U.S.
5 Towboat
6 Tow With Barges
7 Repairboat
8 Other (Explain)
MISC.
9 Pleasure Craft
0 Other (Explain)

NO. PEOPLE (22-24)
Sum of passengers on commercial craft or people in pleasure craft

CHAMBER (21)
R Riverward
C Center
L Landward

BARGES (25-30)
No. of barges in whole tow
Total (25-26)
Loaded (27-28) and
Empty (29-30)

TOW SIZE
LENGTH (33-36) and WIDTH (37-40) of the whole tow as it approached the lock (in feet)
MAX. DRAFT (41-43) of deepest vessel in the tow (in feet and tenths)

COMMODITY TONS (48-52)
Total cargo tonnage for the whole tow

COMMODITY CODE (44-47)
For single commodity tows use 4 digit wcsc commodity code, if known OR Use up to 4 of the following groupings:
A Stone, Sand & Gravel
B Coal & Coke
C Crude Petroleum
D Oil & Gasoline
E Iron & Steel
F Sulphur
G Chemicals
H Grain
J Logs & Lumber
K All Other

WAIT TIME (53-56)
Total time (in minutes) that tow had to wait to use the lock. Include time at A.P. PLUS estimated time tow had to wait before reaching A.P. and any time tow had to wait between the A.P. and the lock sill.

LOCK CODE (76-78)
010 Single Alone
011 Setover Alone
020 Double Alone, either cut
110 Single with others
111 Setover with others
121 Double, first cut with others
122 Double, second cut with others
030 Triple Alone, any cut
040 Quadruple Alone, any cut

ORD Form 886
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PLNG DIV

APPENDIX B: TOW LOCKAGE DATA USED IN STATISTICAL ANALYSIS

Table B1

Tow Lockage Data Used in Statistical Analysis*

Lockage Types	Direction of Tow Travel		Short Entry Data			Long Entry Data			Locking Data		
			All Tows	Empty Tows	Loaded Tows	All Tows	Empty Tows	Loaded Tows	Empty Tows	Loaded Tows	Exit Data
Single	Both directions	(a)**	9.23	8.05	9.07	11.49	--	--	18.75	21.18	5.7
		(b)**	230	107	74	237	--	--	356	232	709
		(c)**	6.79	3.63	4.19	9.30	--	--	10.66	10.05	2.03
	Upstream	(a)	9.18	--	--	12.39	10.48	17.42	--	--	--
		(b)	98	--	--	114	64	33	--	--	--
		(c)	5.45	--	--	11.34	7.28	16.31	--	--	--
	Downstream	(a)	9.26	--	--	10.67	9.02	13.42	--	--	--
		(b)	132	--	--	123	61	43	--	--	--
		(c)	7.58	--	--	6.90	3.82	9.81	--	--	--
Double	Both directions	(a)	12.09	8.31	9.94	18.16	--	--	67.25	82.84	6.6
		(b)	201	52	126	242	--	--	182	452	682
		(c)	9.32	3.52	4.17	12.33	--	--	17.08	17.59	3.17
	Upstream	(a)	11.50	--	--	18.46	17.38	20.00	--	--	--
		(b)	86	--	--	112	43	58	--	--	--
		(c)	8.74	--	--	11.88	13.06	11.04	--	--	--
	Downstream	(a)	12.53	--	--	17.90	14.79	18.31	--	--	--
		(b)	115	--	--	130	24	102	--	--	--
		(c)	9.69	--	--	12.70	9.95	12.95	--	--	--
Knockout	Both directions	(a)	9.64	7.73	9.69	15.08	--	--	31.22	37.75	6.0
		(b)	164	65	94	186	--	--	196	349	562
		(c)	5.91	3.50	4.63	10.34	--	--	13.80	17.62	2.33
	Upstream	(a)	8.95	--	--	15.70	13.45	21.55	--	--	--
		(b)	97	--	--	93	57	29	--	--	--
		(c)	6.03	--	--	11.12	9.29	12.94	--	--	--
	Downstream	(a)	10.66	--	--	14.46	9.38	14.99	--	--	--
		(b)	67	--	--	93	9	82	--	--	--
		(c)	5.57	--	--	9.46	3.90	9.72	--	--	--
Setover	Both directions	(a)	9.63	--	7.97	16.77	--	--	--	58.17	6.3
		(b)	38	--	34	48	--	--	--	111	132
		(c)	7.82	--	3.27	13.57	--	--	--	18.40	2.68
	Upstream	(a)	9.73	--	--	18.21	--	17.78	--	--	--
		(b)	33	--	--	39	--	32	--	--	--
		(c)	8.25	--	--	14.40	--	14.55	--	--	--

Note: The mean short entry times in the column "All Tows" were based on all short entry times whereas the mean short entry times in the columns "Loaded Tows" and "Empty Tows" were based only on short entry times ≤ 20 min. The mean long entry times in the column "All Tows" were based on all long entry times, whereas mean long entry times in the columns "Loaded Tows" and "Empty Tows" were based only on long entry times ≤ 70 min.

* Based on tow traffic data recorded at Lock and Dam 51, Ohio River, during 1969.

** a = mean times (minutes); b = no. of tows in sample; c = standard deviation.

APPENDIX C: SUMMARY OF RESULTS OF THE STATISTICAL ANALYSIS

Table C1

Results of One-Tail t' Tests of Parameters Influencing Mean Entry, Locking, and Exit Times of Tows at Lock and Dam 51, Ohio River

Test Parameter	Calculated Degrees of Freedom ν	Calculated t'	$t_{\alpha,\nu}$ *	Level of Significance for Rejecting H ** %
Type of entry (short versus long)				
Downbound tows only				
Single lockage	254	-1.55	1.29	10.0
Double lockage	239	-3.74	3.34	0.05
Knockout lockage	154	-3.18	3.13	0.10
Setover lockage		Insufficient data		
Upbound tows only				
Single lockage	168	-2.68	2.60	0.5
Double lockage	197	-4.75	3.34	0.05
Knockout lockage	141	-5.17	3.34	0.05
Setover lockage	63	-3.12	2.66	0.5
All tows				
Single lockage	433	-3.01	2.59	0.5
Double lockage	439	-5.89	3.31	0.05
Knockout lockage	301	-6.12	3.31	0.05
Setover lockage	78	-3.06	2.64	0.5
Commodity loading (empty versus loaded)				
Short entry (times ≤ 20 min), all tows				
Single lockage	143	-1.67	1.66	5.0
Double lockage	122	-2.32	1.98	2.5
Knockout lockage	157	-3.10	2.60	0.5
Setover lockage		Insufficient data		
Long entry, downbound tows only				
Single lockage	51	-2.80	2.68	0.5
Double lockage	45	-1.46	1.30	10.0
Knockout lockage	24	-3.32	2.80	0.5
Setover lockage		Insufficient data		
Long entry, upbound tows only				
Single lockage	39	-2.31	2.02	2.5
Double lockage	83	-1.06	0.85	20.0
Knockout lockage	44	-3.00	2.70	0.5
Setover lockage		Insufficient data		
Locking, all tows				
Single lockage	516	-2.80	2.59	0.5
Double lockage	345	-10.31	3.31	0.05
Knockout lockage	489	-4.79	3.31	0.05
Setover lockage		Insufficient data		
Direction of travel (downbound versus upbound)				
Long entry, empty tows only				
Single lockage	97	-1.45	1.29	10.0
Double lockage	61	-0.91	0.85	20.0
Knockout lockage	29	-2.29	2.05	2.5
Setover lockage		Insufficient data		
Long entry, loaded tows only				
Single lockage	79	-1.61	1.29	10.0
Double lockage	136	-0.88	0.85	20.0
Knockout lockage	40	-2.50	2.42	1.0
Setover lockage		Insufficient data		
Long entry, all tows				
Single lockage	185	-1.40	1.29	10.0
Double lockage	240	-0.35	0.25	40.0
Knockout lockage	181	-0.82	0.53	30.0
Setover lockage		Insufficient data		

* Standard table value at the α level of significance and ν degrees of freedom.
** Null hypothesis H : $\mu_x = \mu_y$. Reject this hypothesis when $t' \le -t_{\alpha,\nu}$ and say that $\mu_x < \mu_y$.

Table C2

Results of Two-Tail t' Tests of Parameters Influencing Mean Entry, Locking, and Exit Times of Tows at Lock and Dam 51, Ohio River

Test Parameter	Calculated Degrees of Freedom ν	Calculated $\lvert t' \rvert$	$t_{\alpha/2,\nu}$ *	Level of Significance for Rejecting H ** %
Single versus double lockage				
Short entry, empty, both directions	105	0.33	0.25	80.0
Short entry, loaded, both directions	154	1.31	1.29	20.0
Long entry, empty, downstream	25	2.78	2.49	2.0
Long entry, empty, upstream	39	2.31	2.02	5.0
Long entry, loaded, downstream	105	2.49	2.37	2.0
Long entry, loaded, upstream	83	1.06	0.85	40.0
Locking times, empty, both directions	255	34.98	3.34	0.1
Locking times, loaded, both directions	676	58.21	3.31	0.1
Exit times, both directions	1153	6.28	3.29	0.1
Single versus knockout lockage				
Short entry, empty, both directions	141	0.72	0.53	60.0
Short entry, loaded, both directions	164	0.88	0.84	40.0
Long entry, empty, downstream	10	0.29	0.26	80.0
Long entry, empty, upstream	107	1.96	1.66	10.0
Long entry, loaded, downstream	86	0.87	0.85	40.0
Long entry, loaded, upstream	62	1.35	1.30	20.0
Locking times, empty, both directions	326	10.91	3.31	0.1
Locking times, loaded, both directions	568	14.42	3.31	0.1
Exit times, both directions	1120	2.41	2.33	2.0
Double versus knockout lockage				
Short entry, empty, both directions	111	0.92	0.85	40.0
Short entry, loaded, both directions	190	0.33	0.25	80.0
Long entry, empty, downstream	32	2.24	2.04	5.0
Long entry, empty, upstream	73	1.67	1.66	10.0
Long entry, loaded, downstream	183	1.97	1.97	5.0
Long entry, loaded, upstream	50	0.57	0.53	60.0
Locking times, empty, both directions	349	22.50	3.31	0.1
Locking times, loaded, both directions	749	35.87	3.31	0.1
Exit times, both directions	1228	3.84	3.29	0.1
Single versus setover lockage†				
Short entry, loaded, both directions	83	1.48	1.29	20.0
Long entry, loaded, upstream	64	0.10	Unknown	90.0
Locking times, loaded, both directions	142	19.80	3.39	0.1
Exit times, both directions	160	2.44	2.35	2.0
Double versus setover lockage†				
Short entry, loaded, both directions	66	2.82	2.66	1.0
Long entry, loaded, upstream	52	0.75	0.53	60.0
Locking times, loaded, both directions	163	12.73	3.34	0.1
Exit times, both directions	209	1.14	1.29	20.0
Knockout versus setover lockage†				
Short entry, loaded, both directions	85	2.31	1.99	5.0
Long entry, loaded, upstream	60	1.08	0.85	40.0
Locking times, loaded, both directions	179	10.28	3.34	0.1
Exit times, both directions	181	1.19	0.84	40.0

* Standard table value at the α level of significance and ν degrees of freedom.

** Null hypothesis H : $\mu_x = \mu_y$. Reject this hypothesis when $\lvert t' \rvert \geq t_{\alpha/2,\nu}$ and say that $\mu_x \neq \mu_y$.

† Adequate quantity of data available only for loaded, upbound tows requiring setover lockage.

APPENDIX D: DEFINITION OF TERMS

1. Closed pass: The condition existing at a lock when the movable dams are raised to maintain navigable river depths. Vessels must then use the lock to continue their journey.

2. Double lockage: The lockage of a tow larger than the lock by two lockages.

3. Empty tow: A tow transporting little or no commodity tonnage. To be considered empty, all barges do not have to be empty. A large tow with one or two loaded barges could also be considered empty for purposes of determining the average entry/exit time.

4. Entry time: The period of time in minutes from tow callup until the bow of the tow first crosses the lock sill. Analysis of existing data taken at Lock and Dam 51 required that the entry time commence when a tow departed the approach point (the lock may or may not have been ready to receive a tow at that time) and end when the bow first crossed the lock sill.

5. Exit time: The period of time in minutes beginning when a tow's stern passes over the lock sill on exit and ending when the stern clears the approach point.

6. Knockout lockage: Lockage in which only the towboat is set alongside the tow to accomplish a single lockage.

7. Loaded tow: A tow transporting all or almost all loaded barges. To be considered loaded, all barges do not have to be filled with a commodity. A large tow with one or two empty barges could also be considered loaded for purposes of determining the average entry/exit time.

8. Lockage time: Entry time plus locking (or chambering) time plus exit time in minutes.

9. Locking time: The time in minutes spent by all or part of a tow within the lock chamber. Locking time begins when the bow of the tow first crosses the lock sill on entry and ends when the stern crosses the opposite sill on exit.

10. Long entry: A tow must make a long entry when locked immediately following a tow traveling in the opposite direction. The

entering tow must remain far enough back from the lock to allow safe passage of the exiting tow.

11. Optimization program: The computer program which optimizes the order in which waiting tows are scheduled for lockage.

12. Setover lockage: Lockage in which the towboat and one or more barges are set alongside the remaining barges to accomplish a single lockage.

13. Short entry: A short entry is possible when two tows traveling in the same direction are locked sequentially. The entering tow is permitted to tie to the guide wall only a short distance from the gates of the lock.

14. Single lockage: The lockage of an entire tow in its arrival configuration with a single filling or emptying of the lock chamber.

15. Tow: A river vessel composed of at least one towboat and one barge.

16. Transit time: The total time in minutes required for a tow to pass through a lockage facility, i.e., waiting time plus entry time plus locking (or chambering) time plus exit time.

17. Waiting time: The period of time from tow arrival at the designated approach point or mooring cell until callup.

Unclassified

Security Classification

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author) U. S. Army Engineer Waterways Experiment Station Vicksburg, Miss.	2a. REPORT SECURITY CLASSIFICATION Unclassified 2b. GROUP

3. REPORT TITLE

ANALYSIS OF TOW ENTRY, LOCKING, AND EXIT TIMES AT LOCK AND DAM 51, OHIO RIVER

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)

Final report

5. AUTHOR(S) (First name, middle initial, last name)

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Judith E. Stinehour

6. REPORT DATE March 1974	7a. TOTAL NO. OF PAGES 44	7b. NO. OF REFS 3
8a. CONTRACT OR GRANT NO. b. PROJECT NO. c. d.	9a. ORIGINATOR'S REPORT NUMBER(S) Miscellaneous Paper H-74-4 9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)	

10. DISTRIBUTION STATEMENT

Approved for public release; distribution unlimited.

11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY U. S. Army Engineer District Louisville, Kentucky

13. ABSTRACT

An analysis of a large sampling of the tow traffic data taken in 1969 at Lock and Dam 51 (L&D 51) on the Ohio River was needed primarily to provide a data base for the development of an improved standardized method for sequencing tows waiting in queue. Traffic congestion at L&D 51 has become an increasingly serious problem in recent months, as has been the case at a number of other locks. This situation has intensified interest in low-cost operational improvements which can help alleviate the congestion at such locks without the necessity for expending large sums for structural improvements. Through an analysis of available tow traffic data, literature reviews, and discussions with knowledgeable Corps personnel, it was attempted in this investigation to determine easily identifiable and recordable physical parameters that, as a rule, have a recurring positive influence on the steps of the lockage procedure, i.e., tow entry, locking, and exit. The quality and scope of the available data did not permit as comprehensive an analysis of all significant parameters as desired, but, for the first time, the effects of certain parameters were isolated and quantified to a usable degree of accuracy. Parameters for which an acceptable degree of meaningful information was obtained were (a) entry type (long and short), (b) lockage type (single, double, knockout, and setover), (c) direction of travel (upstream and downstream), and (d) commodity loading (empty and loaded). Other less successful attempts were made to analyze the combined effects of towboat horsepower and commodity loading on tow entry and locking times. An unsuccessful attempt was also made to analyze the degree of loading as a function of the ratio of number of loaded barges to total number of barges in order to quantify the influence of this parameter on entry and locking times. This report is limited primarily to a discussion of those parameters that could be satisfactorily analyzed. Very little information could be gleaned from an analysis of the tow exit times. Unfortunately, the exit time of most tows was recorded only to the nearest 5 min regardless of size, power, or other such factors that contribute to tow speed and maneuverability. The collection of additional data recorded to the nearest minute would undoubtedly provide the necessary data for a more accurate analysis of this and other steps of the lockage procedure.

DD FORM 1473 1 NOV 65 REPLACES DD FORM 1473, 1 JAN 64, WHICH IS OBSOLETE FOR ARMY USE.

Unclassified

Security Classification

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Lock and Dam No. 51, Ohio River						
Locks (waterways)						
Ohio River						
Towed bodies						
Waterway transportation						