ST. ANTHONY FALLS HYDRAULIC LABORATORY
UNIVERSITY OF MINNESOTA

Project Report 31

# DESIGN AND OPERATING CHARACTERISTICS OF HIGH-LIFT LOCKS

## TRANSLATION OF SELECTED DUTCH ARTICLES

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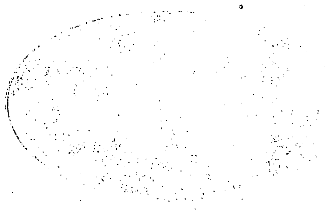

# PREFACE TO ENGLISH TRANSLATION

This report is a translation of a series of five Dutch articles by J. P. Josephus Jitta, Chief Engineer of the Netherlands Waterways Department. The initial text material was furnished by the Corps of Engineers. The translation and preparation of material for publication were made by the St. Anthony Falls Hydraulic Laboratory for the St. Paul District of the United States Department of the Army, Corps of Engineers, under contract W-21-018-eng-414.

The project was administered by Dr. Lorenz G. Straub, Director of the Laboratory. Staff members who prepared the report and rendered assistance were: Loyal Johnson, supervision of manuscript preparation; Meir Pilch, translation and arrangement; Leona Wray and Marilyn Fagerhaug, editing and preparation for publication; and Madhav Manohar and John Casey, drafting.

# ABSTRACT

This compilation comprises five articles dealing with the design and operating characteristics of both actual and hypothetical navigation locks. The first article, the major work of this series, is a thorough analytical and experimental study of filling and emptying systems for locks, undertaken with the objective of determining the optimum design of a proposed lock. The second paper presents a detailed description of the design aspects and operation features of one of the large locks of the Amsterdam-Rhein Canal. The third article deals with the general design aspects and operation details of a large lock. The fourth article constitutes a brief historical survey of filling and emptying systems, with special emphasis on adaptation to high-lift locks. The final article analyzes general and specific aspects of segment and sector valves and gates for lock chambers and culverts.

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# EXPERIMENTS AND ANALYSES FOR DESIGNING THE SYSTEM OF FILLING AND EMPTYING THE CHAMBER OF THE NEW IJMUIDEN LOCK

(Proeven en beschouwingen, welke geleid hebben tot het vaststellen
van het systeem van vulling en lediging van de kilk der
nieuwe schutsluis te IJmuiden)

by

J. A. Ringers and J. P. Josephus Jitta
Chief Engineer and Engineer of the Waterways Department, respectively

Rapporten en Mededeelingen van den Rijkswaterstaat, No. 23

Netherlands Waterways Department, 1927

# PREFACE

With regard to the mode of filling the lock chamber, it is generally known from publications and lectures that a different system was used in the construction of the new lock at IJmuiden from the system accepted in technical circles as the most suitable for large locks.*

The present report was prepared in order to enable the technical world to become acquainted readily with the reasons why it has been decided to deviate from the generally accepted system. This report contains the considerations and experimental results that affected the decision but does not present the entire historical development of the system which was finally selected, because otherwise it would have been excessively long. For the purpose of clarity, moreover, the details are grouped somewhat differently from the way they occurred in actuality.

Considerable influence on the design is attributed to the model tests at Berlin for which the director of that laboratory, Dr. H. Krey (who was also extraordinary professor at the Technische Hochschule of Charlottenburg), and his chief assistant, Dr. R. Winkel (at that time professor at the Technische Hochschule of Danzig), have rendered considerable assistance by virtue of their erudition in the practical and theoretical fields. After completion of the tests, there remained the difficult task of having to decide to carry out the work in conformity with the test results. This decision was made only after J. P. Josephus Jitta, who conducted the experiments together with the undersigned, had made a theoretical analysis of the various phenomena, which was verified by additional experiments and made it possible to form a precise conception of the relation between the model and prototype. The second part of this report deals with this theoretical analysis.

IJmuiden, March 29, 1927.

J. A. Ringers

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*See e.g. De Ingenieur, No. 39, 1924.

# LIST OF ILLUSTRATIONS

# PART I

# THE DESIGN OF THE SYSTEM FOR FILLING AND EMPTYING THE CHAMBER OF THE NEW LOCK AT IJMUIDEN

## INTRODUCTION. THE EFFECT OF THE MODE OF FILLING AND EMPTYING THE CHAMBER UPON THE DESIGN AND ARRANGEMENT OF LOCKS

Establishment of the water level in the lock chambers of the oldest locks was achieved by means of valves in the gates. The valve openings were made as large as possible in order to facilitate establishing the required level in the shortest time possible. As the locks became larger, so that the required quantities of water increased, this mode of admitting the water became less suitable because limits were imposed on the size of the valve openings to fulfill the requirement that the gates should not be excessively weakened and in order to assure relatively tranquil position of the ships in the lock chamber.

Consequently, the procedure involved installing culverts in the walls of the lockheads, with valve controls (Fig. 1). In this way, the only factor limiting the size of the discharge openings was the requirement that the ships should have a calm berth during lockage. Filling the chamber is the principal disturbing effect on the ships. In this respect, improvement was achieved by bending the culverts within the lock chamber proper squarely towards each other (Fig. 2) so that the water jets from both the left and right culverts met on the lock axis and, therefore, the dynamic force of the water partially dissipated before it came in contact with the ships. With regard to the aspect of rapid filling, this improvement is not sufficient in the case of very large locks. A better solution resulted when the culverts extended through the lock-chamber walls and the water discharged through laterals (Fig. 3). The laterals are distributed along the lock chamber as uniformly as possible and are located opposite one another, so that the dynamic force of the water jets issuing from the laterals and meeting at the chamber axis becomes dissipated. These laterals are installed as low as possible, so that the water jets would not strike the ships. The dissipation of the dynamic force of the inflowing water thus occurs no longer locally, but is distributed over the entire chamber.*

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*Similar culverts will be designated in the following as culverts with laterals.

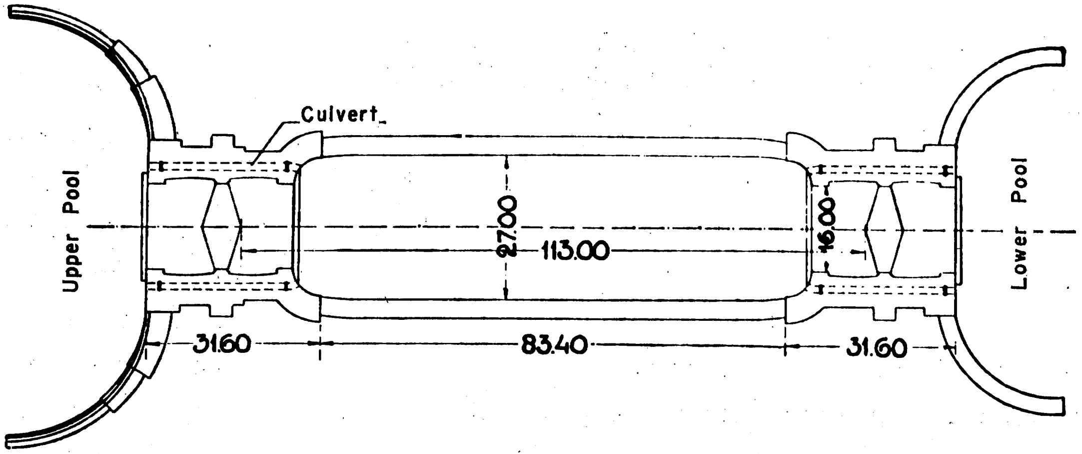

Fig.1 - Plan of the Old Lock at Hansweert (1866)

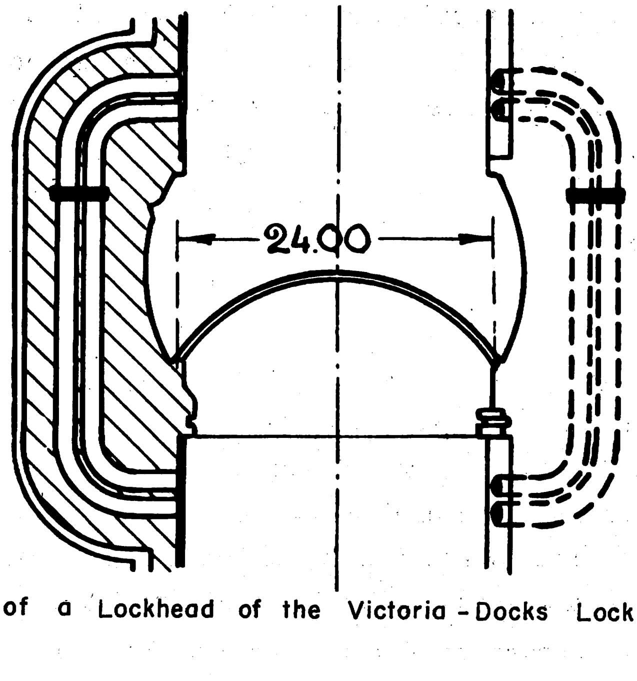

Fig.2 - Plan of a Lockhead of the Victoria-Docks Lock at London

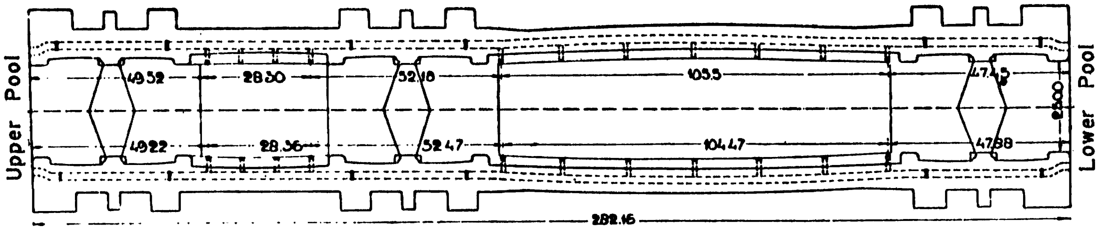

Fig. 3 – Plan of the Existing Large Lock at IJmuiden (1896)
Location of laterals is indicated.
Scale 1:400

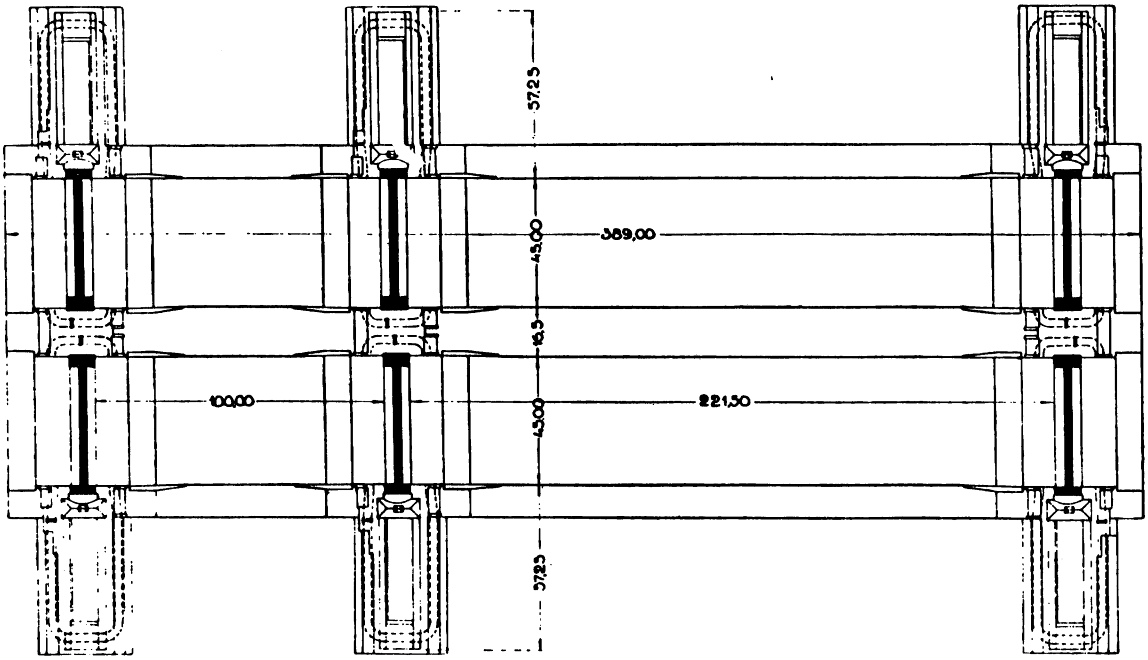

Fig. 4 – Plan of the Double Lock at Brunsbüttelkoog
(Kaiser-Wilhelm Canal, 1934)

The system of culverts with laterals is generally satisfactory but is often quite costly since the lock-chamber walls have to be based at least as low as the level of the chamber floor, whereby the stability of high walls necessitates excessive breadth. Moreover, use of culverts in the walls leads to less simple wall profiles. These objections generally are exclusively of financial nature and are appreciable primarily in designing the newer sea locks for ships with large draft, the locks being not only deep but also long. Therefore, ever since the beginning of this century, such a filling system was avoided; for example, during construction of the double lock for the third dock entrance at Wilhelmshaven* where the culverts are installed only in the lockheads, and in the case of the double sea lock of the Kaiser-Wilhelm Canal at Brunsbüttelkoog* (Fig. 4), which was opened in 1914. Application of this less convenient system of filling the lock chamber (currently still regarded as such) during construction of the latter very large double lock (length of chamber 330 m, effective width 45 m) was effected only after prior laboratory tests had proved it judicious to expect that the proposed design would be quite satisfactory. These tests, conducted by Dr. H. Krey in the Berlin-Charlottenburg Hydraulic Laboratory and described in the Zentralblatt der Bauverwaltung of June 1914, lead to the conclusion that the proposed system for the large locks at Brunsbüttelkoog would be quite satisfactory, provided the valves are operated slowly.

The locks of the Panama Canal were constructed simultaneously with the new German locks. The former involved very high lifts, approximately 10 m. Filling of their chambers through culverts with laterals was regarded as unsatisfactory because the rate of discharge from the laterals during the assumed filling period of 15 min would be so high that measures would be necessary to avoid excessive turbulence of the water in the lock chamber. Accordingly, it was decided to equip the laterals (eleven per culvert) with larger outlets, for which purpose the laterals were extended in the bottom of the lock chamber as transverse or side culverts located normal to the lock axis. Discharge into the lock chamber was achieved by means of five small openings in the upper wall of each transverse culvert, uniformly distributed along the culvert. The bottom of the lock chamber thus became a kind of sieve (Figs. 5 and 6).

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*See Rapporten en Mededeelingen van den Rijkwaterstaat, No. 20.

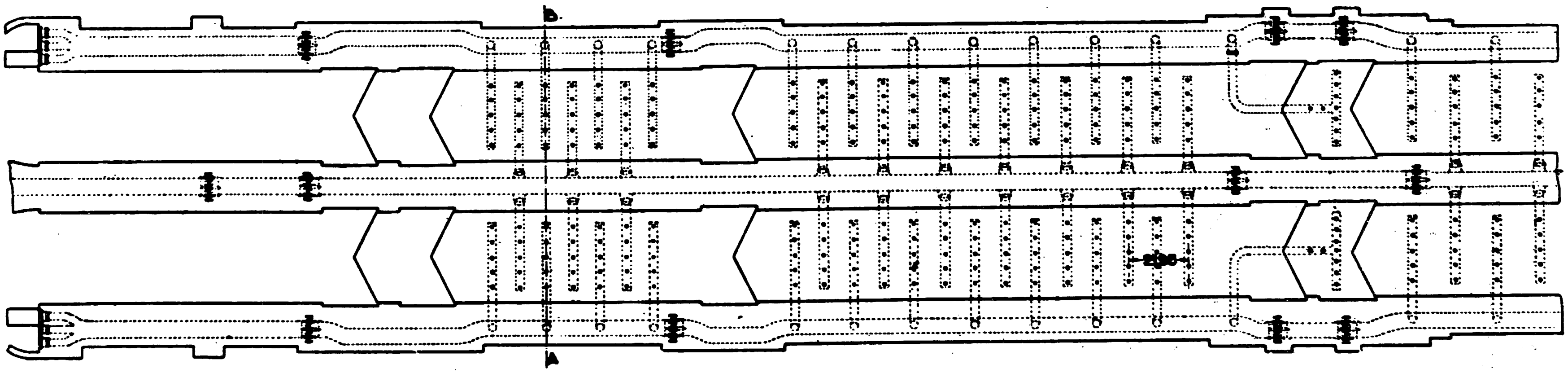

Fig.5 - Plan of the Double Lock of the Panama Canal

Section A-B

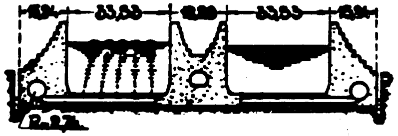

Fig.6 - Transverse Section of the Double Lock of the Panama Canal

The culvert system used in the Panama Canal has not fulfilled in actuality the anticipations. The following chapter deals with the errors involved in this system and with the corresponding explanations.

Another filling system, not yet applied in Europe, is encountered in the wide and 400-m long third lock of the St. Marys Falls Canal (Fig. 7).* The lock operates only in one direction. The lift is about 6 m. Filling of the chamber occurs through six culverts having inlets before the sill of the upper gates (Fig. 7). The culverts are located beneath the floor of the lock chamber, parallel to the chamber walls; four culverts extend nearly to the lower lockhead, while the outermost two culverts extend to the middle of the chamber (the latter arrangement is reasonable because it reduces costs and because the function of the outer culverts, with respect to water distribution, is not so important, since the valves of these culverts are opened somewhat later, so that the head is already reduced then). The discharge from the culverts occurs through short, vertical laterals spaced at decreasing intervals as they approach the lower end of the lock. Moreover, the culverts are interconnected by means of several large laterals, normal to the lock axis, in order to provide better water distribution in the culverts, even when not all the valves are open.

The emptying system consists of six short culverts without laterals, located parallel to the walls of the lock chamber and only in the floor of the lower lockhead.

Peculiarities arise also in this lock; they will be discussed in the following chapter.

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*Described by Sabin in Professional Memoirs, No. 44 of March-April, 1917.

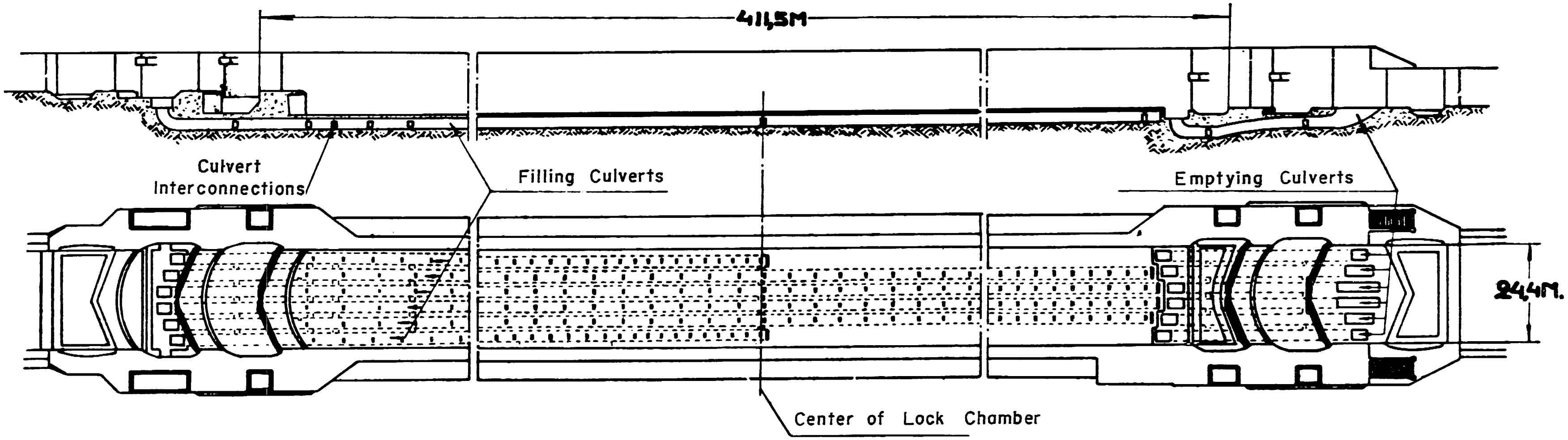

Fig. 7 – Plan and Longitudinal Section of the Third Lock of St. Marys Falls Canal

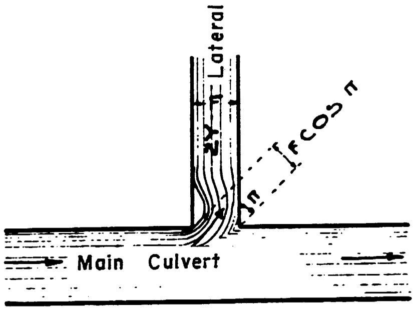

Fig. 8 – Diagram of the Inflow from the Main Culvert into the Lateral

# CHAPTER I

## BRIEF REVIEW OF LITERATURE ON FILLING AND EMPTYING OF LOCK CHAMBERS

It can be concluded from the introduction that the endeavor to find another filling system for the new lock at IJmuiden is based on economic considerations. The study which this necessitated involved collecting the data from the technical literature, which shed a new light on the aspect of filling the chamber and are successively discussed here.

Already in 1893-1894, model tests had established that the distribution of the water flowing into the lock chamber cannot be regarded as ideal when the system of culverts with laterals is used. These tests were conducted by Lieckfeld and Bergius and are described (among others) by Hubert Engels in the Handbuch des Wasserbaues. The experimenters arrive at the conclusion that, in order to avoid longitudinal flows during filling of the lock chamber, the laterals should not be uniformly distributed over the length of the chamber. According to them, the spacing of the laterals may increase nearer the lower lockhead. They give no explanation, so that it is impossible on this basis to conceive of far-reaching changes in the installation of culvert systems for locks in general. Moreover, the need for nonuniform spacing of the laterals, as specified by these writers, vanishes when the lock operates in both directions.

Another important publication is the article by Whitehead, "Hydraulics of the Panama Canal" in the Transactions of the American Engineering Congress (1915). Figures 5 and 6 show that both lock chambers of the double lock of the Panama Canal have a common culvert in the middle wall, so that when this culvert is used for one lock, the transverse culverts which are directed towards the idle lock chamber may be closed. Initially this culvert was intended as a reserve culvert.

After completion of the Panama locks, Whitehead conducted filling experiments at a lift of 9.76 m, during which the reserve culvert was not used. He examined the eddies formed on the surface (Fig. 6) and found that, after the valves of the main culvert were opened, initially only the first transverse culvert discharged water, the second began to discharge very soon afterwards, and then the others began to function successively after brief intervals. Soon after all the transverse culverts were functioning, the last transverse culvert discharged considerably more water than the first, so that the water level near the lower gates rose faster than near the upper gates.

A similar phenomenon occurred during discharge from the openings of the transverse culverts. The discharge from a given side culvert likewise was nonuniform; the opening located farther from the corresponding main culvert discharged more water.

Thus, filling of the chamber actually was quite nonuniform. Firstly, the discharge from all the openings did not begin simultaneously; secondly, the maximum inflow occurred at the side of the nonoperating culvert near the lower gates; and, finally, the direction of flow from the transverse culverts installed in the bottom was not vertical but deviated from the vertical in the direction of the last discharge opening. The largest inflow occurred at the side of the nonoperating main culvert (Fig. 6).

The detrimental effect of these phenomena was that the ships did not remain stable in the lock chamber during lockage. This drawback was overcome by operating the reserve culvert every time. This occurred regularly ever since, but it made it impossible to use simultaneously the two locks located near each other.

This measure, however, eliminated only the effect of the nonuniform discharge of the openings of the side culverts. The fact remained that the most water flowed into the chamber near the lower gates; yet, according to Whitehead, it did not disturb the ships which passed through the locks prior to 1915.

Reverse phenomena were observed during emptying of the lock chamber, although to a much smaller extent.

As far as filling of the chamber is concerned, Whitehead explains the aforementioned phenomena as follows. The velocity of the water in the main culvert past each lateral decreases in the downstream direction. At constant culvert cross section $\omega$, the rate of discharge is $Q = \omega v$ ($\underline{v}$ is the velocity of the water). After the first lateral is discharging, the flow $Q'$ in the main culvert becomes smaller because of the water lost through the first lateral, so that $Q > Q' = v'\omega$ and, consequently, $v > v'$. This is repeated at each successive lateral, so that the flow velocity in the main culvert must gradually decrease in the downstream direction.

The direction of the water jet issuing from the main culvert into the lateral depends on the relative velocities in the main culvert and in the lateral. While the first component gradually becomes smaller towards the end of the culvert, Whitehead regards the second component as practically constant, dependent on the square root of the pressure head of the water in the main culvert. According to Whitehead, the result is that the direction of inflow nearer the lower end of the main culvert deviates ever less from the normal to the culvert axis.

The preceding flow direction greatly affects the discharge from the lateral, as shown in Fig. 8 in which $\pi$ is the angle between the inflow direction and the normal to the culvert axis. The water flows at first through a contracted section, F cos $\pi$, and then continues along the entire cross section F. Thus, an impact loss occurs in the lateral, increasing with increasing $\pi$. The result is that the discharge from the laterals increases as they are located nearer downstream.

With regard to the similar phenomenon which arises during discharge from the openings of the laterals, it should be noted that the discharge from these openings decreases not because of impact phenomena but due to reduction in the effective cross section of the openings (F cos $\pi$, Fig. 8). No impact phenomena occur because very short branches (openings) are involved; therefore, after flowing through the contracted section, the water no longer has to follow the entire cross section of the lateral, as was the case in the transverse culverts. In the case under consideration, the water entered the chamber in an oblique direction, as shown schematically in Fig. 6.

In order to elucidate these analyses, Whitehead included several calculations in his article. These calculations are based on the following assumptions: definite magnitudes of the pressure head for the discharge of the main culvert after the last branching* and for the discharge of this last transverse culvert; with these data he computed the discharge and pressure head of the water in the main culvert before this transverse culvert. He carries out this computation for each preceding transverse culvert and finally establishes the fact that the discharge of the first transverse culvert is

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*Water still flows past the last transverse culvert towards the space between the set of gates, so that there the velocity of the water in the main culvert is not zero.

actually minimal and can be even zero. In a similar manner, he demonstrates that the discharges from the various openings of the laterals actually are not equal.

The culverts of the locks of the Oder Canal system between Cosel and the Neisse Estuary are arranged in approximately the same way (Mohr, Zeitschrift für Bauwesen, 1896). The transverse floor culverts are open manifolds which widen in the downstream direction (hence, in the direction of the opposite wall). According to Mohr, it would have been better if the slots narrowed in this direction (discussed later); this conclusion is in agreement with that which can be derived from Whitehead's observations.

The fourth publication cited here is the article by Sabin, "Filling and Emptying the Third Lock at St. Marys Falls Canal, Michigan," published in the Professional Memoirs of March-April 1917. Also Sabin established that during filling, the laterals begin to function successively. A photograph, taken 3 min after opening of the valves, shows distinctly the boundary between turbulent and calm water. This allows the conclusion that not all laterals are functioning yet (those at the lower end not yet) 3 min after opening of the valves. Sabin found that a difference in level of about 0.60 m occurred between the upper end and lower end of the lock chamber at the beginning of filling under the condition of rapid opening of the valve. In brief explanation he states that the motion of the water in the culvert must first become established; once this motion occurs, the large difference in level is no longer present. Nevertheless, his graphs show that a difference in level, periodically positive or negative, occurs between the upper end and lower end of the lock near completion of the filling.

# CHAPTER II

# THE ADVANTAGE OF CONDUCTING EXPERIMENTS

It is evident from the publications cited in the preceding chapter that the various authors do not agree in all respects. Thus, Lieckfeld and Bergius recommend increasing the spacing between the laterals towards the lower end of the lock, while the opposite is applied in the third lock of St. Marys Falls Canal and the author of the corresponding article is dissatisfied with the manner of lateral distribution along the lock chamber. Considering the experiences obtained at the Panama Canal, it is preferable to accept the recommendation of Lieckfeld and Bergius because there the last laterals yielded the most water.

Moreover, our own observations conflict with some of the published ones. Namely, it was evident during filling of the lock chamber of the third lock at Hansweert that the level of the water in the valve shaft of the closed lower valve rose very slowly at a lift of about 2 m; this indicates that the pressure of the upstream water has not been transmitted towards the end of the culvert. The first laterals discharged perceptibly more water than the last laterals, which conflicts with Whitehead's reports, explanations, or calculations.

Consequently, on the basis of the publications and the observation at Hansweert, it was impossible to determine the point at which the most water entered the chamber during filling of a lock. It was supposed that it was not impossible to consider omitting a portion of the laterals. If this could be assumed with complete sureness, then it would constitute a saving in the cost of lock construction without impairing the usefulness of the lock.

Very thick lock-chamber walls are required for the new lock so as to accommodate the culverts. The elevation of the deck slab is established at 5 m above normal stage, the floor of the lock chamber at 15.50 m below normal stage, so that the height of the walls would be at least 20.50 m. This height is inadequate yet because of the nature of the soil at that place; a layer of clay about 1 m thick, underlain by a thin peat layer, occurs at 16 to 19 m below normal stage. A wall above these layers, on steel foundations, would not provide any complete safety against sliding, so that the walls would have to be based at 19.50 m below normal stage in order to provide such safety. For this reason, it is also essential to base the lock-chamber walls in an inexpensive way. In the first place, a solution was suggested in the form of that used at Brunsbüttelkoog, namely, by considering installation of the culverts only in the lockheads and thus none in the walls (Fig. 4).

However, the question arose whether this solution could likewise be applied to a lock having the dimensions of the proposed IJmuiden lock (length of lock chamber 400 m and width 50 m) without disturbing the stability of the ships in the chamber during lockage. Therefore, several other solutions were simultaneously taken under consideration, whereby the system of culverts with laterals was not entirely abandoned and it was feasible yet to construct the lock-chamber walls in an inexpensive way. Regarding the fact that the discharge of the laterals seems to be nonuniform to a great extent, it can be supposed that the laterals may be locally concentrated in the culvert, without becoming detrimental to the calm position of the ships. In this way, it is possible to derive an advantage in that the largest part of the lock-chamber walls could be based high and only the parts in which the laterals are located would have to be deep.

Since it is unknown where the most water enters into the chamber, the characteristics of filling the chamber not having been established yet, the most suitable location for the concentrations of the laterals cannot be determined from calculations. A structure like the new lock at IJmuiden is also too costly to deviate from the basic suppositions of old practices, whether or not they are fully satisfactory, while also the American practices necessitate caution. It was decided, therefore, to conduct tests on the existing lock at IJmuiden and to establish experimentally the exact function of the various laterals.

## CHAPTER III

## THE EXPERIMENTS ON THE EXISTING LARGE LOCK AT IJMUIDEN

Several simple devices were constructed for the purpose of determining the discharge of the various laterals. The principle of these devices involves determining the flow velocity from the deflection of an object (a wooden bob) suspended from a rod, which is displaced from its equilibrium position by the flow of water (Fig. 9).

A similar installation, revolving about a horizontal axis parallel to the lock-chamber wall, was mounted before the openings of several laterals of the existing large lock at IJmuiden. The deflection was registered on a graduated arc by means of a simple transmission.

The thrust on the small cylinder, which is proportional to the square of the velocity of the water issuing from the lateral (Bernoulli) is balanced by the force (gravity) which will return the pendulum to its original position. The larger the thrust, the greater the deflection of the pendulum. The deflections are approximately proportional to the square of the velocity of the issuing water (impact).

Six instruments were prepared, so that it was possible to test simultaneously six of the eleven laterals of a culvert. Either the odd-numbered or the even-numbered laterals were selected. The first lateral was tested concurrently with the even-numbered laterals in order to obtain a unit for comparison.

An observer was placed near each device, and the reading of the indicator was recorded at intervals of 5 sec. Whistles were used to signal to the observers the beginning of opening of the culvert valve as well as the end of the filling operation.

The devices proved to be effective only during filling tests. During emptying of the chamber, the wooden bobs were drawn towards the wall; the bob ceased to be drawn when the distance between bob and wall was increased. Making the bob heavier produced no improvement.

During the tests the indicators appeared to move continuously to and fro. Therefore, in order to plot the observations, the average of four readings was taken each time, the averages were plotted as ordinates of a coordinate system in which time was the abscissa, and the ends of these ordinates

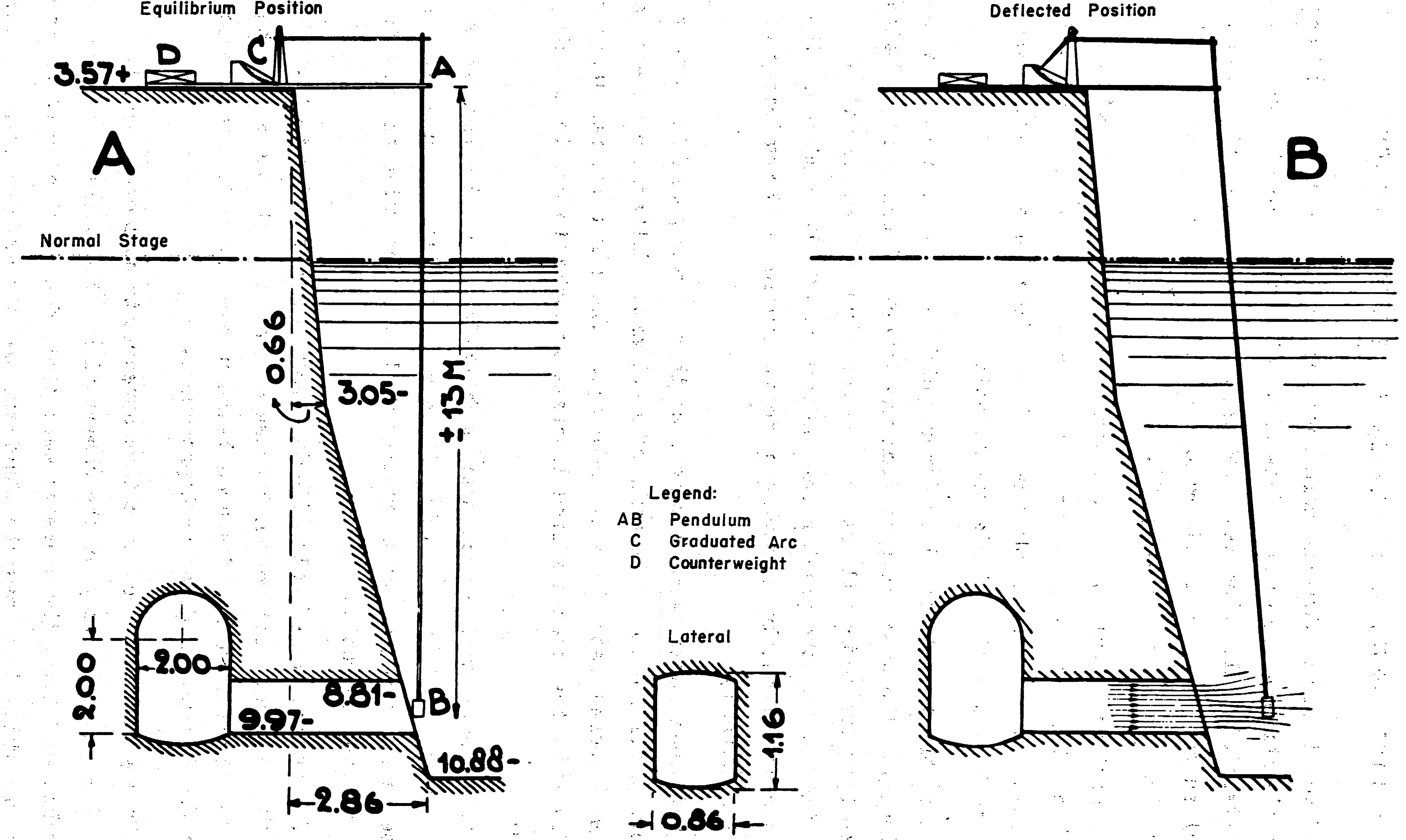

Fig.9 – Diagram of the Apparatus Used for Tests on the Existing Large Lock at IJmuiden
Location of laterals is shown in Fig.3.

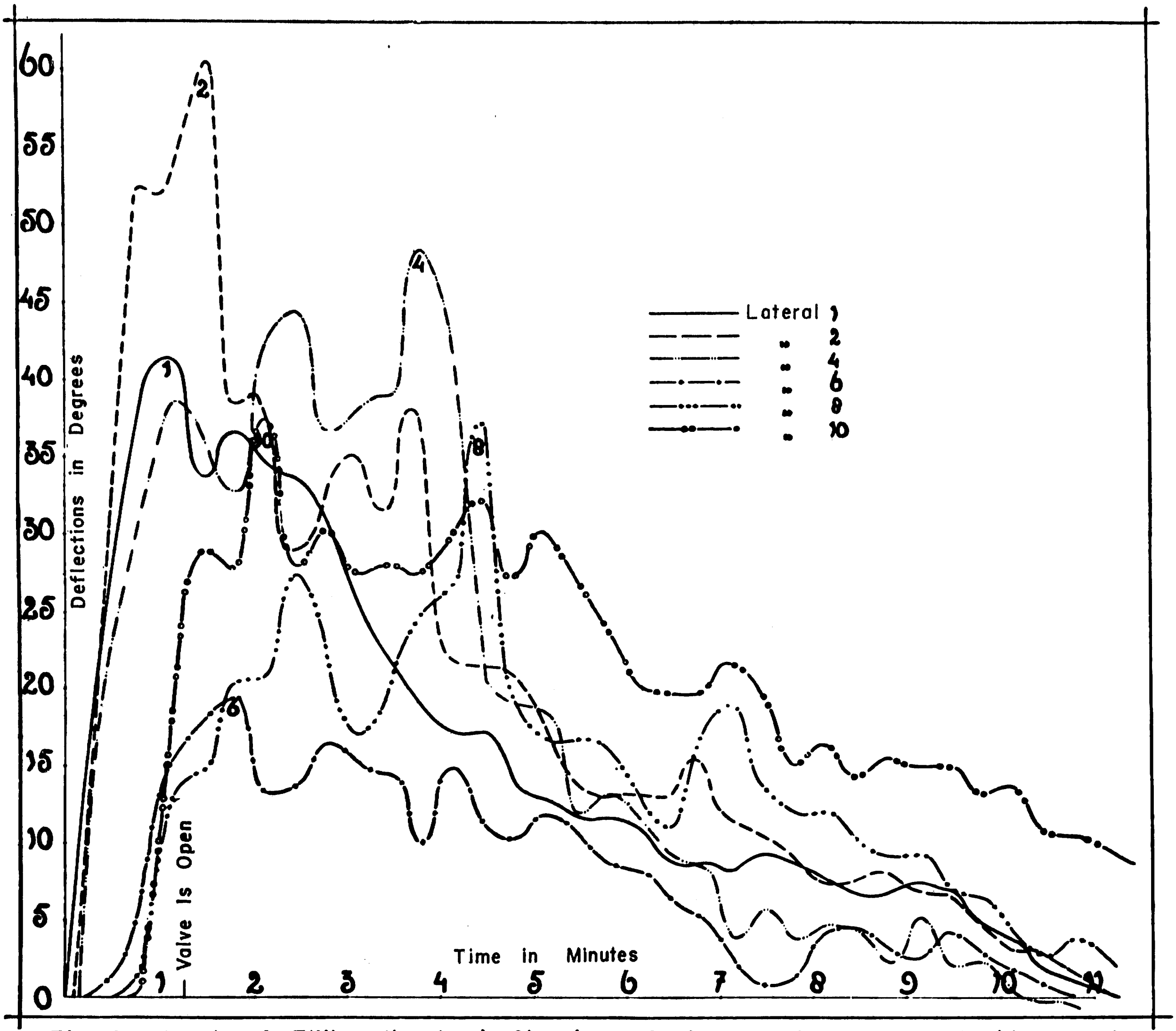

Fig.10 – Graph of Filling the Lock Chamber of the Existing Large IJmuiden Lock at a Head of 1.45 Meters

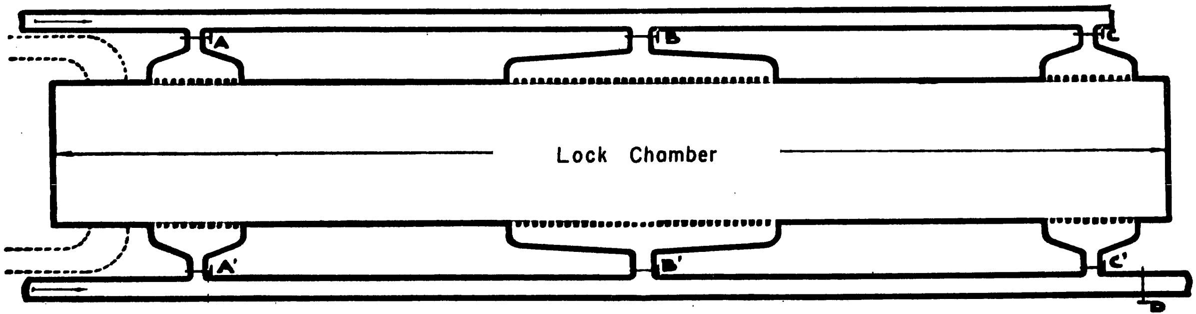

Fig.11 – Diagram of Model Arrangement for the Preliminary Tests

were connected by smooth curves. Figure 10 shows a sample of a plotted graph. The abscissa represents time in seconds, and the ordinate represents the deflection of the indicators in degrees (proportional to the square of the velocity). This will be further discussed in Part II.

Immediately after the twenty graphs were plotted, each consisting of six curves, the following preliminary conclusions became evident:

(1) The laterals begin to function successively in a downstream sequence.

(2) The middle laterals discharge the least water, considering the entire period of the filling operation.

(3) The first laterals discharge the most water, considering the entire period of the filling operation.

(4) The last laterals discharge more water than the first, considering the entire period of the filling operation, when the head is higher.

No opinion could be formed at that time regarding the validity of these conclusions and the exact cause of the established phenomena; the theory (Part II) was first gradually developed during the subsequent model tests. Had the theory been developed sooner, then, for example, greater value would have been attributed to conclusion (1) than to conclusion (2). However, the latter conclusion, later regarded as erroneous, had a considerable effect on the arrangement of the model tests which were already in the process of preparation during the experiments at IJmuiden and were afterwards carried out at the hydraulic laboratory of Berlin-Charlottenburg on behalf of the lock structure at IJmuiden.

# CHAPTER IV

## BRIEF THEORETICAL ANALYSIS OF FILLING OF LOCK CHAMBERS*

In the Zentralblatt der Bauverwaltung of June 1914, Dr. H. Krey presented an analysis of the forces acting on ships in the direction of the lock axis (longitudinal forces) during filling of the lock chamber. They occurred due to longitudinal propagation of the inflowing water. The conclusion derived from his analysis was that the magnitude of the longitudinal forces is proportional to the rate of increase in inflow, so that it was recommended to open slowly the valves admitting the water into the chamber. The largest longitudinal force occurs when the aforementioned increase is maximal, thus, in normal cases, at the beginning of filling.

The importance of the inertia of the water in the culvert gradually became recognized during the IJmuiden experiments; the development of motion of the water in a long culvert proceeds very gradually. In the case of long culverts, therefore, slow opening of the valves, such as recommended by Dr. Krey in 1914, is less necessary.

The inertia of the water in a culvert governs the operation of a culvert with laterals. This causes the successive beginning of discharge from the laterals [preliminary conclusion (1) from the experiments conducted on the existing large lock at IJmuiden]. The following analysis relates to a culvert with normal, thus short laterals, whereby the inertia of the water in the laterals may be neglected.

If this culvert is regarded as divided into sections, the part between the inlet and the first lateral being denoted as the first culvert section, and the part between the first and second laterals being denoted as the second culvert section, and so on, then it can be stated that, after the valve or another controlling device located in the first culvert section has been opened, the water in this section will be set into motion by the pressure difference between the ends of this section. The water in the second section will be set into motion when a pressure difference is formed between the ends of the section. The pressure at the inlets of the laterals is generally equal to the sum of the head losses of the water in the lateral and, therefore, proportional to the square of its velocity. As soon as water flows from the

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*A more detailed discussion is presented in Part II.

first lateral due to development of motion of the water in the first culvert section, a pressure rise occurs in the lateral, with the result that the water in the second culvert section is set into motion. Because of the inertia of the water in the first culvert section, the velocity of the water in the first lateral increases slowly in the case of rapid opening of the valve, with the result that the velocity of the water in the next culvert section increases slowly. Moreover, the mass of the water in the second culvert section further retards the increase. This reasoning indicates that the laterals begin to function appreciably after each other (theoretically, of course, all the laterals will begin discharging simultaneously, yet except for the first lateral no other lateral discharges initially any appreciable amount of water). In the case of the experiments conducted on the existing large lock at IJmuiden, a phase difference of about 1 min was observed between the beginning of discharge from the first and last laterals.

With increasingly smaller cross section of the lateral, in comparison with the cross section of the culvert, the pressure is transmitted more rapidly through the culvert; the water in the culvert section then requires a lower velocity in order to raise the pressure head to a maximum at the inlet of the lateral.

In the case of long laterals, whereby the inertia of the water occurring in them can no longer be neglected, the head loss of the water in the lateral will be increased by a term expressing the inertia (inertia term),* so that in a culvert with such laterals the pressure will likewise be transmitted rapidly.

The locks of the Panama Canal have long laterals (Fig. 6), so that the pressure will be rapidly transmitted through the culvert (page 11). The third lock of the St. Marys Falls Canal (page 12) has many short laterals, so that the pressure will be slowly transmitted through the culvert.

The importance of the phenomenon discussed above was underestimated at first. It will become obvious by taking cognizance of Chapter V and Part II.

Besides the longitudinal forces, additional forces, directed normal to the lock axis, act on the ship during filling. These forces are designated as transverse forces. They arise due to the impact of the inflowing water

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*See page 69.

against the ship or indirectly against the water in the chamber, the latter occurring, for example, when the water can flow beneath the ship. Their magnitude depends on the rate of inflow and, in addition, on the velocity of inflow (in other words, on the momentum of the inflowing water). The largest transverse force occurs when the product of discharge and velocity of the inflowing water is maximal, thus generally in the case of culverts in which the water has a certain inertia, or at slow valve opening in the case of short culverts or openings made in the gates, not at the beginning of filling of the chamber.

If the ship lies in the direct effective path of the water jets issuing from the culverts, then the transverse forces are designated as primary, while if it lies outside this path, then the transverse forces are termed secondary.* The latter are smaller than the former because the water has lost a portion of its energy in the section of the lock chamber directly in front of the culvert outlets. Therefore, the primary transverse forces are generally more important for the ship than the secondary.

The force exerted on the ships in the chamber at a given instant is the resultant of the longitudinal and transverse forces at that instant. Thus, the total discharge of the laterals of a culvert, taken over the entire filling period [preliminary conclusion (2) from the experiments conducted on the existing lock at IJmuiden, page 18], is itself of no significance with respect to the calm position of the ship in the chamber during the filling operation. Of greater importance is the discharge at a given instant.

In general, only the filling process is analyzed and not the emptying process. The reason is that primary transverse forces are involved during filling and not during emptying, while the longitudinal forces acting in a given lock are smaller during emptying than during filling (see Part II, Chapter IV-D); hence, it can be stated that a culvert system is definitely reliable with regard to the emptying operation if it is adequate for the filling operation.

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*It should be noted that the great importance of the transverse forces was first recognized during the Berlin tests.

# CHAPTER V

# THE LABORATORY EXPERIMENTS AT BERLIN

## A. Objective of the Experiments

The experiments conducted on the existing large lock at IJmuiden quickly led to the formulation of the preliminary conclusions presented in Chapter III, from which it seems possible to obtain some insight into the operation of a culvert with laterals. Since the discharge of the laterals appeared to be nonuniform, it became possible to assume that it was not necessary to install laterals along the entire length of the chamber and that laterals in the middle of the lock seemed to be superfluous.

In connection with the preliminary conclusions, some advance designs of the lock chamber were made, whereby the laterals did not extend along the entire length of the chamber but were concentrated locally. Since such concentrations of the laterals have never been applied, so that it was not known whether this arrangement would actually affect the calm position of the ships in the chamber during lockage, it was deemed desirable first to investigate by means of tests in a hydraulic laboratory whether these concentrations are really permissible.

In addition, the laboratory tests were to ascertain whether the culvert system used at Brunsbüttelkoog (merely culverts in the lockheads) would be effective for the new lock at IJmuiden and to enable one to decide which of the preliminary designs with respect to the culvert system of the lock, should be selected for ultimate application.

Since no hydraulic laboratory was available in the Netherlands, the tests had to be conducted abroad. In September 1921, when it was decided to conduct the model tests, it seemed that the most suitable laboratory was the previously mentioned hydraulic laboratory at Berlin-Charlottenburg; its director, Dr. Krey, occupied a prominent position in the experimental field due to his tests on filling the Brunsbüttelkoog and other locks and was entrusted with the problem. His chief assistant, Dr. R. Winkel, and his chief designer, Zschiesche, assisted Dr. Krey in the experiments; they all deserve a word of thanks and tribute for their contribution to the success of the experiments.

## B. The Cases Investigated

It was decided to investigate the following cases:

(1) Concentration of the laterals in the middle of the lock chamber (concisely designated in the following as laterals in the middle).

(2) Concentration of the laterals near both lockheads in such a way that the culvert sections in which the laterals occur (lateral manifolds) are connected by means of a conduit which passes through each lock-chamber wall (concisely designated in the following as laterals near the lockheads, connected by a conduit).

(3) Concentration of the laterals near the lockheads, but without a connecting conduit (designated in the following as laterals near the upper lockhead).*

(4) No laterals, but merely culverts in the lockheads (concisely designated as loop culverts).

## C. Preliminary Designs of the Lock

Preliminary designs were made in conformity with the cases to be investigated and will be briefly described in the following.

After its completion, the new lock at IJmuiden should be able to operate at all occurring lifts. Accordingly, lockage of ships should be possible at upper pool levels varying between ± 3.50 m above normal stage and 2.50 m below normal stage, and at a canal water level of about 0.50 m below normal stage. The maximum lift is thus about 4 m. Nevertheless, such high lifts may occur extremely seldom, so that even a lift of 1.50 m constitutes an exception. Determination of the filling time is based on the premise that it may be neither smaller nor larger than that of the existing large lock. Namely, practice has taught that the filling period of the existing large lock never had any detrimental effect on the time necessary for lockage.

### 1. Design with Laterals in the Middle

The results of the tests conducted on the existing large lock at IJmuiden showed [preliminary conclusion (2)] that the middle laterals discharged the least water; accordingly, during filling of the chamber a hydraulic

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*Filling from the sea occurred through the laterals near the upper lockhead; filling from the canal occurred through the laterals near the lower lockhead.

gradient will occur in the chamber in the direction from the two lockheads towards the middle. If in this case the discharge from the middle laterals is negligible, a reverse gradient of fairly the same magnitude occurs in the lock when the water is supplied exclusively in the middle of the chamber. On this basis it may be supposed that filling and emptying by means of laterals in the middle would be not much more unfavorable for the calm position of the ships in the chamber than filling and emptying by means of a culvert with laterals.

The design of the lock-chamber walls was conceived as follows. As appears from the experiences obtained during construction of the existing large lock, a foundation pit with the bottom at 7.50 m below normal stage stays sufficiently dry with the aid of an open drain. Therefore, the walls should be erected from the level of 7.50 m below normal stage. The section in which laterals do not occur should be based on piles, while the center section containing the laterals can be based in another way if necessary.

The culverts, located at high elevation, can be connected in the middle of the chamber to the manifold, located at lower elevation and containing the laterals, by means of a cylinder valve.

### 2. Design with Laterals near Both Lockheads Connected by a Conduit

In accordance with preliminary conclusion (2) resulting from the tests conducted on the existing large lock at IJmuiden, this design involves merely a simultaneous supply at upstream and downstream ends of the chamber. The principle of this design is virtually the same as that of a culvert with laterals in the middle and is based on the fact that the middle laterals of a culvert with laterals discharge the least water (therefore, the middle laterals are omitted). During filling from the sea, according to the supposition, approximately half the water would pass through the upper lockhead into the chamber, while the other half passes towards the lower lockhead. Accordingly, the connecting conduit is assigned a cross section which is only slightly larger than that of the culvert in the lockheads. The manifold for the laterals may be smaller than in design 1 and may constitute the lower parts of the lockheads.

The culvert will be operated by means of plane valves.

### 3. Design with Laterals near Both Lockheads, Without a Connecting Conduit

In this system the filling from and emptying into the sea occurs through the upper lockhead, while the filling from and emptying into the canal occurs through the lower lockhead. In principle this system is similar to the arrangement of the culverts in the large locks at Brunsbüttelkoog. The difference is that in this system the water arrives through numerous small openings and, therefore, a portion of its dynamic force is lost prior to its entry into the chamber. At the same time the culvert outlet is installed very low.

The great advantage that can be derived from the use of this system is that the lock-chamber walls need contain no culverts, so that the construction of these walls is entirely unaffected by this aspect.

### 4. Design with Loop Culverts in the Lockheads

With respect to the culvert system, this design fully conforms in principle with that of the large locks at Brunsbüttelkoog. Use of this system involves the largest economy possible, since it is not necessary to install either culverts in the lock-chamber walls or lateral manifolds near the lockheads.

## D. Experimental Arrangement

### 1. Introduction

Model tests conducted in a hydraulic laboratory are of practical value only if the results are not regarded as accidental. The results must be analyzed and checked theoretically and practically. The theoretical analysis is based on calculations in accordance with hydraulic and hydrodynamic formulas, while practical verification, in contrast, is based on observations of existing models.

The results of laboratory experiments need not precisely agree with actuality, since in the case of actual hydraulic structures secondary effects always occur which are relatively difficult to simulate in the model.

The great benefit of laboratory tests is that they facilitate determining the laws relating to the occurrence of specific phenomena. When these laws are found, the theoretical analysis or practical verification should confirm their existence. Once convinced that the laws obtained are actually correct, it is possible to find the means to assist or counteract the occurrence of the specific phenomena. Finally, if the methods which were experimentally verified in the laboratory and found correct seem to be suitable for use in the construction, without involving excessive cost of installation or maintenance, then the laboratory tests have yielded a practical result.

## 2. Method of Investigation

Since the number of systems to be investigated is large, it would actually be necessary to prepare many lock models. This would be very costly and, moreover, would take up much time and space. Therefore, in accordance with Dr. Krey's suggestion, it was decided to divide the tests into: (1) preliminary investigations, and (2) final investigations.

The preliminary investigations would involve principally the relative testing of the various individual systems, so that precise simulation of the designs would not be necessary. Therefore, all the systems to be investigated were built into one model. After the preliminary investigations have resulted in a principal choice of the mode of filling and emptying the chamber, the lock model can be altered to simulate the corresponding design as accurately as possible.

An advantage of the consequent system of investigation is that there is ample time to prepare the final culvert design, so that the preliminary designs can be modified gradually when the results obtained from and during the preliminary investigations indicate that such modification is desirable.

# CHAPTER VI
# PRELIMINARY STUDIES

## A. The Preliminary Experiments at Berlin

### 1. Scale

The first question that arises involves choosing the scale for the lock model. Prior to answering this question, it is advisable, for the sake of completeness, to present briefly the general aspects of the scale in model tests.*

It is characteristic that to a given length scale there correspond a definite force scale, volume scale, etc. If the scale of length, width, or height of the model is a:1, then

| | |
|---|---|
| the area scale is . . . . . . . . . . . . . . . . . . | $a^2:1$ |
| the volume scale is . . . . . . . . . . . . . . . . . | $a^3:1$ |
| the head (height) scale is . . . . . . . . . . . | $a:1$ |
| the acceleration scale is . . . . . . . . . . . . . .<br>(the acceleration of gravity remains constant) | $1:1$ |
| the flow velocity ( $\sqrt{2gh}$) scale is . . . . . . . | $\sqrt{a}:1$ |
| the time (velocity/acceleration) scale is . . . . | $\sqrt{a}:1$ |
| the discharge (rate of inflow into the chamber; cross-sectional area times velocity) scale is . | $a^2\sqrt{a}:1$ |
| the force (dimension $m\ell t^{-2}$) scale is . . . . . . | $a^3:1$ |

Except for availability of space, the choice of scale for the model was governed by the presence in the laboratory of the model of the large lock at Brunsbüttelkoog. This model was 1/36 of actual size. Since the prototype locks at Brunsbüttelkoog are 45 m wide, the model was 1.25 m wide; thus, as far as width is concerned, this model could be used for the proposed lock at IJmuiden if the scale were altered to 1/40:1 (the width of the IJmuiden lock is 50 m). The length of the model could readily be adjusted (to 10 m), and the depth seemed adequate (the level of normal stage must amount to 15.00/40 = 0.375 m above sill elevation).

The scales of the various magnitudes measured in the model are readily determined in accordance with the preceding. Thus, the force scale is 1/64,000 and the time scale is $1/\sqrt{40}$ (so that a filling time of 10 min in the prototype corresponds to about 1.5 min in the model).

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*See Die Wasserbaulaboratorien Europas by G. de Thierry and C. Matschoss, 1926, pp. 48-.

Multiplying a magnitude measured in the model by its scale yields the corresponding value for the prototype. Only the coefficient of skin friction of the water along the culvert walls cannot be simulated to scale in the model, so that the magnitudes depending on this friction (such as the filling time), multiplied by their scale, would not exactly agree with the corresponding values in the prototype.

## 2. Arrangement of the Model; Additional Test Systems

As stated previously, all of the systems to be investigated were combined in one model (Fig. 11). For this purpose, the manifolds for the laterals were installed in the sidewalls, in accord with the preliminary designs, and interconnected by a conduit (an iron pipe). A total of six manifolds were used, three in each wall. Any one of these manifolds could be put in operation by opening or closing the valves located in the branches connecting the manifolds to the main culvert. If it is desired to conduct a filling test by means of laterals in the middle, for example, then the valves A, A', C, and C' are closed.

Thus, it is likewise possible to put in operation all the laterals simultaneously, so that filling or emptying occurs through culverts having three large systems of laterals each (in each culvert, one near each lockhead and one in the middle). Also this mode of filling and emptying the chamber is tested because it furnishes an approximate picture of establishment of the water level in the chamber by means of culverts with laterals distributed along the entire chamber (the tests with this system are designated as filling or emptying through all laterals simultaneously).

The cross section of the pipe in the model is constant throughout and corresponds to the combined cross section of the two culverts which are installed in each wall. Therefore, the connecting conduit between the manifolds is too large in the case of testing system 2 (page 25); as will be seen later, this fact does not affect the validity of the tests in this case.

In addition, the sum of the areas of the two end manifolds in the model is equal to that of the center manifold (± 1.5 times the culvert cross section), so that the discharge opening is actually too small in the case of testing system 3 (page 26).

The loop culverts in the lockheads are shown as dashed lines in Fig. 11. They are located outside the piping system. In the model, they are made of zinc.

It was decided to test also the system of filling and emptying by means of openings in the gates, as it seemed to be very simple. To this end, openings were made in the upper gate, one set as low as possible and another as high as possible, so that filling and emptying could occur from the high as well as the low openings (designated in the following as filling and emptying through the uppermost or lowermost gate openings). The openings in the gates could be closed by means of planks in a nonadjustable manner.

Finally, it was decided to make a series of observations (purely with a scientific objective) on filling from the sea, exclusively through the laterals near the lower lockhead (the valves A, A', B, B' closed, and C and C' open, Fig. 11).

Little importance was attached to the layout of the culverts for the preliminary investigations. For the sake of convenience, it was arranged symmetrically, although this is not the case in the preliminary designs because of the presence of the gate recesses at one side of the lock.

## 3. Experimental Lifts

In connection with the maximum lift that may occur at IJmuiden (page 24) and with the normal high lift, the tests were conducted at a lift of 4 m (upper pool 3.50 m above normal stage, canal surface 0.50 m below normal stage) and at a lift of 1.40 m (upper pool 1 m above normal stage, canal surface 0.40 m below normal stage).

In addition, tests were made at several other lifts in the case of the system chosen for the proposed lock, so that the forces occurring during an adequate number of lifts could be observed, making it possible to determine by interpolation the forces occurring at an arbitrary lift.

## 4. Difference in Specific Weights of Sea Water and Canal Water

The difference in the specific weights of sea water and canal water (about 1 per cent) was not simulated because such simulation would complicate the tests and it does not have any principal effect on the problem.

## 5. Types of Ships Tested

The ship models are hollow shapes made of paraffin. After the pouring, their true shapes were simulated. The desired draft was achieved by means of ballast (sand, shot, weights).

The proposed lock at IJmuiden would be used by ships of various sizes. Since it was deemed quite likely that large ships might retain a stable position in the chamber during lockage while small ships would be subjected to lurching due to the surface motion of the water, and since it seemed not improbable that ships with small draft might stay calm during lockage and ships with large draft would not because the latter ships would be affected by the deeper motion of the water, it was considered necessary to conduct tests with ship models of various sizes. This test series should reveal which filling systems may be disregarded as far as future application is concerned. Thus, it would not be necessary to make tests with other ships under condition of these systems.

The model selected to represent the largest ship (the model with which the entire test series was made) was one having a length and width approximately equal to that of the steamship Limburgia but with a larger draft. The prototype ship was 182.20 m long, 23.53 m wide, and had a draft of 13.00 m (these dimensions were reduced to 1/40 in the model). The displacement of this ship is 45,200 tons. At a draft of 10 m, a similar ship would have a capacity of ± 25,000 gross register tons. The abnormal draft is chosen in order to increase the submerged part of the ship so that a larger surface would be exposed to the deeper flow. Since the dimensions of length and width of this ship are in disagreement with the very large depth dimension, it is logical to presume that a similar ship, which is 285 m long, 33 m wide, and has a capacity of ± 75,000 register tons, would be less suitable for studying the various positions with respect to the gates because of the excessive length of this ship in comparison with that of the lock.

The following prototype ships were selected to represent the smaller ship types--the Riouw of the Netherlands Steam Navigation Company, 113.60 m long, 16.80 m wide, with a draft of 8.40 m, a capacity of 7526 register tons, and a displacement of 14,600 tons; the Astrea of the Royal Netherlands Steamship Company, 80 m long, 11.90 m wide, with a draft of 6.23 m, and a displacement of 4550 tons (the Astrea has a capacity of 1400 register tons; its normal displacement is ± 3200 tons).

## 6. Location of the Ships in the Lock Chamber

Since the design of the proposed lock at IJmuiden specified installation of floating buffers along the lock chamber walls, against which the ships would rest, the ships were always moored during the tests at a distance of 1.50 m from the lock-chamber walls; (1.50 m is the breadth of the floating fenders).

The ships are generally tested in the chamber at five points, namely, with the prow 5 m from the upper gates (0.125 m in the model), in the middle of the chamber, with the stern 3 m from the lower gate (0.075 m in the model), and at two intermediate points. In addition, the ship is moored in special cases with its prow 20 m from the upper gate (0.50 m in the model).

## 7. Filling and Emptying the Lock Chamber Through One Side and Both Sides

Since it was impossible to foretell whether filling through one side (for example, when it is necessary to repair the valves of the culverts on one side) in given cases has a more unfavorable effect on the calm position of the ship during the filling than filling through both sides, it was decided to test all cases also by means of filling through one side.

Most ships would not be located symmetrically in the chamber but would be moored to one wall (the wall from which direction the wind blows, so that the wind would drive the ship towards the lock axis when the ship is leaving the lock). In connection with this, the effect of lockage is controlled with the aid of the one as well as the other culvert.

## 8. The Upper Pool

The reservoir (the sea) from which the chamber is filled during filling operations (designated in the following as upper pool), must be maintained at a constant level during the tests because in the prototype this pool likewise remains at constant level. This occurs through continuous pumping of water into the reservoir. The level is artificially kept constant by means of an arrangement shown in Fig. 12. The water flows towards the reservoir in the direction indicated by the upward arrows. Constant level is assured by the float. If the level becomes too low, the outlet (shown in the figure) is closed by a beam; if it becomes too high, then the outlet is opened and the excess water can flow out (in the direction of the downward arrows).

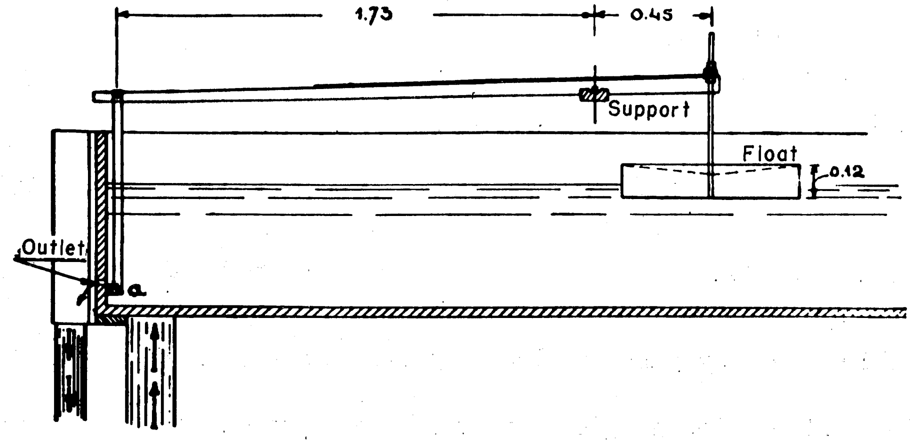


Fig.12 - Diagram of the Installation for Maintaining a Constant Upper Pool Level

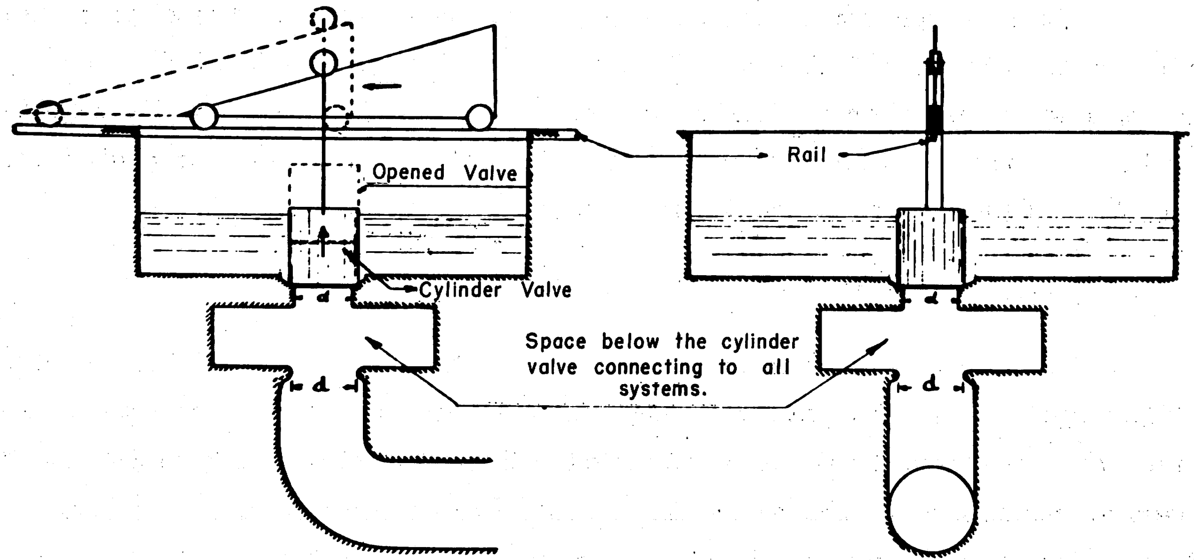


Fig.13 - Diagram of the Installation for Valve Operation

It is obvious that the level still fluctuates. A man operating the pump observes the fluctuations of the level on a gage and regulates the water supply in such a way that the fluctuations remain small.

## 9. Valves

The valves in the model are cylinder valves. The advantage of these relative to plane valves is that the inlet opening increases linearly during uniform motion of the cylinder valves, regardless of the shape of the culvert cross section, while in the case of plane valves this increase depends on the shape of the culvert cross section at the location of the valves.

Each culvert of the model has a cylinder valve. However, the valves are not connected directly to the culverts because the same valves must also be used for the loop culverts as well as for filling and emptying through the gates. Therefore, the valves are connected to a manifold serving all filling systems.

The two valves installed in the model can be operated simultaneously or separately so that either both culverts can be activated or each culvert separately (the culvert containing the valves A, B, and C will be designated in the following as the north culvert, and the other culvert will be designated as the south culvert or also the right culvert).

The valves can be operated at various uniform speeds. For this purpose an arrangement is used, shown schematically in Fig. 13. Raising or lowering the valve in a given time is achieved by rolling the triangle horizontally with a definite speed.

The diameter d of the control opening beneath the valve in the prototype is 6 m, being slightly larger than the actual culvert diameter (5.75 m). The valves are regarded as fully open when they are raised a distance of h = 0.8 d (that is, 4.80 m in the prototype), which is a practical laboratory result.

## 10. Emptying the Lock Chamber

Since the filling tests are more important than the emptying tests and, therefore, are made more frequently, it was essential after a filling operation to remove the admitted water as rapidly as possible in order to facilitate immediate processing of the next test. This was achieved by opening the valve D (Fig. 11). During the subsequent filling test, this water is again pumped into the upper pool.

## 11. Mooring the Ships in the Lock Chamber

The ships are elastically secured in the chamber in the same way as in the locks of the Panama Canal where each hawser is fastened to an electrical tow locomotive (Fig. 14). During the preliminary model tests, elastic fastening of the hawsers was achieved by tying their ends on the land side of the walls to hollow metal cylinders C (Fig. 15) which were freely suspended in wider cylinders W partially filled with water. Due to the forces acting on the ships during filling and emptying of the chamber, the ships would lurch to and fro and, consequently, the cylinders tied to the hawsers would move up and down in the water. Moreover, the water level in the cylinders would vary. In order to reduce the friction of the hawsers along their paths, the hawsers pass through pulleys.

The weight of the cylinder C must be so large that, whatever its position, it would not force out the water in the cylinder W. The mode of fastening the hawsers on the land side is clearly shown in Fig. 15.

The mode of fastening the hawsers to the ship requires some additional elucidation. In order to obtain the truest possible measurement of the forces, it is desirable that the hawsers do not move up and down with the ship during lockage. Therefore, they are fastened to a light metal frame (R, Fig. 15) which can move in a horizontal plane by being suspended from the ceiling of the laboratory. Holes are made in the front and rear of the frame, in which the foremast and aftmast of the ship can move up and down. To facilitate this motion, the masts pass through three rollers which can rotate in planes forming an angle of 120° with one another (r, Fig. 15). In this way, the vertical movements of the cylinders C are equal to the horizontal movements of the masts. The frame makes the same horizontal movements. Pencil points are attached to the frame near the masts, in a manner shown in Figs. 15 and 15a, which record the displacements of the masts on a sheet of paper that has a fixed place in the model. The hawser forces can be determined by measuring the magnitudes of the displacements.

This can be elucidated as follows. When the ship (Fig. 15) moves in the direction indicated by the arrow (longitudinal displacement), cylinders 1 and 2 become submerged deeper in the water and cylinders 3 and 4 emerge from the water precisely as much as the other cylinders have submerged. If the force causing the displacement is denoted by K, each of the cylinders 1 and 2

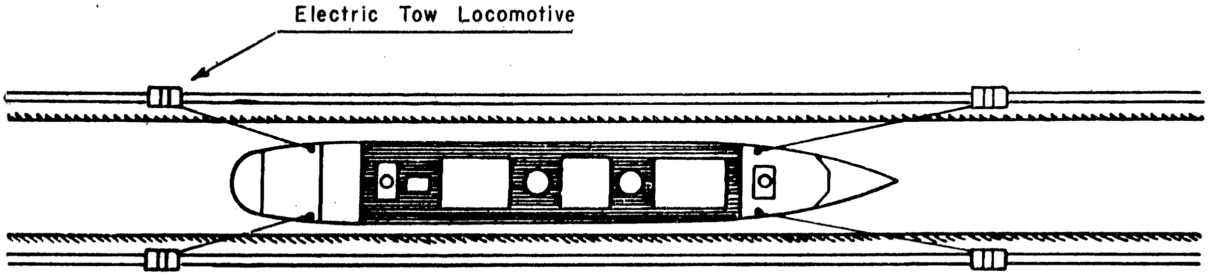


Fig.14 - Diagram Showing the System for Mooring Ships in the Panama Canal Locks

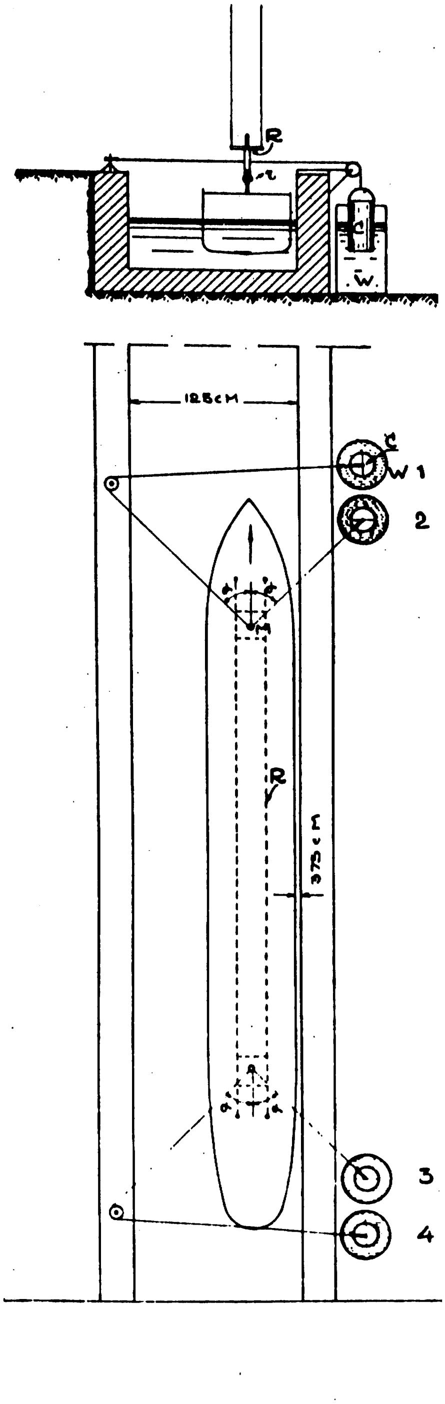


Fig.15 - Diagram of Elastic Mooring of Ships in the Lock Chamber

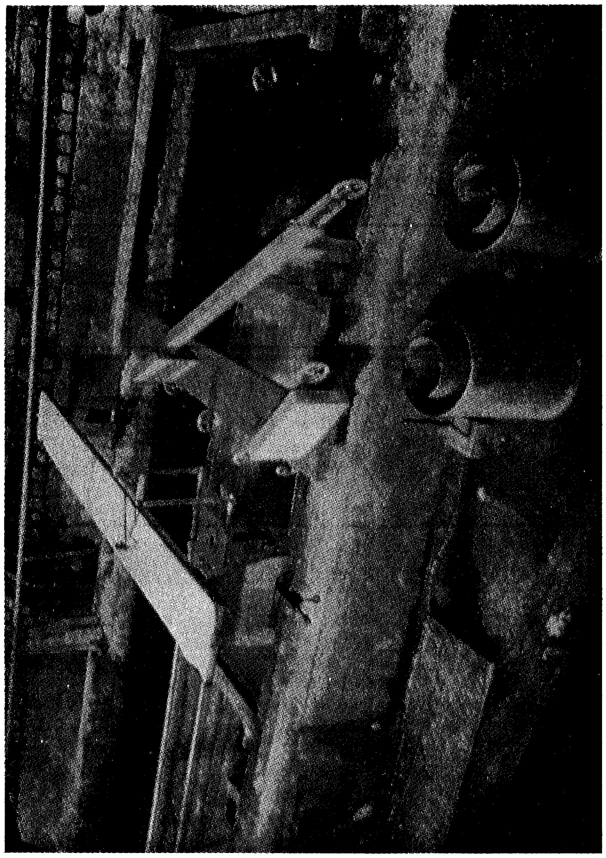


Fig.15a - Photograph of Elastic Mooring of Ships in the Lock Chamber becomes *a* grams lighter because of deeper submergence, each of the cylinders 3 and 4 becomes *a* grams heavier because of its additional emergence from the water; and if the angle $\alpha$ between the hawsers and the direction of the force remains constant during the motion (this may be assumed approximately if the hawsers are sufficiently long in comparison with the displacements), then the following balance equation can be written:

$$K - 2a \cos \alpha = 2a \cos \alpha \quad \text{or} \quad K = 4a \cos \alpha$$

Besides the specific weight of the liquid in the cylinder *W*, the magnitude of *a* depends on the diameters of the two cylinders. If the diameter of cylinder *C* is $d_1$ cm and that of cylinder *W* is $d_2$ cm, then, when *C* rises *h* cm, the water in *W* is lowered

$$h \frac{\pi d_1^2}{\pi d_2^2 - \pi d_1^2} = h \frac{d_1^2}{d_2^2 - d_1^2} \text{ cm}$$

so that cylinder *C* protrudes above the water $h \left[1 + (d_1^2/d_2^2 - d_1^2)\right]$ cm more than it rose initially. Thus, if the specific weight of the liquid in *W* is equal to unity, cylinder *C* became heavier by

$$a = h \frac{\pi d_1^2}{4} \left( 1 + \frac{d_1^2}{d_2^2 - d_1^2} \right) = h \frac{\pi d_1^2}{4} \; 1 + \frac{1}{\left( \frac{d_2}{d_1} \right)^2 - 1} \text{ grams}$$

If *a* is known, *K* can be computed. By means of calibration, *K* is determined for 1-cm displacement of the ship in the longitudinal direction (the frictional resistances of the pulleys and $\cos \alpha$ are accounted for at the same time by means of calibration, so that the longitudinal components of the hawser forces can be measured from the displacement records.

Also the transverse components of the hawser forces can be determined from direct measurements of the graphs drawn by the pencils. Namely, if the mast *M* (Fig. 15) undergoes a displacement which is exclusively normal to the arrow, due to the force acting on the ship, then the magnitude of this force is

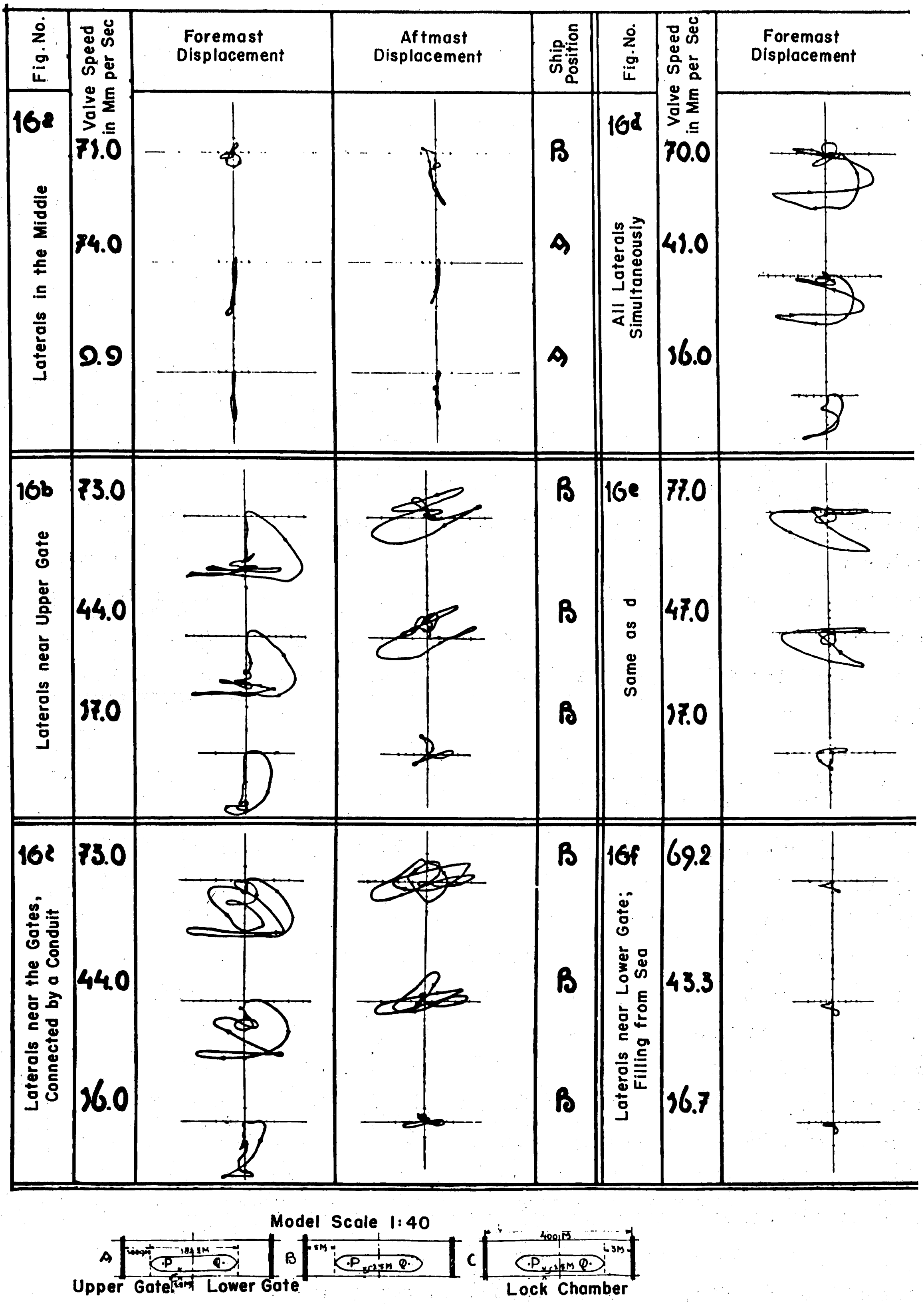
$$K = 2a \sin \alpha$$

Since the displacement graphs can be used directly for measuring the magnitudes of the hawser forces, these graphs will be designated in the following as force diagrams. All of these diagrams (Fig. 16) have a compact form because after completion of filling, the ship resumes precisely its original equilibrium position by means of the cylinders C (Fig. 15). The irregular form should not be attributed to accident because the pencils record the same diagrams when the test is repeated under similar conditions. In order to determine whether a diagram is actually correct, all the tests were repeated several times.

The compact diagrams do not indicate the instant during filling or emptying at which a given displacement has occurred. Therefore, the displacements are additionally transmitted to a recording drum which is actuated electrically and revolves at a definite speed. To avoid excessive complication of the tests, only the longitudinal displacements of the ship model are recorded on the revolving drum (Fig. 17, CD) during the preliminary investigations. In addition, the following are simultaneously recorded on the drum: the time distribution (AB), the level of the upper pool during the filling tests (EF), the motion of the valve (GH), and the change in the water level of the chamber (JK).

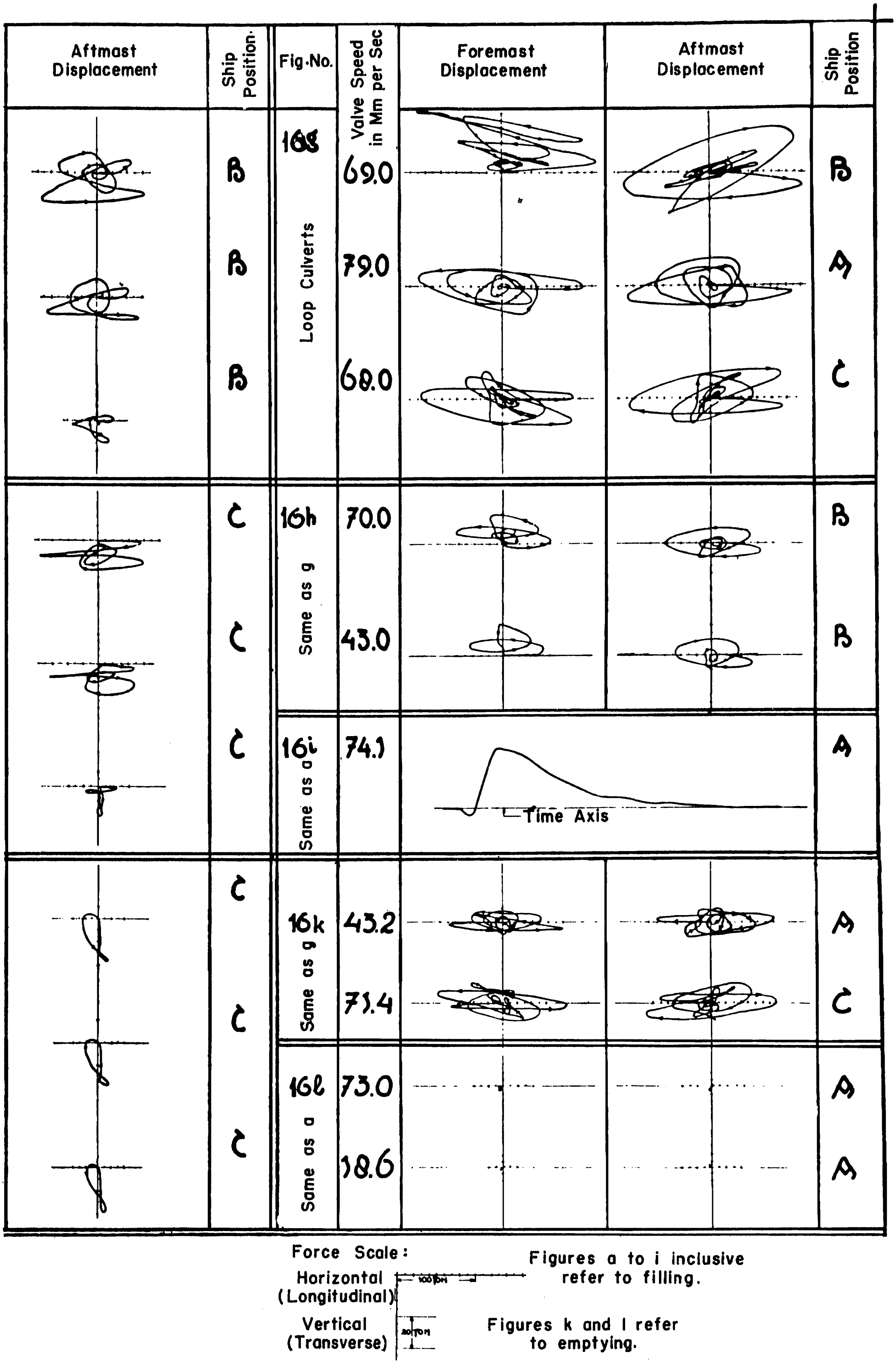
### 12. Difference Between the Magnitudes of the Forces Acting on the Ship Model and the Measured Hawser Forces

It should be noted here that the force diagrams, which can be obtained in the case of elastic hawser fastening (Fig. 14) as a result of the motion of the ship, do not represent the magnitudes of the forces acting on the ship model proper but those of the forces acting on the hawsers, as the forces causing motion of the ship model are those acting on the model itself. At first it acquires an acceleration and then a retardation (due to the continually increasing resisting forces a, page 38). Due to this motion, the ship acquires a momentum which must be dissipated by the hawsers. Therefore, the hawser forces will always be greater than the forces actually acting on the ship. Moreover, it is quite likely that the force which causes motion of the ship ceases to act before the motion of the ship stops, or that even a new, oppositely directed force arises. Thus besides the magnitude of the force acting on the ship, the factor affecting the magnitude of the hawser force is the acceleration of the ship, hence the mass of the ship and the degree of elasticity of the hawsers (the sizes of the cylinders).



P. Foremast. Q. Aftmast. Distance P-Q=112M.

Fig. 16 – Force Diagrams
45200-ton ship at a lift of 4m.



Figures a to i inclusive refer to filling.

Figures k and l refer to emptying.

Fig. 16 - Force Diagrams

Valve speed is same as in prototype.

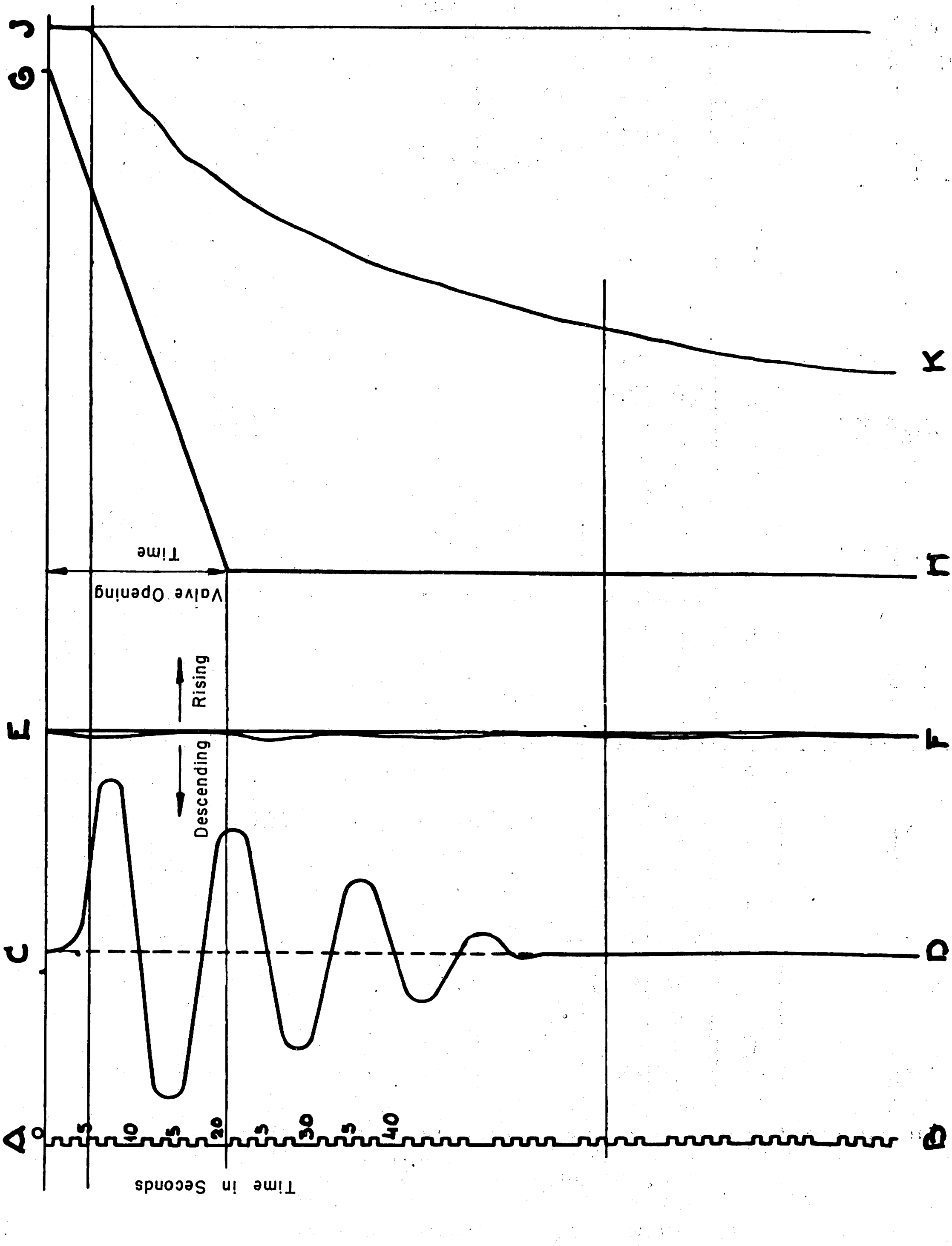


Fig.17 – Graphs Recorded on the Revolving Drum

A given difference in level, transverse to the ship, will exert on the ship a force which would impart to the ship a greater acceleration than the force arising due to a similar difference in level in the longitudinal direction (the accelerations will be approximately related as the length of the ship to its width). The inertia motion, acquired by the ship when the force ceased to exist or changed direction, is more rapidly dissipated by the larger opposing resistance when the ship moves transversely than when it moves longitudinally. Therefore, the transverse displacements in the diagrams will be in better agreement with the actual transverse forces acting on the ship than the agreement between the longitudinal displacements and the actual longitudinal forces.

In the case of nonelastic fastening of the ship in the chamber, such as used at IJmuiden (Fig. 18), the resultant of all the hawser forces will approximately correspond to the resultant of the actual forces acting on the ship (nevertheless, there is the aspect of some elasticity even in this case because the hawsers either droop or are stretched). The small longitudinal displacement to which the ship is subjected will be mostly counteracted by the friction which the ship experiences along the floating buffer.

An experiment at Berlin with cylinders of various diameters (various degrees of elasticity) proved that the magnitude of the hawser forces differs only little, so that the forces obtained at a given degree of elasticity give an accurate picture of the actual hawser forces. This means that the magnitudes of the hawser forces, such as those measured at Berlin, are sufficiently accurate also for the case of ships rigidly moored to the lock walls (IJmuiden).

## 13. Water Level in the Lock Chamber and Evaluation of Filling Time

The water level in the lock chamber during filling and emptying operations was transmitted to a revolving drum by means of a float. The curve JK (Fig. 17) was used to determine the filling time for the case tested. During previous laboratory tests, this was determined with the aid of electrical contacts. However, since the filling curve is not a taut line, it repeatedly seemed that the contact acted too early at the end of the filling. Thereby it should not be forgotten that the scale is very small and that the upper pool fluctuates. Therefore, this method has been abandoned.

Determination of the filling time from the curve is not accurate either, because near K the curve gradually becomes a straight line, so that

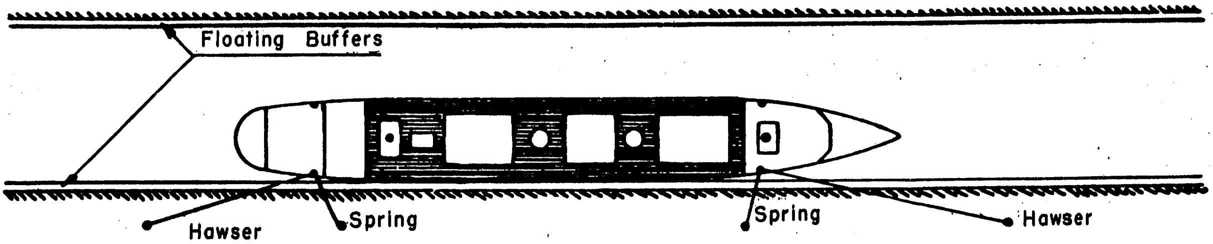


Fig.18 - Diagram Showing the System for Mooring Ships in the IJmuiden Locks

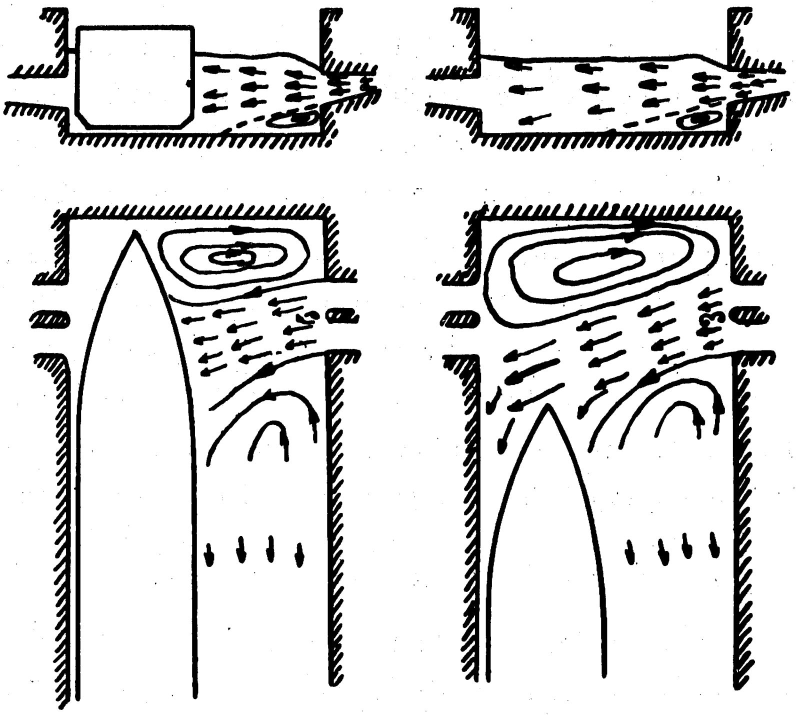


Fig.19 - Diagram of the Test Demonstrating the Oblique Flow from the Culverts

the point of tangency cannot be accurately determined. Also in practice it is difficult to establish the location of the tangency point, as was the case during obtaining a filling curve at the existing IJmuiden lock. This is the reason why it was decided there to compute the filling time from the curve, although it proceeds not without difficulties because the curve is not a normal filling parabola.*

Since the filling time of the model (page 29) is not purely a matter of scale, extraordinary accuracy is not the important aspect. The main point during the preliminary tests is to be able to compare to some extent the filling time of the various culvert systems.

## B. The Results of the Preliminary Experiments

### Introduction

The true motion of the water in culverts was not yet well known when the preliminary tests were conducted. If this (Chapter IV and Part II) had truly been the case during arrangement of the model, the arrangement could have been simpler. Fewer cases would have been investigated then.

Since cooperation between the tests at IJmuiden and Berlin has led to the development of the theory, on the whole no unnecessary operation was conducted at Berlin, as will be evident later. The comprehensive investigations in Berlin have merely relied on the correctness of the developed theories and have contributed a great deal to the understanding of the phenomena which generally occur during filling and emptying of a lock chamber.

The following discussion of the various filling systems is based on the experimental diagrams, presented in Fig. 16, which are merely a selection from the thousands of diagrams involved.

## C. Discussion of the Various Systems Tested at Berlin**

### 1. Filling the Lock Chamber Through Laterals in the Middle (Figs. 16a, 16i, and 16ℓ)

Applying the system of laterals in the middle results in forces which are primarily transverse forces. If the ship lies midway between the

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*When these filling-time computations were carried out at Berlin, the theory was not yet developed, so that the computations were merely approximate.

**See also Part II, Chapter V-B.

upper and lower lockheads, the longitudinal forces are negligible because the water from the laterals becomes distributed in the chamber towards both ends. The transverse forces draw the ship towards the wall near which it lies because the water streams beneath the ship and causes a rise in level on the other side. The pattern of the diagram on the drum shows that the largest transverse force occurs when the velocity of the inflowing water is the highest (Fig. 16i).

Because of the large culvert length, the rate of valve opening has little effect on the course of the filling operation. This rate affects the course somewhat only when the rate is very slow.

During emptying of the lock chamber (Fig. 16$\ell$), the forces are extremely small in the case of a ship lying in the middle of the chamber; the primary transverse force (page 21) does not occur.

### 2. Filling the Lock Chamber Through Laterals near the Lockheads, Without a Connecting Conduit (Figs. 16b and 16f)

Although only the system of laterals near the upper lockhead is of importance in practice, the system of laterals near the lower lockhead is also investigated in order to obtain a better insight into the flow pattern, while in both cases the filling occurs with water supplied from the upper pool.

In the case of the former system, the longitudinal forces at the beginning of filling are the largest, while the transverse forces gradually increase in magnitude in accordance with the square of the velocity of discharge from the laterals (Fig. 16b). In the case of the latter system, the longitudinal forces are small even at sudden valve opening because of the large culvert length (± 400 m in the prototype). The transverse forces, being dependent on the velocity of the discharge from the laterals, are considerable because the water in the culvert finally develops velocity, even though very gradually. The rate of valve opening has little effect on the filling time and on the magnitude of the forces (Fig. 16f).

### 3. Filling the Lock Chamber Through Laterals near both Lockheads, Connected by a Conduit (Fig. 16c).

The resulting diagrams show that the laterals located farthest upstream are the first to discharge water. The magnitude of the occurring forces does not differ much from that observed in the system in which the water is delivered exclusively through the laterals near the upper lockhead. With regard to the longitudinal forces, this can be explained by the facts that the water from the laterals near the lower lockhead discharges later than from the laterals near the upper lockhead and that the effect of the former discharge on the magnitude of the longitudinal forces is small due to the large inertia of the water in the long connecting conduit (small increase in the rate of inflow to the last manifold). With respect to the transverse forces, the difference between this system and the system of laterals near the upper lockhead is not large because the velocity of discharge from the laterals near the lower lockhead is almost the same in both cases.

The phenomenon which motivated the formulation of preliminary conclusion 1 (page 18) proves that the system is less valid, yet at that time the great importance of this conclusion was underestimated.

### 4. Filling the Lock Chamber Through all the Laterals Simultaneously (Figs. 16d and 16e)

When the water is simultaneously admitted through the laterals near both lockheads and the laterals in the middle, the filling may be regarded as actually occurring through a culvert with large laterals of which each is subdivided. Therefore, it constitutes approximately a culvert with laterals.

Consequently, this filling system requires little additional discussion. The manifolds again discharge successively considerably more water; the effect of the last two manifolds on the magnitude of the forces is small. The filling period is shorter than in the case of filling through fewer laterals.

### 5. Filling Through Openings in the Gates

In using this system of filling, the inertia of the water in the culvert is absent, yet this loss can be compensated by slower opening of the valve. During the Berlin tests of this case, no valves were installed in the gate; for the purpose of simplicity, one valve was installed at some distance from the gate, which closed off a head basin. Since this basin actually constituted a buffer, the correctness of these tests is regarded as less valid.

This system was never considered for use at IJmuiden because the valve constructions would have made the gates less simple. Chambers would have had to be prepared between skin plates of the gate (7.30 m apart), in which to install adjustable valves, while the valves would have occupied a large area with respect to the gate surface.

### 6. Filling the Lock Chamber Through Loop Culverts (Figs. 16g and 16k)

In the case of loop culverts, the process is principally similar to that of the system of laterals near the upper lockhead so that a separate discussion is superfluous. Figure 16k shows that, under otherwise similar conditions, the forces during emptying are smaller than during filling.

## D. Comparison of the Various Systems

The test results show that it is possible to achieve in all systems extremely small forces acting on the ships if the rate of valve operation is reduced. However, a given small force on the ship in the chamber will be achieved in one system at a faster rate of valve operation than in another system; accordingly, the filling time for the various systems already is not equal. The most efficient system is that in which the filling period is the shortest, while the hawser forces do not exceed a certain maximum.

Therefore, the first comparison is of the filling time in the various systems. Table I gives the filling time in the various systems at a high lift (4 m), filling from both sides, and equal rate of valve opening (60 mm per sec).

TABLE I

| No. | System | Actual Filling Time | |
|---|---|---|---|
| | | Minutes | Seconds |
| 1 | Laterals in the middle | 11 | 45 |
| 2 | Laterals exclusively near the upper lockhead | 15 | 25 |
| 2a | Laterals exclusively near the lower lockhead (filling from the sea) | 17 | 10 |
| 3 | Laterals near the lockheads, connected by a conduit | 10 | 45 |
| 4 | All laterals simultaneously | 9 | 35 |
| 5 | Loop culverts | 10 | 40 |
| 6 | Openings in the gates | 12 | 50 |

The filling periods of cases 2 and 2a of this table cannot be compared with those of the other systems because the sum of the discharge openings in these cases is much smaller than the culvert cross section (page 30).

According to the table, the shortest filling time at the assumed rate of valve operation occurred during filling through all the laterals simultaneously.

The second comparison is with respect to the magnitude of the hawser forces at a given filling period. To this end, the following table was compiled (Table II); it gives the largest hawser forces occurring in the various systems at a high lift (4 m) and filling from both sides, when the filling lasted 12 min.

The hawser forces involved are obtained by combining the longitudinal and transverse forces measured at the same instant. If the observations are adequate, it is possible to find in each system a relationship between the rate of valve operation and the filling time, as well as between either of these two and the longitudinal and transverse forces. For this purpose, the two magnitudes, between which it is desired to establish the relationship, are plotted on a coordinate system and curves are drawn. In this way it is possible to compile tables like the following ones.

TABLE II

| No. | System | Filling Time in minutes | Rate of Valve Opening in mm per sec | Maximum Resultant Hawser Force in tons | Remarks |
|---|---|---|---|---|---|
| 1 | Laterals in the middle | 12 | 45 | 47 | The largest transverse force occurred when the ship lay between the middle of the chamber and the upper gate. |
| 2 | Laterals near the upper lockhead | - | - | - | Minimum filling time = ± 15 min. |
| 2a | Laterals exclusively near the lower lockhead (filling from the sea) | - | - | - | Minimum filling time = ± 17 min. |
| 3 | Laterals near both lockheads, connected by a conduit | 12 | 20 | 57 | |
| 4 | All laterals simultaneously | 12 | 14 | 46 | |
| 5 | Loop culverts | 12 | 20 | 56 | |
| 6 | Openings in the gate | 12 | 80 | 140 | |

Table II presents the assumed filling time, the corresponding rate of valve operation, and the maximum resultant hawser force, all magnitudes referring to a high lift (4 m) and filling from both sides.

The next table (Table III) presents the filling time and resultant hawser force at a low lift (1.40 m) and filling from both sides, the rates of valve operation being the same as in the preceding table.

TABLE III

| No. | System | Filling Time | Rate of Valve Opening in mm per sec | Maximum Resultant Hawser Force in tons | Remarks |
|---|---|---|---|---|---|
| 1 | Laterals in the middle | 7'30" | 45 | 20 | |
| 2 | Laterals near the upper lockhead | - | - | - | Remains undetermined |
| 3 | Laterals near both lockheads, connected by a conduit | 8' 0" | 20 | 25 | |
| 4 | All laterals simultaneously | 8' 0" | 14 | 20 | |
| 5 | Loop culverts | 8' 0" | 20 | 20 | |
| 6 | Openings in the gate | 7'25" | 80 | 45 | |

Table II shows that at a high lift, whereby the hawser forces are maximal, systems 1 and 4 are the most satisfactory. The next best are systems 3 and 5. It can readily be ascertained how long the filling time would be in the latter systems if the maximum hawser forces of 46 to 47 tons were not to be exceeded (that is, the hawser forces occurring in systems 1 and 4 at a filling time of 12 min, as seen from Table II). This filling time in systems 3 and 5 would be 13'30" and 12'20", respectively.

It follows, therefore, that the maximum hawser force in system 5 at a filling time of 12'20" is equal to that occurring in system 1 or system 4 at a filling time of 12 min. Accordingly, systems 1, 4, and 5 (laterals in the middle, all laterals simultaneously, and loop culverts, respectively) may be considered as practically equivalent systems in preliminary comparison.

## E. Selection of a System

The second of the three systems regarded as equivalent systems offers no economic advantage for construction of the proposed lock, so that this system need not be considered any further. The most inexpensive of the remaining systems is the system of loop culverts, in which no culverts occur in the lock-chamber walls and the foundation can be laid at 7.50 m below normal stage (page 25). Nevertheless, both remaining systems must be further investigated before it becomes possible to proceed with making a choice.

Firstly, it must be determined which hawser forces are allowable. Since, as far as known, literature contains no information about this aspect, it was decided to obtain some insight into this subject by means of measurements in the existing IJmuiden lock. In the case of a ship of 1148 register tons and a submerged beam area of ± 60 sq m, hawser forces of 2.7 tons were measured; these forces occurred not during filling but during and after opening of the gates and were caused by the difference in specific weight of brackish (canal) water and salt (sea) water. Larger hawser forces occurred when the ship was pulled sideways (so-called heaving of the hawsers), primarily due to strong wind; the magnitude of these forces could not be measured because of lack of instruments of adequate capacity.

Considering the fact that a hawser force of 2.7 tons occurred in the case of a ship having a submerged beam area of ± 60 sq m, it may be assumed that a hawser force five times as large, or 13.5 tons, would occur due to flow of fresh water and salt water in the case of a ship having a displacement of 45,200 tons and a submerged beam area of 300 sq m. Although this assumption is debatable and theoretically not entirely true, yet it yields a point of departure. The assumption is by no means extreme, considering the fact that very large hawser forces occur even during the heaving of a small ship.

Consequently, if hawser forces of 13.5 tons can be anticipated after the water level in the chamber has been established, there is no reason to make provisions that the maximal forces occurring during lockage should be smaller than 13.5 tons. Therefore, the maximum allowable hawser force is taken as 13.5 tons for the case of lockage at a high lift (4 m), which is an exceptional case. At lower lifts, however, the maximum hawser force will be smaller, provided the valves are operated at the same speed as in the case of high lift (4 m). It finally appeared possible, nevertheless, to reduce the hawser forces at the highest lift to less than 5 tons.

During the preliminary model tests, the lowest effective rate of valve operation was initially taken as about 15 mm per sec, so that the valves were fully open in approximately 15 min. However, the graphs showed that in such a case the forces which the hawsers must sustain at a high lift (4 m) are considerably larger than 13.5 tons, which indicated that the rate of valve operation still was too high. Therefore, the filling operations by means of laterals in the middle and loop culverts were tested further at lower rates of valve operation, up to approximately 5 mm per sec (filling time = 16 min). It was found then that the transverse forces which the hawsers had to sustain during filling through laterals in the middle still remained fairly large in spite of the very low rate of valve operation. The direction of the force acting on the ship is indeed favorable for the hawsers in the case of filling from both sides and mooring of the ship in the manner used at IJmuiden (Fig. 18), since the ship becomes pressed close against the installed floating buffers, so that the hawsers do not become stressed. When the ship lies at the south wall, on the other hand, the hawsers become highly stressed, according to the tests, in the case of one-sided filling from the north culvert, so that the hawser forces obtained in this case must really be taken into consideration. In addition, it is necessary to consider the possibility that the ships will be moored later in the manner used at the locks of the Panama Canal (Fig. 14).

In the case of filling through loop culverts, the longitudinal forces are larger than the transverse forces. The longitudinal forces decrease considerably with decreasing rate of valve opening, while the transverse forces decrease to a lesser extent, primarily when the ship lies in the direct sphere of the culverts (page 114). At the very low valve-opening rate of 5 mm per sec, the longitudinal forces attain an allowable magnitude. The transverse forces, however, remain too large at the abnormal lift of 4 m when the ship lies partly in front of the culvert outlets. At this position the resultant hawser force exceeds 13.5 tons. However, this position of the ship need not occur in practice. In due time, when the gates would be protected by safety screens, the ships will not be able to approach the gates closer than up to 35 m, which is the distance from the screens to the gates. Then the culverts will discharge in the chamber section between the gates and screens, this section acting somewhat as a stilling basin.

If the system of laterals in the middle is compared now with the system of loop culverts, it can be stated that, in order to achieve the allowable hawser force, the first system requires a longer filling time than the second system (15 min in the case of the latter, while even at a filling time of 18 min the maximum hawser force still is 30 tons in the case of the former); this is due primarily to the fact that the large transverse forces can be reduced in the case of loop culverts (location of the ship outside the direct sphere of the culverts), while it is impossible in the case of the other systems. In addition, the system of loop culverts is the cheapest. These factors simplify the final choice of a system; accordingly, in the case of the proposed IJmuiden lock it was decided to arrange the establishment of the water level in the lock chamber by means of loop culverts which occur only in the lockheads.

At a normal high lift (1.40 m), the maximum occurring hawser force is 5 tons in the case of a ship of 45,200-ton displacement when the prow of the ship is located 20 m from the upper gate (that is, next to the culvert outlets in the preliminary model).

## F. Further Testing of the Selected System

### 1. Tests with Small Types of Ships

The choice of a system for filling the lock chamber was made on the basis of tests on the largest ship model. It is still necessary to determine whether the selected system (loop culverts) is not less suitable with respect to the hawser forces in smaller ship types. The other ship types (listed on page 32), however, seem to be subjected to smaller forces, at the appropriate rate of valve operation, than those corresponding to the ratio of the submerged beam areas of these ships to that of the ship of 45,200-ton displacement, as the longitudinal force acting on the ship (the principal force in the present case) is proportional not only to the submerged beam area but also to the length of the ship (page 104).

The forces on the smallest ship tested (4550-ton displacement) were very small even then. Even when this ship was situated partly in front of the culvert outlets, the transverse forces remained within allowable range, so that such a ship may well be placed with its prow against the gates. This is of importance for mass lockage operations (many small ships near each other in the chamber) which now often occur at IJmuiden. When the safety screens are installed, the capacity of the chamber could be increased as follows: after the small ships are at rest with their prows against the screens, the screens can be stretched and enable the ships to be moored still nearer the gate.

### 2. Rate of Valve Opening

If the valves were to be operated at a rate of 5 mm per sec, the opening would last 16 min. At a high lift (4 m), the chamber would then be filled in about the same time. At low lift the filling would last 10 min (the valves will operate about 6 min after the chamber has been filled), this period being even somewhat shorter than that of the existing large IJmuiden lock at a similar lift. Since higher lifts than 1.40 m are regarded as exceptions, it can be stated that on the whole the filling time of the future lock is equal to that of the existing lock, even if the former were constructed in conformity with the poorly installed culverts of the model used in the preliminary tests. The filling period will be longer in the exceptional cases, yet this cannot be regarded as a disadvantage in any respect, the more so as the filling period of the existing large IJmuiden lock likewise would be longer in the exceptional cases (at present no lockage is carried out at IJmuiden with a lift higher than 2 m, due to the established lockage level).

The layout and shape of the culverts in the preliminary tests were relatively arbitrary. More attention was paid to these factors during the final tests; this resulted in an improvement in the relation between the hawser force and rate of valve operation (smaller hawser forces at higher rate of valve operation, thus a shorter filling period).

# CHAPTER VII
# DEFINITIVE STUDIES

## A. The Final Tests

After the preliminary tests had resulted in the choice of a given filling system, it became possible to proceed with further investigations of the selected system with the objective of achieving the most satisfactory design of the IJmuiden lock. Since the nonuniformity of the culvert outline, resulting from the presence of the gate recesses on the north side only, was not taken into consideration during the preliminary tests, this factor was properly considered in the final tests.

### 1. Determination of Culvert Shape

In the final tests, attention was paid particularly to suitable outline and cross section of the culverts. The endeavor involved designing the culverts in such a way that the forces acting on the ships during lockage would be as small as possible.

To begin with, the primary transverse forces must be eliminated; this requires that the ships should not be situated in the direct sphere of the culverts. Initially it was supposed that it would be satisfactory if the culverts discharged into the section of the chamber where the ships would never have to be located and if the discharge of the culverts were directed normal to the lock axis.* The results of tests with such culverts showed, however, that the water jets entered the chamber at an angle, which is understandable in the case of the south (shortest) culverts because the water must turn through 90° shortly before discharging (centrifugal force). Ships moored at one wall with the prow at some distance from the culvert outlets are subjected during filling to forces due exclusively to the water jets of the culverts located in the other wall.

An experiment, in which sawdust was supplied with the water and made visible by means of a light at the bottom of the lock, confirmed the supposition (Fig. 19). Accordingly, the design of the lock was modified in such a way that the ends of the culverts were directed towards the gates.

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*This section is located between the gate and the safety screen (to be installed in due time) which will serve to protect the gate against collision.

Since the magnitudes of the primary and secondary transverse forces are proportional to the area of the discharge opening and the square of the discharge velocity (page 21), it was decided to make the culvert outlets as large as possible in order to obtain as low a discharge velocity as possible, without exceeding the filling period fixed in advance. For this purpose, the culverts are gradually diverged.

In order to make the valves as small as possible, they were installed in the narrow culvert section. In view of the construction of the walls, two culverts were installed next to each other on both sides. This provides the additional advantage that filling of the chamber can occur through three culverts when one valve is out of order.

Divergence of the culverts must occur at a small angle in order to prevent separation of the water from the culvert walls, which produces eddies and nullifies the effect of the divergence. It was established experimentally that the angle between two opposite surfaces of the culvert walls should not exceed 10°.

The combined culvert cross section on each side of the lock is 26.50 sq m at the location of the valves and about 60 sq m at the outlets. The divergence of the south culverts of the lower lockhead begins at the east side immediately beyond the valve shafts. Since the southernmost culvert is longer than the other culvert, its outlet is the largest. The other culvert outlets are made in conformity with the outlets of the culverts of the lower lockhead.

The divergence of the culverts on the chamber side and on the sea or canal side is made in the same way, with the result that, at equal rate of valve operation, the filling time and emptying time are the same at equal lift. The curving of the culverts towards the gate, on the outer side of the gate recess, is motivated by consideration of symmetry and for the purpose of calm position of the ships outside the lock.

To reduce the longitudinal forces, which can be particularly troublesome at the beginning of filling and afterwards rapidly diminish in magnitude, it should be possible to operate the valves at a uniformly accelerated motion --extremely slowly at the beginning and then gradually faster. This would lead to a fairly complicated actuating mechanism of the valves. Therefore, it is essential to find another solution, which involves assigning a special profile to the culverts at the location of the valves (Figs. 20a and 20b).

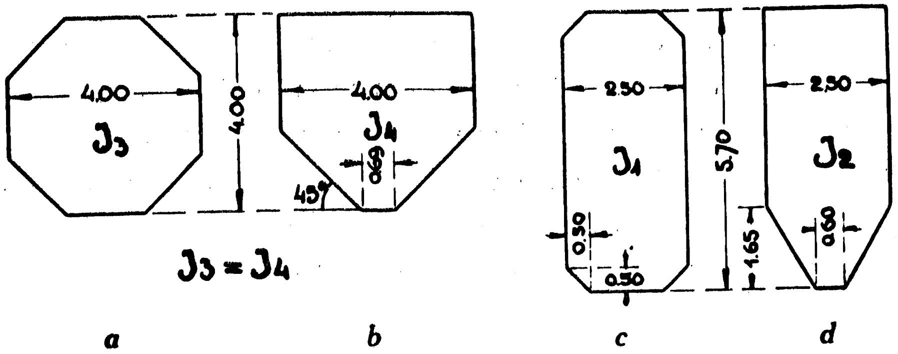

Fig. 20 - Culvert Cross Sections
a and b show the initial design;
c and d show the final design.

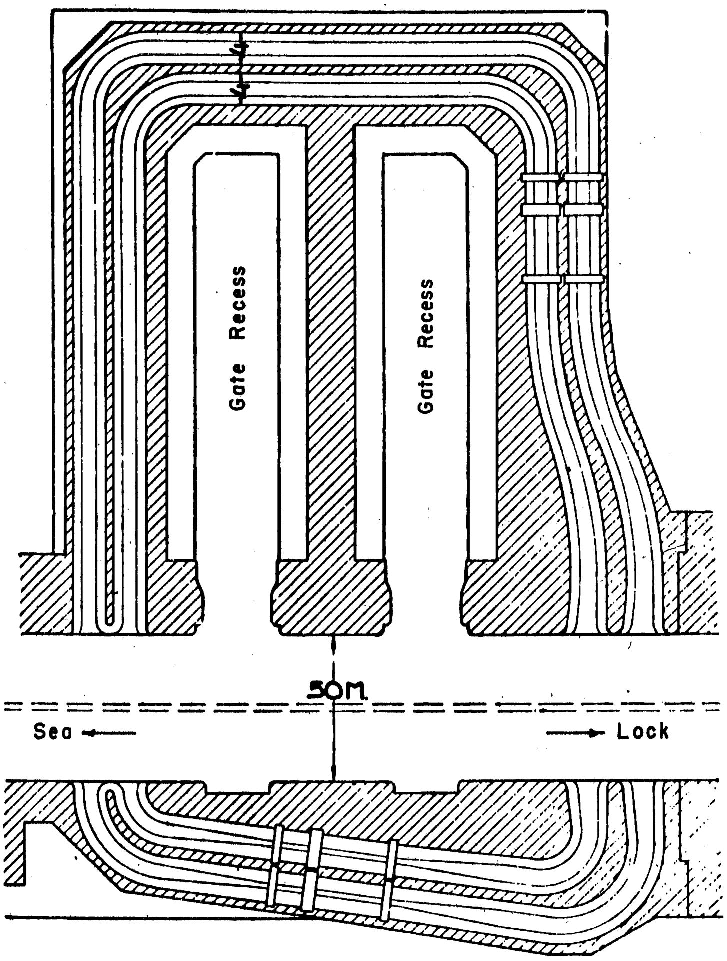

Fig. 21 - Culvert Arrangement in the Initial Design

When the valves are rectangular and operated at uniform speed, their resistance to the flow is gradually eliminated more rapidly.*

The final tests were conducted initially with culverts which had the regular octagonal shape in the normal narrow section (Fig. 20a, inscribed circle with a diameter of 4 m) and the outline shown in Fig. 21. However, in order to economize on wall thickness, the culvert shape was somewhat modified subsequently and finally became 2.50 m wide and 5.70 m high (Figs. 20c and 20d). The final outline of the culverts of the upper lockhead is shown in Fig. 22.

The culverts of the upper lockhead were tested only with the cross sections shown in Figs. 20a and 20b, while the culverts of the lower lockhead were tested with the modified profile and outline. Since the former culverts are longer than the latter and thus are functioning under more favorable conditions as far as the forces exerted on the ships are concerned, it was regarded as unnecessary to modify the model of the upper lockhead, prepared in accordance with Fig. 21. In order to check the results of the upper lockhead, the model of the lower lockhead was tested at lifts that occur only in the case of the upper lockhead (the maximum lift for the lower lockhead is 2.70 m during filling; the investigation was extended to a range of lifts up to 4 m).

## 2. Upper Lockhead

### a. Arrangement of the Model

On the basis of experiences obtained during the tests, the culverts of the upper lockhead were initially arranged as shown in Fig. 21 and finally as shown in Fig. 22. The culverts were simulated in the Berlin-Charlottenburg laboratory to 1:40 of prototype size, in accordance with Fig. 21. The culvert cross section pertaining to Fig. 21 is generally the one presented in Fig. 20a. The cross section shown in Fig. 20b was used only at the location of the valves in the shortest culverts (the cross-sectional areas of the culvert at the location of the valves and in the normal narrow sections are the same). The transition between the cross sections is very gradual.

Since the culverts passing around the gate recesses are much longer than the other culverts, the large inertia of the water eliminates the need for a special culvert profile at the location of the valves in the long culverts.

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*In the case of cylinder valves, this can be achieved by using the patent of D. J. Klink (among others). See De Ingenieur, No. 31, 1927.

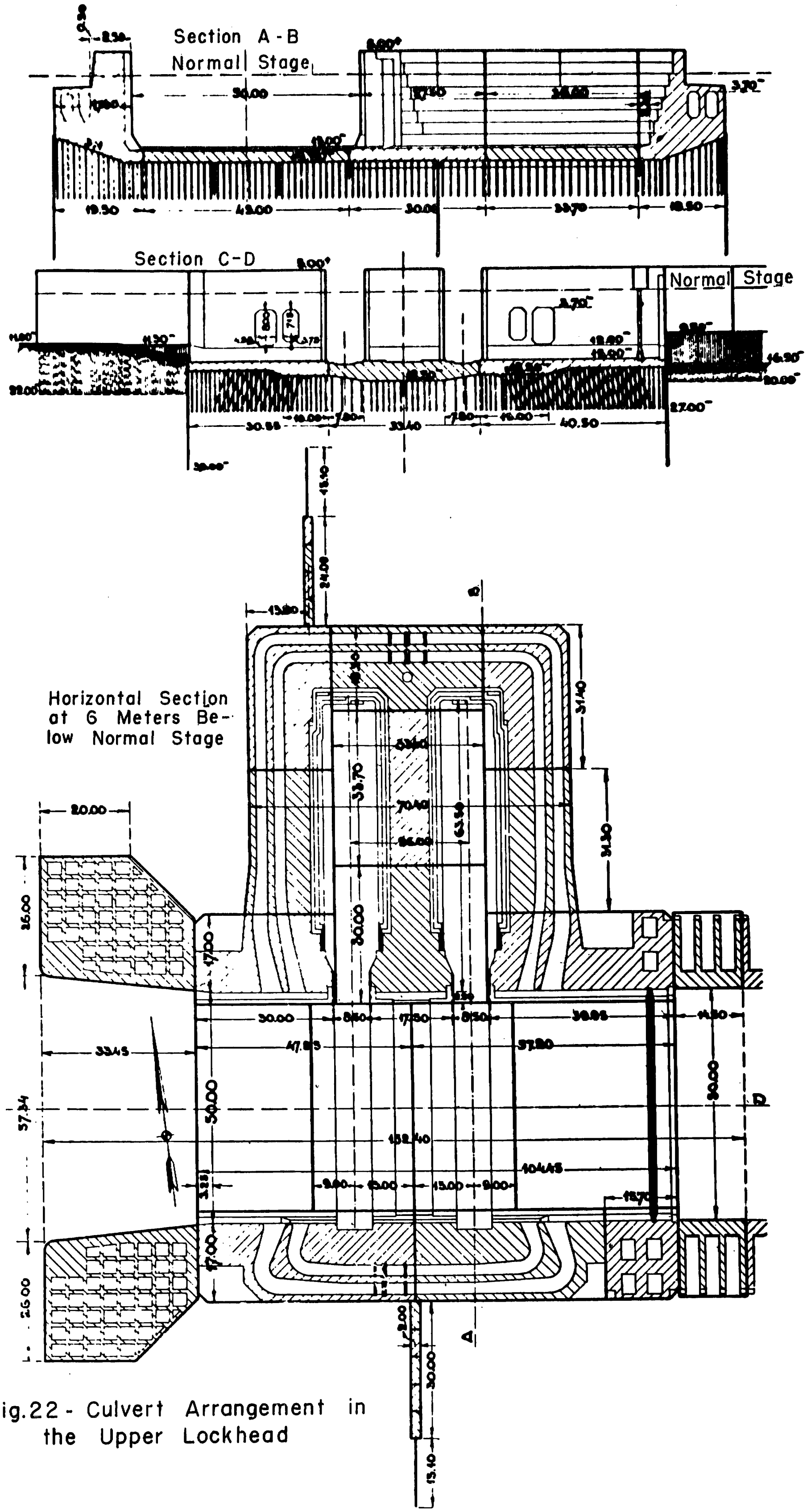


Fig.22 - Culvert Arrangement in the Upper Lockhead

To make the culvert models, a paraffin core was first prepared and concrete was poured around it (Fig. 23). After the concrete had hardened, the core was melted with the aid of steam and withdrawn.

Fig.23 - Photograph of Paraffin Culvert Model in Initial Design

The valves in the final tests are plane valves, as in the prototype, actuated in a manner corresponding to that illustrated in Fig. 13.

The model used for the preliminary experiments was left as intact as possible, so that it is feasible to carry out further investigations of the various systems if desired.

b. The Test Results

The results of the final tests satisfied the expectations. The effect of the difference in culvert length of the north and south culverts was well manifested; the first longitudinal force in the case of filling only through the shortest culverts was larger than that arising in the case of filling exclusively through the long culverts, at the same rate of valve opening. At the same time, it indicated that the culvert shape, corresponding to Fig. 20b, at the location of the valves of the shortest culvert is not effective. Also the maximal transverse forces, produced by the water discharging from the short culverts, are always larger than those caused by the water discharging from the long culverts, at equal valve speed. However, this is not of paramount importance (page 120). Finally, the filling period at filling only through the short culverts is shorter than at filling exclusively through the long culverts.

It appears that the hawser forces have an allowable magnitude when the valves are opened at a rate of 10 mm per sec. One-sided filling resulted in larger forces than two-sided filling when the culverts used were on the side where the ship was not moored. In this case, a rise in level occurred opposite the wall where the ship was moored, so that a pulling force was exerted on the ship (the ship was drawn towards the discharging culverts, as it were).

Filling through three culverts was also investigated (which occurs in practice when one culvert is closed for valve repairs). The maximum hawser forces in this case were smaller than at one-sided filling and larger than at filling through four culverts.

### 3. Lower Lockhead

At the beginning of the laboratory experiments, it was still intended to equip both the lower and upper lockheads with two gate recesses each. Because of economic considerations, it was decided to install only one gate recess in the lower lockhead, as planned by the Kraus Government Commission and for which contributions were promised by the Provincie Noordholland and the Gemeente Amsterdam.

The first result of this reversal to the original plans, arrived at during the tests, was that the results of the tests on the model of the upper lockhead were not applicable to the lower lockhead because the particularly short culvert (at the side of the gate recess) of the lower lockhead is relatively shorter than that of the upper lockhead, so that at similar lift and rate of valve operation the longitudinal and transverse forces near the lower lockhead are larger.

However, during the filling operation the lift at the lower lockhead is never higher than 2.70 m (from 0.20 m above normal stage in the canal to 2.50 m below normal stage in the sea), while the maximum lift at the upper lockhead is 4 m. During the emptying operation, of course, the maximum lift at the lower lockhead is 4 m, but the hawser forces of ships in the chamber are smaller during emptying than during filling (page 21), as established from a special series of observations. Figures 16h and 16k show the difference in hawser forces of the same ship, occurring during filling and emptying of the chamber under otherwise similar conditions.

Therefore, where the conditions during filling are considerably more favorable for the lower lockhead than for the upper lockhead, it was investigated whether it would be permissible to use a simpler culvert arrangement in the lower lockhead, that is, to pass the culverts through the gate recess instead of around it (Fig. 24).

The culverts are used only when the gate is closed, that is, when it is withdrawn from its recess, so that it never interferes with the passage of the water. The situation is different in the case of the upper lockhead because there the reserve gate is always in the way and, in addition, it is essential to be able at any time to drain one gate recess in order to place into dry dock the gate which is not in use. Accordingly, the culvert system used in the lower lockhead is not considered for the upper lockhead.

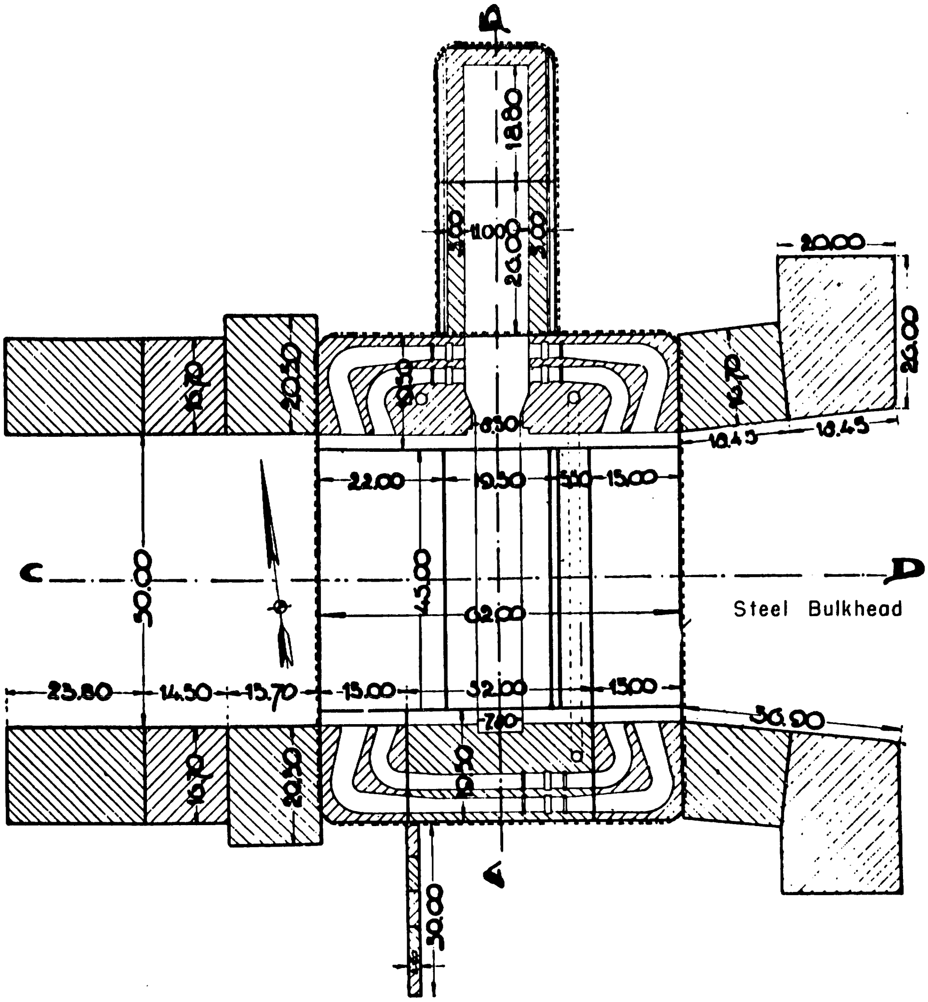
The designed lower lockhead was simulated for testing in the laboratory. The culverts were prepared in full accord with the final design, as far as outline and cross sections are concerned.

It was found that interruption of the culverts through the gate recess had no appreciable effect on the hawser forces. During filling from the two culvert pairs separately, the hawser forces were fairly equal and the filling time did not differ much either.

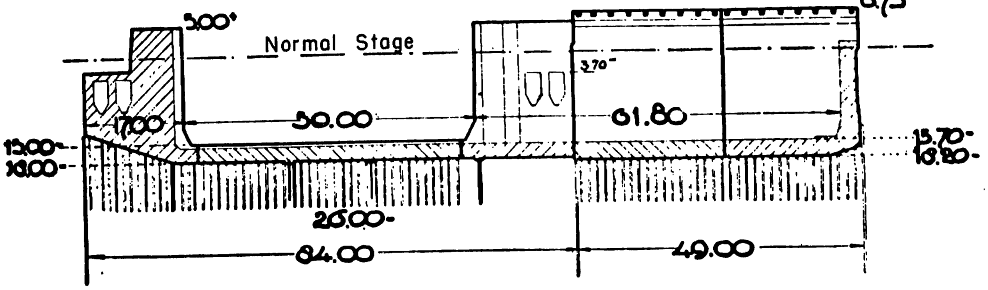
During the process of establishing the water level in the chamber, the water in the gate recess attains a level which is between the level in the lock chamber and that in the canal--the gate recess has become a part of the culvert. The level drop in the gate recess can be determined by means of the following consideration: the culverts on one side of the gate recess must supply, per unit time, as much water as the culverts on the other side discharge. This phenomenon has some effect on the design of the roller gates, of which each must be able to function separately in the lower lockhead. This aspect is discussed in the article dealing with gates, published in De Ingenieur, No. 10, 1927.

The water levels in the gate recess during establishment of the water level in the chamber were recorded in the laboratory (Fig. 25). The slower

Plan



Section A-B



Section C-D

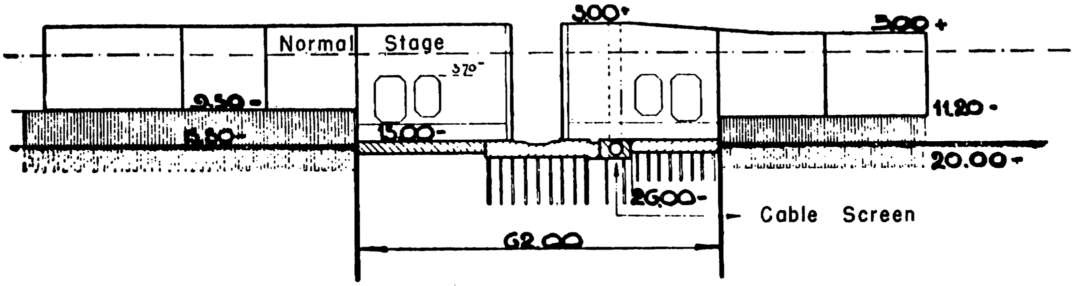


Fig. 24 - Design of Lower Lockhead

the valve operation, the lower the flow velocity in the culverts and the smaller the temporary level drop in the gate recess. In the case of emptying or filling the chamber exclusively through the interrupted culverts, the level difference in the lock will vanish more slowly, so that the flow velocity in the operating culverts will be higher than in the case of two-sided filling. Figure 25 shows, accordingly, that in the case of filling exclusively through the interrupted culverts the temporary level drop in the gate recess is larger than in the case of two-sided filling.

When the lift is 2.50 m (almost the highest lift at which the chamber is filled through the lower lockhead) and filling occurs through both sides at the assumed rate of valve operation (10 mm per sec), the largest hawser force on a ship of 45,200-ton displacement, located with its prow 35 m from the gate, is 3 tons (if the lift were 4 m, the hawser force would be 4 tons) and the filling time is 10.5 min (12 min at a lift of 4 m). In the case of one-sided filling from the culverts located farthest from the ship and at a lift of 2.70 m, the hawser force is larger than in the case of two-sided filling, the bow of the ship being 35 m from the lower gate, yet this force remains below the assumed allowable hawser force of 13.5 tons (page 51).

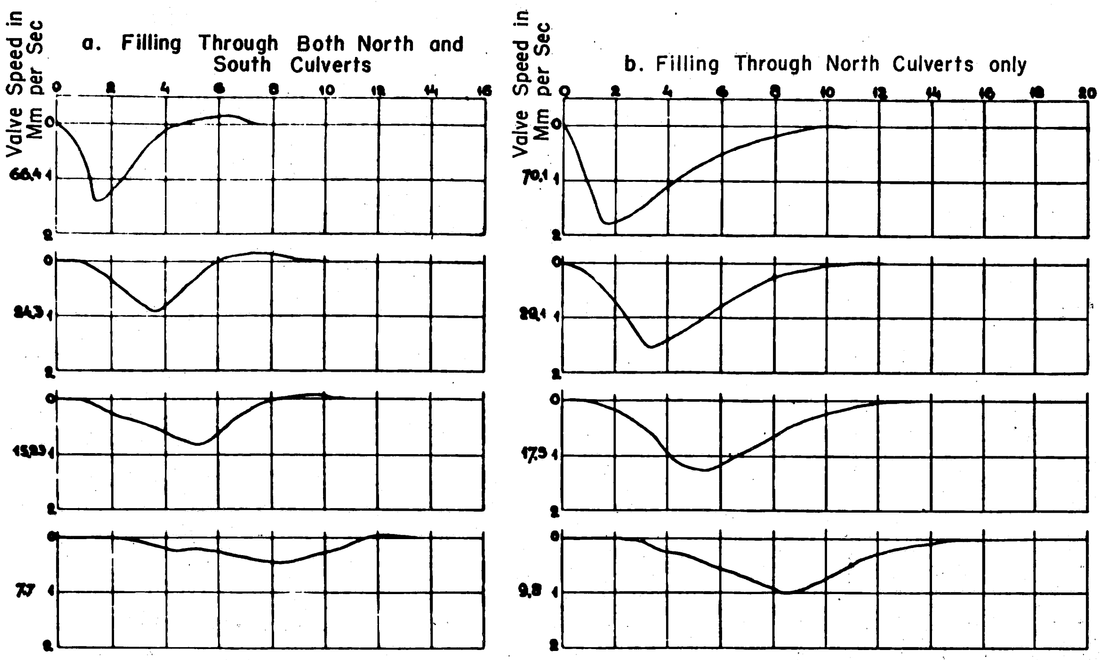


Fig. 25 – Pattern of Water Levels in the Gate Recess of the Lower Lockhead During Filling

Upper pool at normal stage, lower pool at 2.50m below normal stage.
Ordinate = meters below normal stage, abscissa = time in minutes.

Figure 26 is a photograph of the prototype culvert cross section immediately before the valves.

## B. Conclusions

The theory (Part II), developed during and as a result of the experiments, was repeatedly tested in the laboratory and discussed with leading authorities. This established confidence in its results. In order to determine how the theory agrees with practice, an additional experiment was conducted in the laboratory with a simulated 1200-ton sandbox belonging to the firm Den Breejen van den Bout te Berg en Dal which was kind enough to promise to make this box available, after acceptance of the lock, for experimental verification (as shown in Fig. 15)* of the comparative values of the hawser forces measured in the model and the actual forces.

It was possible to establish that the model tests were a complete success only after these verification tests had been carried out.

But for the tests, the design of the new lock would perhaps not have been altered so as to abandon the system of culverts with laterals, and the project would have cost an additional 1,000,000 to 1,500,000 florin. Moreover, the design of the lower lockhead would probably not have been modified (culverts through the gate recess), this modification constituting a saving which was initially (before completion of the design of the lockheads) estimated at 250,000 florin (see De Ingenieur, No. 39, 1924) and at present, the designs of both lockheads having been completed and contracted for, can be more reliably estimated at 500,000 florin.**

The success achieved in this case may constitute a stimulus to our colleagues to become familiar, better than heretofore, with the flow phenomena by means of further model tests. It would thus be found that superior knowledge leads simultaneously to greater economy.

IJmuiden, March 29, 1927
J. A. Ringers
J. P. Josephus Jitta

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*For this purpose, several concrete cylinders will be placed behind the lock-chamber walls.

**These savings on construction costs are reduced by the sum of 26,500 florin which constitutes the cost of the model tests.

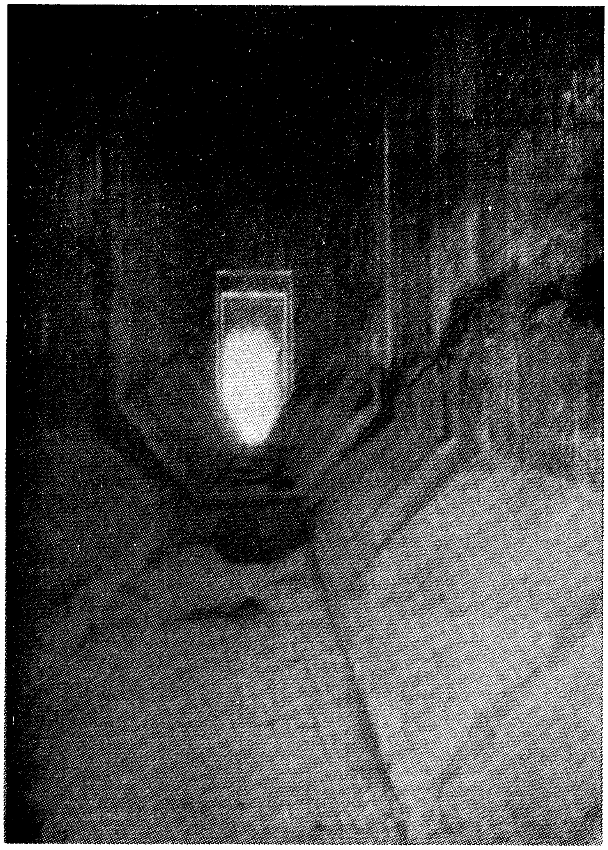

Fig. 26 - Photograph Taken in One of the South Culverts of the Lower Lockhead
Light passes through the valve shafts.

# PART II

# CONTRIBUTION TO THE COMPREHENSION OF THE PHENOMENA OCCURRING DURING FILLING OR EMPTYING A LOCK CHAMBER IN CONNECTION WITH THE DESIGN OF A LOCK

## INTRODUCTION

The phenomena occurring during filling and emptying a lock chamber have been a source of numerous studies, and justly so, as these phenomena dominate to a great extent the design of each lock. Since the phenomena are not yet fully known, a contribution to the enlargement of such knowledge is, in my opinion, not misplaced.

Primarily filling and emptying a lock chamber with the aid of culverts will be discussed here. This subject is theoretically analyzed to some extent in Chapters I and II, which deal with tracing the motion of the water in conduits in general. Chapters III and IV describe the application of the theory to locks, and Chapter V contains experimental verification of the theory.

The effect of filling and emptying the lock chamber on ships located outside the lock, in the canal approaches, for example, is not discussed in this work. With regard to this, reference is made to the article by Dr. R. Winkel, published in Die Bautechnik of February 26, 1926, and to the corresponding bibliography.

# CHAPTER I

## UNSTEADY MOTION OF WATER IN PIPES WITHOUT BRANCHES

### A. Derivation of the Basic Formulas

When two constant-level tanks, the difference in their levels being h, are filled with water of specific weight equal to unity and are interconnected by a pipe of length $\ell$ and of a cross section infinitely smaller than that of the tanks, so that the velocity of the water in the tanks is negligible in comparison with the flow velocity in the pipe, then the following approximate relationship can be written for a given instant if the atmospheric pressure is everywhere the same:

$$h = \sum \text{head losses} + \frac{\ell}{g} \int_0^{\ell} \frac{dv}{dt}\, d\ell \tag{1}$$

The first term (loss term) of the second member of this equation represents the portion of the head used to overcome the resistances experienced by the water in the pipe, while the second term (inertia term) represents the portion of the head used to increase the velocity of the water.

#### 1. Pipe of Constant Cross Section

If the cross section of the pipe is constant, Eq. (1) becomes

$$h = \sum \text{head losses} + \frac{\ell}{g}\frac{dv}{dt} \tag{2}$$

The losses comprise entrance loss, skin-friction loss, bend losses, and exit loss. All the head losses can be expressed as a function of $v^2/2g$, so that

$$\sum \text{head losses} = \eta^2 \frac{v^2}{2g}$$

Accordingly, Eq. (2) becomes

$$h = \eta^2 \frac{v^2}{2g} + \frac{\ell}{g}\frac{dv}{dt} \tag{2a}$$

Hence,

$$\frac{dv}{dt} = \frac{g}{\ell}\left( h - \eta^2 \frac{v^2}{2g} \right) \tag{2b}$$

or

$$t = \frac{\ell}{\eta\sqrt{2gh}} \log_e \frac{\sqrt{2gh} + \eta v}{\sqrt{2gh} - \eta v} + \text{constant} \tag{3}$$

The constant is determined as follows. Equation (3) is written in the form

$$t = \frac{\ell}{\eta\sqrt{2gh}} \log_e \frac{\sqrt{2gh} + \eta v}{\sqrt{2gh} - \eta v} + \log_e C$$

When $t = 0$, $v = v_o$; hence,

$$0 = \log_e \left( \frac{\sqrt{2gh} + \eta v_o}{\sqrt{2gh} - \eta v_o} \right)^{\frac{\ell}{\eta\sqrt{2gh}}} + \log_e C$$

or

$$C = \left( \frac{\sqrt{2gh} - \eta v_o}{\sqrt{2gh} + \eta v_o} \right)^{\frac{\ell}{\eta\sqrt{2gh}}}$$

and

$$t = \frac{\ell}{\eta\sqrt{2gh}} \log_e \frac{\sqrt{2gh} + \eta v}{\sqrt{2gh} - \eta v} + \frac{\ell}{\eta\sqrt{2gh}} \log_e \frac{\sqrt{2gh} - \eta v_o}{\sqrt{2gh} + \eta v_o} \tag{3a}$$

If $v = 0$ at $t = 0$, then the constant becomes equal to zero, and

$$t = \frac{\ell}{\eta\sqrt{2gh}} \log_e \frac{\sqrt{2gh} + \eta v}{\sqrt{2gh} - \eta v} \tag{4}$$

From formulas (3a) and (4), there follows that $\eta v = \sqrt{2gh}$ or $v = \sqrt{2gh}/\eta$ when $t = \infty$.

The customary formula for the velocity of the water in a pipe of constant cross section at steady flow, $v = \sqrt{2gh}/\eta$, is thus theoretically valid only at infinity—the velocity v is attained only asymptotically. Thus, theoretically, steady motion of water in pipes does not exist. Practically, of course, the formula involved is correct.

## 2. Pipe of Variable Cross Section

A straight pipe of circular cross section and total length $\ell$ is chosen as an example. Along a length $\ell_1$ the cross section is $F_o$, while along a length $\ell_2$ the pipe diverges linearly. The terminal cross section is $F_e$. It is supposed that the divergence is such that the water follows the pipe walls (hence, small divergence: maximum angle at the cone apex is $10^o$). The flow of the water occurs in the direction from $F_o$ to $F_e$ (Fig. 27).

At a given instant,

$$h = \Sigma \text{head losses} + \frac{1}{g}\int_o^{\ell} \frac{dv}{dt}\, d\ell = \Sigma \text{head losses} + \frac{\ell_1}{g}\frac{dv_o}{dt} + \frac{1}{g}\int_o^{\ell_2} \frac{dv_x}{dt}\, dx \qquad (5)$$

In this formula, $dv_x/dt$ is the rate of increase at a given instant of the mean flow velocity at a distance $\underline{x}$ from the beginning of the divergence.

$$\Sigma \text{head losses} = \frac{1}{2}\frac{v_o^2}{2g} + \lambda\frac{\chi}{F_o}\ell_1\frac{v_o^2}{2g}$$

$$+\int_o^{\ell_2} \lambda\frac{\chi_x}{F_x}\, dx \frac{v_x^2}{2g} + \frac{(v_e - v_o)^2}{2g} \sin\delta + \frac{v_e^2}{2g}$$

The members of this equation represent, respectively, the following losses:

1. Entrance loss at sharp inlet.
2. Head loss due to skin friction in the pipe section $\ell_1$; $\lambda$ is the coefficient of skin friction, taken here as constant, but actually depending on the flow velocity and the pipe cross section; $\chi$ is the wetted perimeter, that is, the pipe circumference in this case.
3. Head loss due to skin friction in the pipe section $\ell_2$; $\chi_x$, $F_x$, and $v_x$ relate to a cross section at a distance $\underline{x}$ from the beginning of the divergence.
4. Head loss in the divergence, as given by Fliegner (see Hütte, for example); $\delta$ is the apex angle of the cone.
5. Exit loss (velocity head), which is also taken as 1.1 $(v_e^2/2g)$ (see Hydromechanik des Wassers in Druckleitungen by Dr. R. Winkel).

Since $v_oF_o = v_eF_e = v_xF_x$,

$$\Sigma \text{head losses} = \frac{1}{2}\left(\frac{F_e}{F_o}\right)^2\frac{v_e^2}{2g} + \lambda\frac{\chi}{F_o}\ell_1\left(\frac{F_e}{F_o}\right)^2\frac{v_e^2}{2g}$$

$$+\int_o^{\ell_2} \lambda\frac{\chi_x}{F_x}\, dx \frac{v_e^2}{2g}\left(\frac{F_e}{F_x}\right)^2 + \frac{v_e^2}{2g}\left(\frac{F_e - F_o}{F_o}\right)^2 \sin\delta + \frac{v_e^2}{2g}$$

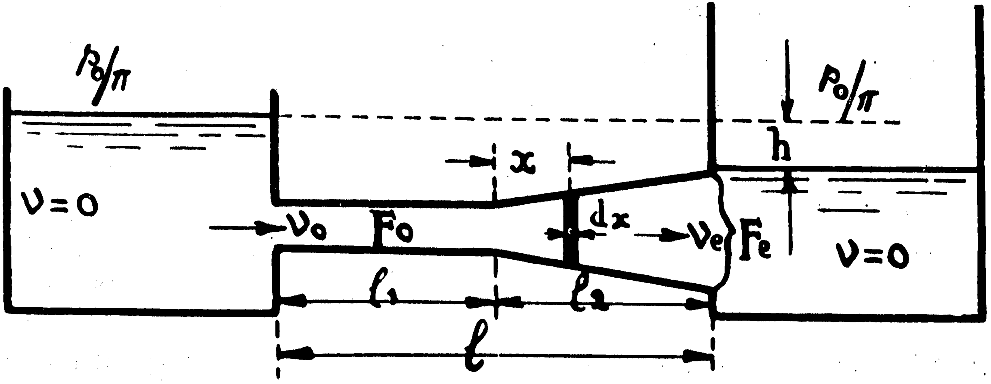

Fig.27 - Pipe of Variable Cross Section

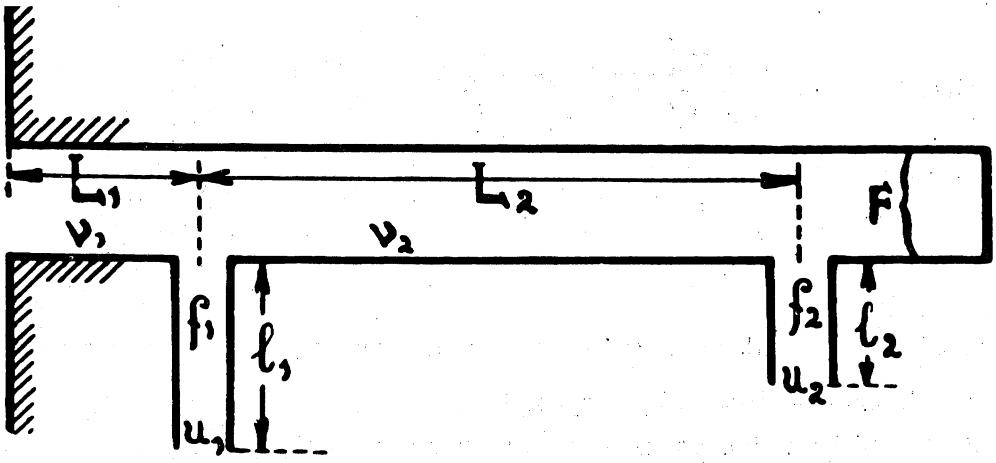

Fig.28 - Pipe with Two Laterals

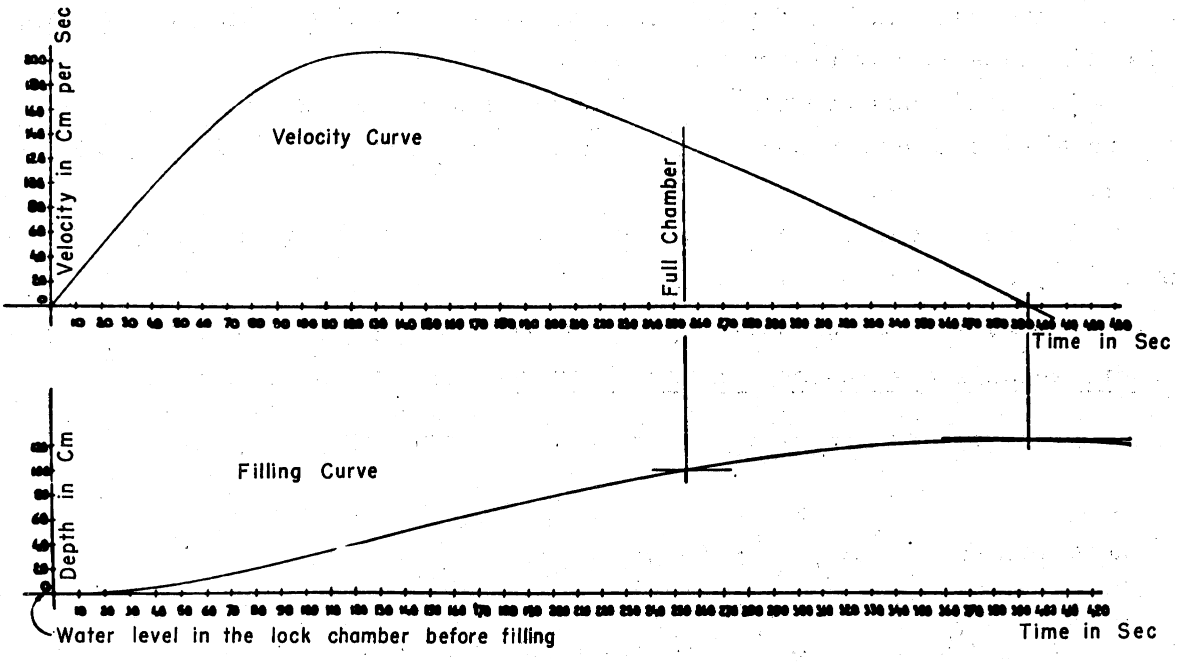

Fig.29 - Velocity and Filling Curves at Filling Through a Culvert Without Laterals

in which

$$\int_0^{\ell_2} \lambda \frac{\chi_x}{F_x}\, dx \left(\frac{F_e}{F_x}\right)^2 = \frac{\sqrt{\pi}}{2} \lambda F_e^{\,2} \int_0^{\ell_2} \frac{dx}{F_x^{\,5/2}}$$

$$= \frac{\sqrt{\pi}}{2} F_e^{\,2} \int_0^{\ell_2} \frac{dx}{\left[\sqrt{F_o} + (\sqrt{F_e} - \sqrt{F_o})\, \frac{x}{\ell_2}\right]^5}$$

$$= \frac{\sqrt{\pi}}{8} \lambda \frac{(\sqrt{F_e} + \sqrt{F_o})\,(F_e + F_o)}{F_o^{\,2}}\, \ell_2$$

In abbreviated form, the following obtains:

$$\sum \text{head losses} = \phi^2 \frac{v_e^{\,2}}{2g}$$

in which the constant $\phi^2$ had the value calculated in accordance with the above. Thus,

$$h = \phi^2 \frac{v_e^{\,2}}{2g} + \frac{\ell_1}{g} \frac{F_e}{F_o} \frac{dv_e}{dt} + \frac{1}{g} \int_0^{\ell_2} \frac{dv_x}{dt}\, dx \qquad (5a)$$

in which

$$\frac{1}{g} \int_0^{\ell_2} \frac{dv_x}{dt}\, dx = \frac{F_e}{g} \int_0^{\ell_2} \frac{dv_e}{dt} \frac{d_x}{F_x}$$

$$= \frac{F_e}{g} \frac{dv_e}{dt} \int_0^{\ell_2} \frac{dx}{\left[\sqrt{F_o} + (\sqrt{F_e} - \sqrt{F_o})\, \frac{x}{\ell_2}\right]^2}$$

$$= \frac{F_e}{g} \frac{\ell_2}{\sqrt{F_o F_e}} \frac{dv_e}{dt} = \frac{\ell_2}{g} \sqrt{\frac{F_e}{F_o}} \frac{dv_e}{dt}$$

Finally, Eq. (5a) becomes:

$$h = \phi^2 \frac{v_e^{\,2}}{2g} + \left(\frac{\ell_1}{g} \frac{F_e}{F_o} + \frac{\ell_2}{g} \sqrt{\frac{F_e}{F_o}}\right) \frac{dv_e}{dt} \qquad (6)$$

Let

$$\ell_1 \frac{F_e}{F_o} + \ell_2 \sqrt{\frac{F_e}{F_o}} = \ell_v$$

then

$$h = \phi^2 \frac{v_e^2}{2g} + \frac{\ell_v}{g} \frac{dv_e}{dt} \qquad (7)$$

The length $\ell_v$ is a special, fictitious length of the pipe, which must be introduced into the inertia term. This length will be designated as virtual pipe length.* It must be determined for each given case and taken with respect to the cross section involving the flow velocity under consideration (with respect to $F_e$ in the present case).

## B. The Effect of a Valve in the Pipe on the Motion of the Water

In practice, the flow of water in a pipe usually is controlled by means of a valve or a similar device. When the water flows through a partially open valve, the pressure drop can be represented by $\delta(v^2/2g)$ [Weisbach]. As long as the valve is closed, $v = 0$, $\delta(v^2/2g) = h$, and $\delta$ is thus infinitely large. As the valve is opened, $\delta$ rapidly decreases; it vanishes practically entirely when the valve is fully opened.

The location of the valve in the pipe is not without effect on the motion of the water. It makes a difference whether the valve occupies such a place in the pipe that the water beyond the valve again fills the entire pipe profile or whether the valve is installed at the downstream end of the pipe.

If in the first case the flow cross section within the valve is $F_s$ at a given instant, the resistance to the flow through the contracted cross section is $v^2/2g\left([(F/mF_s) - 1]^2 + 1/9\right)$ (according to Hydraulique by Flamant for example); this formula is partly empirical and partly based on consideration of impact (m is the contraction coefficient). The factor m in this formula should not be taken as constant because it increases with increasing opening of the valve and is maximal, approximately equal to unity, when the valve is fully open. Therefore, it is recommended to use empirical values of valve resistance. Weisbach has determined the magnitude of $\delta$ for various

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*If $\ell_1 = 0$ and $F_e = 2\,F_o$, then $\ell_v = \ell_2 \sqrt{2} = 1.4\,\ell_2$.

valve conditions in the case of given, very small pipe cross sections.* Knichling determined $\delta$ for a larger cross section (diameter 0.61 m) and found slightly deviating values of $\delta$. The value of $\delta$ for very large cross sections has never been determined yet.

Accordingly, assuming that the valve is installed in the pipe section having a cross section $F_o$, Eqs. (2a) and (7) become, respectively,

$$\frac{dv}{dt} = \frac{g}{\ell}\left[h - (\eta^2 + \delta)\frac{v^2}{2g}\right] \tag{8}$$

(culvert of constant cross section) and

$$\frac{dv}{dt} = \frac{g}{\ell_v}\left(h - \left[\phi^2 + \delta\left(\frac{F_e}{F_o}\right)^2 \frac{v_e^2}{2g}\right]\right) \tag{9}$$

If in the second case (valve at the downstream end of the pipe) the valve is operated with uniform speed so that the flow cross section within the valve increases proportionally with time and the valve is fully open in T sec, then $F_s = (t/T)\,F$ at time $\underline{t}$ $(t<T)$. If the size of the valve is negligible in comparison with the pipe length, then

$$\frac{dv}{dt} = \frac{g}{\ell}\left(h - \eta^2\frac{v^2}{2g} - \frac{v_s^2}{2g}\right)$$

in which $v_s$ is the exit velocity. Now,

$$v_s = \frac{F}{mF_s}\,v = \frac{T}{t}\,\frac{v}{m}$$

and, hence,

$$\frac{dv}{dt} = \frac{g}{\ell}\left(h - \eta^2\frac{v^2}{2g} - \frac{T^2}{t^2m^2}\,\frac{v^2}{2g}\right) \tag{10}$$

in which $\eta^2\,(v^2/2g)$ is the entrance loss plus the head loss due to bends and skin friction. The contraction coefficient $\underline{m}$ in this formula is taken as

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*The correctness of the assumption that $\underline{m}$ increases when the valve is opened wider can be established by writing $\delta = [(F/mF_s) - 1]^2 + 1/9$ and computing the contraction coefficient $\underline{m}$ for various values of $\delta$ and $F/F_s$.

constant, although this is not quite the case in actuality (when the valve is fully open m approaches unity). Differential Eq. (10) can be solved approximately.

In order to make it obvious that Eq. (10) is not valid for the first case (where the flow beyond the valve reoccupies the entire pipe profile), Eq. (8) is replaced by the following equation in which $\delta$ is replaced by $\left[(F/mF_s) - 1\right]^2 + 1/9$:

$$\frac{dv}{dt} = \frac{g}{\ell}\left[h - \eta^2 \frac{v^2}{2g} - \left(\frac{T}{mt} - 1\right)^2 \frac{v^2}{2g} - \frac{1}{9}\frac{v^2}{2g}\right]$$

(in which $\eta^2\ (v^2/2g)$ is the entrance loss plus the head loss due to bends and skin friction plus exit loss) or

$$\frac{dv}{dt} = \frac{g}{\ell}\left[h - (\eta^2 + \frac{10}{9})\frac{v^2}{2g} - \frac{T^2}{m^2t^2}\frac{v^2}{2g} + \frac{2T}{mt}\frac{v^2}{2g}\right] \qquad (8a)$$

# CHAPTER II

# UNSTEADY FLOW OF WATER IN PIPES WITH BRANCHES

To avoid unnecessary complication of the problem, it is assumed at first that the water inflow into the laterals is in the direction of the axes of the laterals; in other words, that the resistance coefficient of inflow into the laterals is zero (section A). Subsequently, this inflow resistance is analyzed in greater detail and is afterwards introduced into the calculations (section B).

## A. Unsteady Flow of Water in Pipes with Branches under Assumption that the Direction of Inflow into the Branches is along Their Axes

The first analysis pertains to the case of two reservoirs connected by a pipe having a closed downstream end and two laterals leading to the reservoir with the lower water level. The subsequent analysis pertains to the same case, except that more than two laterals are involved.

### 1. Unsteady Flow of Water in a Pipe Having Two Laterals of Arbitrary Lengths (Fig. 28)

Given a pipe with two laterals of lengths $\ell_1$ and $\ell_2$ and cross sections $f_1$ and $f_2$, respectively—the pipe section upstream of the first lateral, designated as the first pipe section, has a length $L_1$ and a cross section $\underline{F}$; the pipe section between the two laterals, designated as the second pipe section, has a length $L_2$ and likewise a cross section $\underline{F}$. The flow velocity at time $\underline{t}$ after the beginning of flow in the pipe is as follows: $v_o = 0$ in the two reservoirs connected by the pipe, $v_1$ in the first pipe section, $v_2$ in the second pipe section, $u_1$ in the first lateral, and $u_2$ in the second lateral. The hydrodynamic pressure head in each reservoir at time $\underline{t}$ after the beginning of flow in the pipe is constant and equal. The head (difference in level between the two reservoirs) is constant and equal to $\underline{h}$.

The sum of the loss coefficients (entrance, friction, bend, and valve) in the first pipe section is $\gamma^2$; the sum of the friction and bend coefficients in the second pipe section is $\Delta^2$; the sum of the corresponding coefficients (friction, bend, and exit) in the first and second laterals is $\Sigma_1^{\ 2}$ and $\Sigma_2^{\ 2}$, respectively.

In accordance with Bernoulli's law, the head $\underline{h}$ at a given instant is:

$$h = \gamma^2 \frac{v_1^{\,2}}{2g} + \Sigma_1^{\,2} \frac{u_1^{\,2}}{2g} + \frac{L_1}{g}\frac{dv_1}{dt} + \frac{\ell_1}{g}\frac{du_1}{dt} \qquad (11)$$

$$h = \gamma^2 \frac{v_1^{\,2}}{2g} + \frac{(v_1 - v_2)^{2*}}{2g} + \Delta^2 \frac{v_2^{\,2}}{2g} + \Sigma_2^{\,2} \frac{u_2^{\,2}}{2g} + \frac{L_1}{g}\frac{dv_1}{dt} + \frac{L_2}{g}\frac{dv_2}{dt} + \frac{\ell_2}{g}\frac{du_2}{dt} \qquad (12)$$

Equating Eqs. (11) and (12) yields

$$\Sigma_1^{\,2} \frac{u_1^{\,2}}{2g} + \frac{\ell_1}{g}\frac{du_1}{dt} = \Delta^2 \frac{v_2^{\,2}}{2g} + \frac{(v_1 - v_2)^2}{2g} + \Sigma_2^{\,2} \frac{u_2^{\,2}}{2g} + \frac{L_2}{g}\frac{dv_2}{dt} + \frac{\ell_2}{g}\frac{du_2}{dt} \qquad (13)$$

In addition, $Fv_1 = f_1u_1 + f_2u_2$; hence, if $f_1 = \alpha F$ and $f_2 = \beta F$, then

$$v_1 = \alpha u_1 + \beta u_2 \qquad (14)$$

$Fv_2 = f_2u_2$, so that

$$v_2 = \beta u_2 \qquad (15)$$

and

$$v_1 = \alpha u_1 + v_2 \qquad (16)$$

or

$$v_o - v_2 = \alpha u_1 \qquad (16')$$

Differentiation of Eq. (15) with respect to time yields:

$$\frac{dv_2}{dt} = \beta \frac{du_2}{dt} \quad \text{or} \quad \frac{du_2}{dt} = \frac{1}{\beta}\frac{dv_2}{dt}$$

so that Eq. (13) becomes

$$\left( \Sigma_1^{\,2} - \alpha^2 \right) \frac{u_1^{\,2}}{2g} + \frac{\ell_1}{g}\frac{du_1}{dt} = \frac{\ell_2 + \beta L_2}{\beta g}\frac{dv_2}{dt} + \left( \Delta^2 + \frac{\Sigma_2^{\,2}}{\beta^2} \right) \frac{v_2^{\,2}}{2g} \qquad (17)$$

The motion of the water in a pipe with two branches can be approximately determined with the aid of Eqs. (11) and (17). To this end, use is made of short consecutive periods of a constant number of seconds, t', occurring from the beginning of the flow and during which the different variables

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*Impact term.

are regarded as constant, and it is established how the flow velocities in the pipe sections vary during these periods.

First Period:

In this period the terms $(\Sigma_1^2 - \alpha^2)(u_1^2/2g)$ and $\left[\Delta^2 + (\Sigma_2^2/\beta^2)\right](v_2^2/2g)$ of Eq. (17) are neglected ($u_1$ and $v_2$ are small). Thus,

$$\frac{\ell_1}{g}\frac{du_1}{dt} = \frac{\ell_2 + \beta L_2}{\beta g}\frac{dv_2}{dt} \quad \text{or} \quad \frac{du_1}{dt} = \frac{\ell_2 + \beta L_2}{\beta \ell_1}\frac{dv_2}{dt} \tag{18}$$

Equation (16) yields

$$\frac{dv_1}{dt} = \alpha\frac{du_1}{dt} + \frac{dv_2}{dt}$$

so that the following equation can be derived with the aid of Eq. (18):

$$\frac{dv_1}{dt} = \alpha\frac{du_1}{dt} + \frac{\beta\ell_1}{\ell_2 + \beta L_2}\frac{du_1}{dt} \quad \text{or} \quad \frac{dv_1}{dt} = \frac{\alpha\ell_2 + \alpha\beta L_2 + \beta\ell_1}{\ell_2 + \beta L_2}\frac{du_1}{dt} \tag{19}$$

Combining Eqs. (19), (16), and (11) yields:

$$h = \frac{(v_1 - v_2)^2}{2g\alpha^2}\Sigma_1^2 + \frac{\ell_1}{g}\frac{\ell_2 + \beta L_2}{\alpha\ell_2 + \alpha\beta L_2 + \beta\ell_1}\frac{dv_1}{dt} + \gamma^2\frac{v_1^2}{2g} + \frac{L_1}{g}\frac{dv_1}{dt}$$

or

$$h = \frac{dv_1}{dt}\,\frac{\ell_1\ell_2 + \beta\ell_1 L_2 + \alpha\ell_2 L_1 + \alpha\beta L_1 L_2 + \beta L_1\ell_1}{g(\alpha\ell_2 + \alpha\beta L_2 + \beta\ell_1)}$$

$$+ \gamma^2\frac{v_1^2}{2g} + \frac{v_1^2}{2g}\left(1 - \frac{v_2}{v_1}\right)^2\frac{\Sigma_1^2}{\alpha^2} \tag{20}$$

In order to obtain a solvable equation, $v_2$ will be expressed now in terms of $v_1$. At the beginning of the flow in the pipe, thus as long as Eq. (18) is valid,

$$u_1 = \frac{\ell_2 + \beta L_2}{\beta\ell_1}v_2 \tag{21}$$

and according to Eq. (16):

$$v_1 = \frac{\alpha \ell_2 + \alpha\beta L_2}{\beta \ell_1} v_2 + v_2$$

or

$$v_2 = \frac{\beta \ell_1}{\alpha \ell_2 + \alpha\beta L_2 + \beta \ell_1} v_1 \tag{22}$$

Introducing this value of $v_2$ into Eq. (20) gives:

$$h = \frac{dv_1}{dt} \frac{\ell_1 \ell_2 + \beta \ell_1 L_2 + \alpha \ell_2 L_1 + \alpha\beta L_1 L_2 + \beta L_1 \ell_1}{g\ (\alpha_2 + \alpha\beta L_2 + \beta_1)}$$

$$+ \gamma^2 \frac{v_1^2}{2g} + \frac{v_1^2}{2g}\left(1 - \frac{\beta \ell_1}{\alpha \ell_2 + \alpha\beta L_2 + \beta \ell_1}\right)^2 \frac{\Sigma_1^2}{\alpha^2}$$

or

$$h = \frac{dv_1}{dt} \frac{\ell_1 \ell_2 + \beta \ell_1 L_2 + \alpha \ell_2 L_1 + \alpha\beta L_1 L_2 + \beta L_1 \ell_1}{g\ (\alpha \ell_2 + \alpha\beta L_2 + \beta \ell_1)}$$

$$+ \frac{v_1^2}{2g}\left[\gamma^2 + \left(\frac{\alpha \ell_2 + \alpha\beta L_2}{\alpha \ell_2 + \alpha\beta L_2 + \beta \ell_1}\right)^2 \frac{\Sigma_1^2}{\alpha^2}\right] \tag{23}$$

Finally, if

$$\frac{\ell_1 \ell_2 + \beta \ell_1 L_2 + \alpha \ell_2 L_1 + \alpha\beta L_1 L_2 + \beta L_1 \ell_1}{\alpha \ell_2 + \alpha\beta L_2 + \beta \ell_1} = L_v \tag{24}$$

and

$$\gamma^2 + \left(\frac{\alpha \ell_2 + \alpha\beta L_2}{\alpha \ell_2 + \alpha\beta L_2 + \beta \ell_1}\right) \frac{\Sigma_1^2}{\alpha^2} = \phi^2 \tag{25}$$

then Eq. (23) becomes:

$$h = \frac{L_v}{g} \frac{dv_1}{dt} + \phi^2 \frac{v_1^2}{2g} \tag{26}$$

or

$$\frac{dv_1}{dt} = \frac{g}{L_v}\left(h - \phi^2 \frac{v_1^2}{2g}\right)$$

Integration yields

$$t' = \frac{L_v}{\phi\sqrt{2gh}} \log_e \frac{\sqrt{2gh} + \phi v_1}{\sqrt{2gh} - \phi v_1} + 0 \tag{26a}$$

In this equation t' represents the duration of the first period and $v_1$ is the velocity of the water in the first pipe section at the end of this period. If $v_1$ is computed with the aid of Eq. (26a), then $u_1$ can be found from Eqs. (21) and (16) and $du_1/dt$ from Eqs. (19) and (26).

Second Period:

Since $u_1$ and $du_1/dt$ at the end of the first period are known, the value of $v_2$ for the second period can be solved from Eq. (17). Setting $(\Sigma_1{}^2 - \alpha^2)(u_1{}^2/2g) + (\ell_1/g)(du_1/dt) = h'$ and considering h' as constant during the second period, the following obtains:

$$h' = \frac{\ell_2 + \beta L_2}{\beta g}\frac{dv_2}{dt} + \left(\Delta^2 + \frac{\Sigma_2{}^2}{\beta^2}\right)\frac{v_2{}^2}{2g}$$

or

$$\frac{dv_2}{dt} = \frac{\beta g}{\ell_2 + \beta L_2}\left[h' - \left(\Delta^2 + \frac{\Sigma_2{}^2}{\beta^2}\right)\frac{v_2{}^2}{2g}\right]$$

$$= \frac{\beta g}{\ell_2 + \beta L_2}\left[h' - \mu^2\frac{v_2{}^2}{2g}\right] \qquad (27)$$

in which $\mu^2 = \Delta^2 + (\Sigma_2{}^2/\beta^2)$. Thus,

$$t' = \frac{\beta g}{\mu(\ell_2 + \beta L_2)\sqrt{2gh'}}\log_e\frac{\sqrt{2gh'} + \mu v_2}{\sqrt{2gh'} - \mu v_2} + 0 \qquad (27a)$$

Once $v_2$ is known, $u_2$ is likewise known from Eq. (15).

The magnitude of $v_1$ at the end of the second period can subsequently be computed from Eq. (11), for which purpose the following is written:

$$h = h'_1 + \gamma^2\frac{v_1{}^2}{2g} + \frac{L_1}{g}\frac{dv_1}{dt} \qquad (11a)$$

The term $h'_1$ in this equation is assumed as constant during the period under consideration and is known from the preceding period.

If $h - h'_1 = h''$ (h'' is considered constant during the period), the following obtains:

$$h'' = \gamma^2 \frac{v_1^2}{2g} + \frac{L_1}{g}\frac{dv_1}{dt} \tag{11b}$$

and

$$t' = \frac{L_1}{\gamma\sqrt{2gh''}} \log_e \frac{\sqrt{2gh''} + \gamma v_1}{\sqrt{2gh''} - \gamma v_1} + \frac{L_1}{\gamma\sqrt{2gh''}} \log_e \frac{\sqrt{2gh''} - \gamma v_o}{\sqrt{2gh''} + \gamma v_o} \tag{11c}$$

in which $v_o$ is the magnitude of $v_1$ at the beginning of the second period or at the end of the first period.

Third Period:

The magnitude of h' for the third period results from Eq. (16'):

$$u_1 = \frac{v_1 - v_2}{\alpha}$$

(both $v_1$ and $v_2$ are already known from the previous period)

$$\frac{dv_1}{dt} = \alpha\frac{du_1}{dt} + \frac{dv_2}{dt} \quad \text{or} \quad \frac{du_1}{dt} = \left(\frac{dv_1}{dt} - \frac{dv_2}{dt}\right)\frac{1}{\alpha}$$

(both $dv_1/dt$ and $dv_2/dt$ are already known from the previous period, so that $du_1/dt$ can be computed).

During the third period h' again is regarded as constant, and the calculation proceeds as in the preceding two periods.

## 2. Unsteady Flow of Water in a Pipe Having Two Laterals of Zero Length (Openings in the Pipe Wall)

Inserting $\ell_1 = \ell_2 = 0$ into formula (17) yields:

$$(\Sigma_1^2 - \alpha^2)\frac{u_1^2}{2g} = \frac{L_2}{g}\frac{dv_2}{dt} + \left(\Delta^2 + \frac{\Sigma_2^2}{\beta^2}\right)\frac{v_2^2}{2g} \tag{17a}$$

(the term $(\ell_1/g)$ $(du_1/dt)$ becomes zero because $du_1/dt$ always has a finite value, as seen from the formula $(dv_1/dt) = \alpha(du_1/dt) + (dv_2/dt)$ in which $dv_1/dt$ and $dv_2/dt$ are always finite).

At the beginning of the flow $u_1$ and $v_2$ are small and, therefore, $(\Sigma_1^2 - \alpha^2)\, u_1^2/2g$ and $\left[\Delta^2 + (\Sigma_2^2/\beta^2)\right]$ $(v_2^2/2g)$ may be neglected. Accordingly, formula (17a) becomes:

$$0 = \frac{L_2}{g}\frac{dv_2}{dt} \quad \text{or} \quad \frac{dv_2}{dt} = 0$$

Expressed in words, this means: at the beginning of flow in a pipe having two openings (short laterals) the water will flow almost exclusively in the first pipe section and will therefore discharge only through the first opening.

As soon as the term $(\Sigma_1^{\,2} - \alpha^2)\,(u_1^{\,2}/2g)$ attains a magnitude which is no longer negligible, the other opening will also actually discharge water.

Inserting $\ell_1 = \ell_2 = 0$, formula (11) becomes:

$$h = \gamma^2 \frac{v_1^{\,2}}{2g} + \Sigma_1^{\,2} \frac{u_1^{\,2}}{2g} + \frac{L_1}{g}\frac{dv_1}{dt} = \Sigma_1^{\,2} \frac{(v_1 - v_2)^2}{2g\alpha^2} + \gamma^2 \frac{v_1^{\,2}}{2g} + \frac{L_1}{g}\frac{dv_1}{dt} \qquad (11')$$

$$= \frac{v_1^{\,2}}{2g}\left(1 - \frac{v_2}{v_1}\right)^2 \frac{\Sigma_1^{\,2}}{\alpha^2} + \gamma^2 \frac{v_1^{\,2}}{2g} + \frac{L_1}{g}\frac{dv_1}{dt} \qquad (11'')$$

In addition, formula (24) becomes

$$L_v = L \qquad (24')$$

and formula (25) becomes

$$\phi^2 = \gamma^2 + \frac{\Sigma_1^{\,2}}{\alpha^2} \qquad (25')$$

With the aid of these formulas, the motion of the water in a pipe with openings can be approximately determined in the same way as in section A-1 of this chapter.

### 3. Unsteady Flow of Water in a Pipe Having More than Two Laterals

When a pipe with n laterals is considered, no difficulties arise if the same method is used as in the preceding sections 1 and 2 of this chapter. The flow velocities in the various pipe sections and laterals are designated, respectively, as $v_1, v_2, v_3 \ldots\ldots v_n$ and $u_1, u_2, u_3 \ldots\ldots u_n$. In case the length of all laterals is zero (openings in the pipe wall), the velocities $v_2, v_3, v_4 \ldots\ldots v_n$ and $u_2, u_3, u_4 \ldots\ldots u_n$ for the first flow period under consideration may be set equal to zero. Then $v_1$ and $u_1$ can be determined in accordance with the calculations developed in the preceding two sections.

In the case of the second period, $v_3$, $v_4 \ldots\ldots v_n$ and $u_3$, $u_4 \ldots\ldots u_n$ are set equal to zero; for the third period, $v_4 \ldots\ldots v_n$ and $u_4 \ldots\ldots u_n$ are set equal to zero, and so on.

When the laterals have negligible length (openings in the pipe wall), the first opening will discharge almost exclusively, then also the second, and afterwards the third, etc. That is, the openings will begin to discharge water in downstream sequence after one another.

For the purpose of satisfactory accuracy, the selected periods should be increasingly shorter as the number of laterals in the pipe increases.

## B. Unsteady Flow of Water in Pipes with Laterals under Consideration that the Direction of Inflow into the Laterals Is Generally Not along Their Axes

In his paper "Hydraulics of the Panama Canal," published in Transactions of the Engineering Congress of 1915, Whitehead discusses a phenomenon which occurred during filling of the Panama Canal locks, namely, that the last laterals of the culvert discharged more water than the first laterals. He explains this as follows.

The angle of inflow from the culvert into the laterals is not the same for all laterals. For each lateral the tangent of the angle between the inflow direction and the axis of the lateral is $\tan \pi = v_1/u_1$, in which $v_1$ is the mean flow velocity in the culvert section upstream of the lateral and $u_1$ is the mean flow velocity in the lateral after the flow fills its entire profile. Because of the oblique direction of the water jet, a contraction occurs near the beginning of the lateral (Fig. 8). If the lateral is so long that the water reoccupies the entire profile of the lateral beyond the contraction, then an impact loss equal to $[u_1^2/2g][(1/\cos \pi) - 1]^2$ will occur in the lateral. If the lateral is extremely short (opening in the culvert wall), the water will leave the culvert at an oblique angle. In this case, the real cross section of the water jet is smaller than the cross section f of the lateral, namely, $f \cos \pi$.

Since the velocity $v_1$ in a culvert of constant cross section decreases in the downstream direction beyond each lateral and, according to Whitehead, $u_1$ may be regarded as equal for each lateral, $\tan \pi$ will decrease correspondingly and $\cos \pi$ will increase. Accordingly, in long laterals the resistance will decrease in the downstream direction, while in short laterals the flow cross section will increase in the downstream direction. The discharge of a given culvert lateral, therefore, will increase as the lateral is located farther downstream.

It is not difficult to introduce the variable direction of inflow into the laterals of a pipe into the equations for flow varying with time. Since $\tan\pi = v_1/u_1$, the following equation obtains:

$$1 + \tan^2\pi = \frac{v_1^2 + u_1^2}{u_1^2} \quad \text{or} \quad \frac{1}{\cos\pi} = \frac{\sqrt{v_1^2 + u_1^2}}{u_1}$$

Accordingly, the impact loss in long laterals is

$$\frac{u_1^2}{2g}\left(\frac{\sqrt{v_1^2 + u_1^2}}{u_1} - 1\right)^2$$

and the coefficient $\Sigma_1^2$ in formulas (11) and (17) becomes

$$\Sigma'^2_1 = \Sigma_1^2 + \left(\frac{\sqrt{v_1^2 + u_1^2}}{u_1} - 1\right)^2$$

If the motion of the water in the pipe is divided into periods, as in the preceding analyses, whereby different variables are regarded as constant during each period, the values of $v_1$ and $u_1$ from the preceding period can be inserted in order to obtain the approximate value of $\Sigma'^2_1$ for a given period. For the first period, it is permissible to use $\Sigma'^2_1 = \Sigma_1^2$ because $v_1$ is still small then.

In the case of short laterals (openings), the coefficient $\alpha$ which occurs in formula (16) and others is variable.

$$\alpha = \frac{f\cos\pi}{F} = \frac{f}{F}\,\frac{u_1}{\sqrt{v_1^2 + u_1^2}}$$

When $v_1$ for a given period is computed and $v_2$ is known from the preceding period, $u_1$ can be calculated from formula (16) if $\alpha$ is determined from the above formula. The values of $v_1$ and $u_1$ from the preceding period can be used, while for the first period $\alpha = f/F$.

It is obvious from the above formulas that the effect of the oblique inflow increases with increasing $v_1$ with respect to $u_1$, that is, as more water flows past the lateral under consideration. Since the quantity of water flowing past the foremost branches gradually increases, the discharge of the foremost laterals gradually becomes reduced, so that the last laterals discharge more water and the first laterals discharge less water than would be obtained from the calculation in accordance with section A of this chapter.

# CHAPTER III

# APPLICATION OF THE DERIVED FORMULAS

## A. Filling the Lock Chamber Through Culverts Without Laterals

The first practical case that will be analyzed in detail is the filling of a lock chamber by means of two culverts without branches (laterals). Prior to the filling operation there exists a level difference $\underline{h}$ between the upper pool and the water in the lock chamber. When the culvert valves are opened, the water in the culverts will be set into motion, the chamber will gradually fill, and the head $\underline{h}$ will thus gradually vanish.

At time $\underline{t}$ after the beginning of flow in the culverts, the quantity of water which flowed into the lock chamber is $Q = F \int_0^t v\,dt$, in which $\underline{F}$ is the combined cross section of the two culverts. The corresponding thickness of the water layer in the chamber is then $s = (F/O) \int_0^t v\,dt$, in which $\underline{O}$ is the surface area of the lock chamber. Hence, at time $\underline{t}$ the head has become $h' = h - s$.

In accordance with formula (8), the differential equation of the flow in the culverts is then

$$\frac{dv}{dt} = \frac{g}{\ell}\left[h - (\eta^2 + \delta)\frac{v^2}{2g} - \frac{F}{O}\int_0^t v\,dt\right] \tag{29}$$

This equation can be solved approximately. For this purpose, the filling time is considered as divided into periods of a given number of seconds. During each period, $\delta$ and $h - (F/O) \int_0^t v\,dt = h'$ are regarded as constant, so that these magnitudes vary stepwise.

At the beginning of filling $(F/O) \int_0^t v\,dt = 0$ and, therefore, $h' = h$; Eq. (29) for the first period thus becomes:

$$\frac{dv}{dt} = \frac{g}{\ell}\left[h - (\eta^2 + \delta)\frac{v^2}{2g}\right] \tag{29a}$$

The magnitude of $\delta$ is taken as its value at the end of the first period (at the beginning $\delta = \infty$). The flow velocity $v_1$ at the end of the first period can be determined from Eq. (29a).

The magnitude of $v_1$ for the second period is the initial velocity, while h' is known because the thickness s of the water layer flowing into the chamber at the beginning of this period can be calculated. The magnitude of the flow velocity during the second period increases from $v_1$ to $v_2$.

The velocity $v_2$ for the third period is the initial velocity and is thus known. Thus, a new solvable differential equation obtains for each period, so that the variation of the flow velocity in the culverts can be traced. The accuracy of the calculation depends to a large extent on the chosen duration of the period and, for the rest, on the precision with which the resistance coefficients are determined experimentally.

The solution of the differential equations presents no difficulties. The following six different categories are involved (for the sake of simplicity, use is made of the substitution terms $h - (F/O) \int_0^t v\,dt = h'$ and $\eta^2 + \delta = \eta_1^2$):

(a) $h' - \eta_1^2 (v^2/2g) > 0$ (flow velocity increases). The solution is similar to that of Eq. (2b).

(b) $h' - \eta_1^2 (v^2/2g) = 0$ (the flow velocity during the period is considered constant); $(dv/dt) = 0$, or v = constant.

(c) $h' - \eta_1^2 (v^2/2g) < 0$; h' is positive (flow velocity decreases; the chamber is not yet filled to the level of the upper pool).

$$\frac{dv}{dt} = \frac{g}{\ell}\left(h' - \eta_1^2 \frac{v^2}{2g}\right)$$

or

$$-\,dt = \frac{dv}{\frac{g}{\ell}\left(-\,h' + \eta_1^2 \frac{v^2}{2g}\right)}$$

Hence,

$$t' = \frac{\ell}{\eta_1 \sqrt{2gh'}} \log_e \frac{\eta_1 v + \sqrt{2gh'}}{\eta_1 v - \sqrt{2gh'}}$$

$$+ \frac{\ell}{\eta_1 \sqrt{2gh'}} \log_e \frac{\eta_1 v_o - \sqrt{2gh'}}{\eta_1 v_o + \sqrt{2gh'}} \qquad (30)$$

(d) $h' - \eta_1^2 (v^2/2g) < 0$; h' = 0 (flow velocity decreases, the chamber is filled to the level of the upper pool).

$$\frac{dv}{dt} = \frac{g}{\ell}\left(-\eta_1^{\,2}\,\frac{v^2}{2g}\right)$$

Hence,

$$t' = \frac{2\ell}{\eta_1}\left(\frac{1}{v} - \frac{1}{v_o}\right); \quad v = \frac{2\ell v_o}{v_o\eta_1 t + 2\ell} \tag{31}$$

(e) $h' - \eta_1^{\,2}\,(v^2/2g) < 0$; $h'$ is negative (water continues to flow into the chamber after it is filled to the level of the upper pool).

$$\frac{dv}{dt} = \frac{g}{\ell}\left(-h' - \eta_1^{\,2}\,\frac{v^2}{2g}\right)$$

Hence,

$$t' = \frac{2\ell}{\eta_1\sqrt{2gh'}}\left(\text{arc tan}\,\frac{\eta_1 v_o}{\sqrt{2gh'}} - \text{arc tan}\,\frac{\eta_1 v}{\sqrt{2gh'}}\right) \tag{32}$$

(f) $v = 0$. After $\underline{v}$ has become equal to zero, the water in the culverts will tend to flow back because the water level in the chamber is then higher than the level of the upper pool. The equations given under (a) to (f) are again valid for the motion of the water in the culverts.

Due to the inertia of the water in the culverts, the water level in the lock chamber will drop below the level of the upper pool and after that the direction of flow in the culverts will change once again. Thus, the water in the culverts acquires a fluctuating motion and, theoretically, the chamber remains filled to the level of the upper pool only at infinity. Because of the resistances to which the water in the culverts is subjected, the amplitude of the fluctuations will diminish, so that in actuality the equilibrium of the water in the lock chamber will be established quickly.

If the velocity of the water in the culverts after each period is plotted on coordinates of which the abscissa is time and the ordinate is the flow velocity, then the smooth curve connecting the points involved constitutes the velocity curve of the water in the culverts. When the depth $\underline{s}$ of the additional water layer occurring in the chamber after each period is plotted on coordinates of which the abscissa is time and the ordinate is the depth, the smooth curve connecting the points involved represents the filling curve of the lock chamber.

Numerical Example. Given a lock with a chamber having a surface area of 20,000 sq m: filling occurs by means of two culverts, each with two bends having a mean radius of 4.20 m and a developed length of 250 m. The culvert cross section is constant, rectangular (4 m by 6.25 m), and has an area of 25 sq m. The inlets of the culverts are rounded on all sides. The valves are slide valves installed in the culvert at at arbitrary point and are opened simultaneously. The opening time of the valves is T = 100 sec. The lift is 1 m.

The motion of the water in the culverts is given by formula (29) under consideration of the aspects previously discussed in this chapter.

The factor $\eta^2$ is to be determined from the resistances (losses) to which the water in the culverts is subjected. These are: (a) entrance loss; (b) loss due to skin friction of the water along the culvert walls; (c) loss in the bends; (d) exit loss.

With reference to (a), the entrance head loss is taken as $w_1 = 0.1 (v^2/2g)$.

With reference to (b), the head loss due to skin friction is $w_2 = (\lambda) (\chi/F) (\ell) (v^2/2g)$ [page 71] in which $\lambda = 0.014/4$* (considered constant;** see losses listed on page 71).

$\chi = 2 (4) + 2 (6.25) = 20.50$ m.

$F = 2 (25)$ sq m.

$\ell = 250$ m.

Hence, $w_2 = (0.014/4) (20.50/25) (250) (v^2/2g) = 0.72 (v^2/2g)$.

With reference to (c), in accordance with Weisbach's empirical formulas,*** the head loss in the bends is

$$w_3 = 2 (0.355) \frac{v^2}{2g} = 0.71 \frac{v^2}{2g}$$

---

*In the locks of the Panama Canal, the measured value was 0.013/4.

**If it is known how λ varies with the velocity, it is necessary to use the variable λ. As long as the valve is still in the process of motion, however, the valve resistance predominates to such an extent that the effect of λ at the beginning of the filling operation is very small.

***See Hütte I, for example.

With reference to (d), the exit head loss is

$$w_4 = 1.1 \frac{v^2}{2g}$$ [*]

Accordingly, $\eta^2 = (w_1 + w_2 + w_3 + w_4)/(v^2/2g) = (0.1 + 0.72 + 0.71 + 1.1) = 2.63$.

The magnitude of the factor $\delta$ has been empirically determined by Weisbach. The following values of $\delta$ are given in Hydraulik by Forchheimer:

$\delta$ = 193 when the valve frees one-tenth of the culvert cross section, that is, after t = 10 sec.
$\delta$ = 44.5 after t = 20 sec.
$\delta$ = 17.8 after t = 30 sec.
$\delta$ = 8.12 after t = 40 sec.
$\delta$ = 4.02 after t = 50 sec.
$\delta$ = 2.08 after t = 60 sec.
$\delta$ = 0.95 after t = 70 sec.
$\delta$ = 0.39 after t = 80 sec.
$\delta$ = 0.09 after t = 90 sec.
$\delta$ = 0.00 after t = 100 sec (valve fully open).

After the valve is fully open, the magnitude of $\delta$ remains constant at $\delta = 0.00$.

The corresponding values of $\eta_1$ are as follows:

$\eta_1^2$ = 193 + 2.63 = 195.63 after t = 10 sec; $\eta_1$ = 14.
$\eta_1^2$ = 44.5 + 2.63 = 47.13 after t = 20 sec; $\eta_1$ = 6.86.
$\eta_1^2$ = 17.8 + 2.63 = 20.43 after t = 30 sec; $\eta_1$ = 4.51.
$\eta_1^2$ = 8.12 + 2.63 = 10.75 after t = 40 sec; $\eta_1$ = 3.28.
$\eta_1^2$ = 4.02 + 2.63 = 6.65 after t = 50 sec; $\eta_1$ = 2.58.
$\eta_1^2$ = 2.08 + 2.63 = 4.71 after t = 60 sec; $\eta_1$ = 2.17.
$\eta_1^2$ = 0.95 + 2.63 = 3.58 after t = 70 sec; $\eta_1$ = 1.89.
$\eta_1^2$ = 0.39 + 2.63 = 3.02 after t = 80 sec; $\eta_1$ = 1.74.
$\eta_1^2$ = 0.09 + 2.63 = 2.72 after t = 90 sec; $\eta_1$ = 1.65.
$\eta_1^2$ = 0.00 + 2.63 = 2.63 after t = 100 sec; $\eta_1$ = 1.62.

After the valve is fully open, $\eta_1$ remains constant and equal to 1.62.

---

[*] The assumed values of $w_1$ and $w_4$ are excessive.

It is possible now to evaluate the variation in flow velocity during the consecutive periods of 10 sec each, under consideration that the head and the coefficient of valve resistance remain constant during these periods.

First Period of 10 Sec:

$$\eta_1 = 14; \; h' = 1.00 \text{ m}; \; \sqrt{2gh'} = 4.43$$

$$10 = \frac{250}{14\,(4.43)} \log_e \frac{4.43 + 14v}{4.43 - 14v} + 0$$

Hence, v = 0.268 m per sec.

The depth s of the water layer occurring in the chamber during the first period is

$$s = \frac{F}{O} v\,(10) = \frac{1}{40}\,(0.268) = 0.007 \text{ m}$$

Second Period of 10 Sec:

$$\eta_1 = 6.86; \; h' = 0.993 \text{ m}; \; \sqrt{2gh'} = 4.42$$

$$10 = \frac{250}{(6.86)\,(4.42)} \left[ \log_e \frac{4.42 + 6.86\,v}{4.42 - 6.86\,v} + \log_e \frac{4.42 - 6.86\,(0.268)}{4.42 + 6.86\,(0.268)} \right]$$

Hence, v = 0.506 m per sec; s = 0.007 + (1/40) 0.506 = 0.019 m.

Third Period of 10 Sec:

$$\eta_1 = 4.51; \; h' = 1.00 - 0.019 = 0.981; \; \sqrt{2gh'} = 4.39$$

$$10 = \frac{250}{4.51\,(4.39)} \left[ \log_e \frac{4.39 + 4.51\,v}{4.39 - 4.51\,v} + \log_e \frac{4.39 - 4.51\,(0.506)}{4.39 + 4.51\,(0.506)} \right]$$

Hence, v = 0.732 m per sec; s = 0.019 + (1/40) 7.32 = 0.037 m.

The subsequent values are obtained in the same manner. The resulting velocity curve I and filling curve II are plotted in Fig. 29.

## B. Filling the Lock Chamber Through Culverts with Laterals

The second practical case which will be discussed in the following is the filling of a lock chamber by means of culverts with laterals. In this case, the formulas developed in Chapter II-A (Part II) remain valid, except that the head h is reduced by the thickness s of the water layer occurring in the chamber at the beginning of the period under consideration. Thus, the term h'' occurring on page 81, for example, becomes equal to $h - h'_1 - s$.

Numerical Example for a Culvert with Two Laterals. Given a lock with a chamber having an area of 10,000 sq m: filling occurs by means of a straight culvert 250 m long. The culvert cross section is constant, rectangular (4 m by 6.25 m), and has an area of 25 sq m. A lateral of negligible length and having a cross section of 12.50 sq m is located at 25 m and at 250 m from the upstream end of the culvert. The downstream end of the culvert is closed. The valve is a slide valve installed in the first culvert section. The opening time of the valve is T = 100 sec; the lift is 1 m.

Analysis is made of the flow during successive periods of 10 sec each during which the different variables such as the head and $\delta$ are regarded as constant. It is assumed that the direction of inflow into the laterals always is normal to the culvert axis.

First Period of 10 Sec:

Determination of $v_2$ and $u_2$: it is assumed that during this period $v_2$ (and thus also $u_2$) = 0.

Determination of $v_1$ and $u_1$: in accordance with Eq. (11''),

$$h = \frac{v_1^2}{2g}\left[\gamma^2 + \left(1 - \frac{v_2}{v_1}\right)^2 \frac{\Sigma_1^2}{\alpha^2}\right] + \frac{L_1}{g}\frac{dv_1}{dt}$$

In this equation, $\gamma^2$ is the sum of the coefficients of the following head losses: entrance, skin friction, and valve. Accordingly,

$$\gamma^2 = 0.1 + \frac{0.014}{4}\,\frac{20.50}{25}\,25 + 193^{*} = 0.1 + 0.075 + 193 = 193.175$$

$$\alpha = \frac{f}{F} = 0.5; \quad \alpha^2 = 0.25; \quad \Sigma_1^2 = 1.1$$

If $\gamma^2 + (1 - v_2/v_1)^2\,(\Sigma_1^2/\alpha^2) = \phi_1^2$, then, for the first period,

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[*] See the coefficients obtained by Weisbach.

$$\phi_1^2 = 193.175 + 1\left(\frac{1.1}{0.25}\right) = 197.6;\ \phi_1 = 14.06;\ \sqrt{2gh} = 4.43$$

$$10 = \frac{25}{14.06\ (4.43)} \log_e \frac{4.43 + 14.06\ v_1}{4.43 - 14.06\ v_1} + 0$$

$$v_1 = \frac{4.43}{14.06} = 0.315 \text{ m per sec};\ u_1 = \frac{v_1}{\alpha} = 2\ (0.315) = 0.630 \text{ m per sec}$$

Second Period of 10 Sec:

Determination of $v_2$ and $u_2$: if $(\Sigma_1^2 - \alpha^2)\ (u_1^2/2g)$, which is the first member of formula (17a), is set equal to h', then $h' = (1.1 - 0.25)\ (0.630)^2/2g$ and $\sqrt{2gh'} = 0.58$. In addition, if the term $\Delta^2 + (\Sigma_2^2/\beta^2)$ of this formula is set equal to $\mu^2$, then

$$\mu = \sqrt{\frac{0.014}{4}\ \frac{20.50}{25}\ 225 + \frac{1.1}{0.25}} = 2.245$$

Thus,

$$10 = \frac{225}{2.245\ (0.58)} \log_e \frac{0.58 + 2.245\ v_2}{0.58 - 2.245\ v_2} + 0$$

$v_2 = 0.0075$ m per sec; $u_2 = 2\ v_2 = 0.0150$ m per sec.

Determination of $v_1$ and $u_1$:

$$\phi_1^2 = 0.1 + 0.0075 + 44.5 + \left(1 - \frac{0.0075}{0.315}\right)^2 = 48.85$$

$$\phi_1 = 6.99$$

The quantity of water flowing into the chamber during the first 10 sec is (10) (0.315) (25) = 78.8 cu m, so that the corresponding depth is s = 0.0079 m.

$$h_{10}^{*} = 1 - s_{10} = 0.992 \text{ m};\ \sqrt{2gh_{10}} = 4.42$$

---

*Reads: h after 10 sec.

$$10 = \frac{25}{(6.99)\ (4.42)} \left[ \log_e \frac{4.42 + 6.99\ v_1}{4.42 - 6.99\ v_1} + \log_e \frac{4.42 - 6.99\ (0.315)}{4.42 + 6.99\ (0.315)} \right]$$

$v_1 = 0.632$ m per sec; $u_1 = (v_1 - v_2)/\alpha = (0.632 - 0.0075)/(1/2) = 1.25$ m per sec [see Eqs. (14) and (16)].

Third Period of 10 Sec:

Determination of $v_2$ and $u_2$:

$$\mu = 2.245;\ h' = (1.1 - 0.25)\ \frac{(1.25)^2}{2g}\ ;\ \sqrt{2gh'} = 1.15$$

$$10 = \frac{225}{2.245\ (1.15)} \left[ \log_e \frac{1.15 + 2.245\ v_2}{1.15 - 2.245\ v_2} + \log_e \frac{1.15 - 2.245\ (0.0075)}{1.15 + 2.245\ (0.0075)} \right]$$

$v_2 = 0.0367$ m per sec; $u_2 = 2\ v_2 = 0.0734$ m per sec.

Determination of $v_1$ and $u_1$:

$$\phi_1^{\ 2} = 0.1 + 0.0075 + 17.8 + \left(1 - \frac{0.0367}{0.632}\right)^2 \frac{1.1}{0.25} = 21.88$$

$$\phi_1 = 4.67$$

$$s = 0.0079 + \frac{1}{40}\ 0.632 = 0.0237$$

$$h' = 0.9763;\ \sqrt{2gh'} = 4.38$$

$v_1 = (4.38/4.67) = 0.938$ m per sec; $u_1 = (v_1 - v_2)/(1/2) = 2\ (0.938 - 0.0367) = 1.802$ m per sec.

The subsequent values are determined in the same manner. The resulting velocity curves and filling curve are shown in Fig. 30 (I and II, respectively). The middle velocity curve pertains to the flow in the first culvert section.

If another lateral were present between the two laterals of this numerical example (culvert with three laterals), the velocity and filling curves could be obtained in a similar way. Figure 31 is a partial plot of such velocity and filling curves.

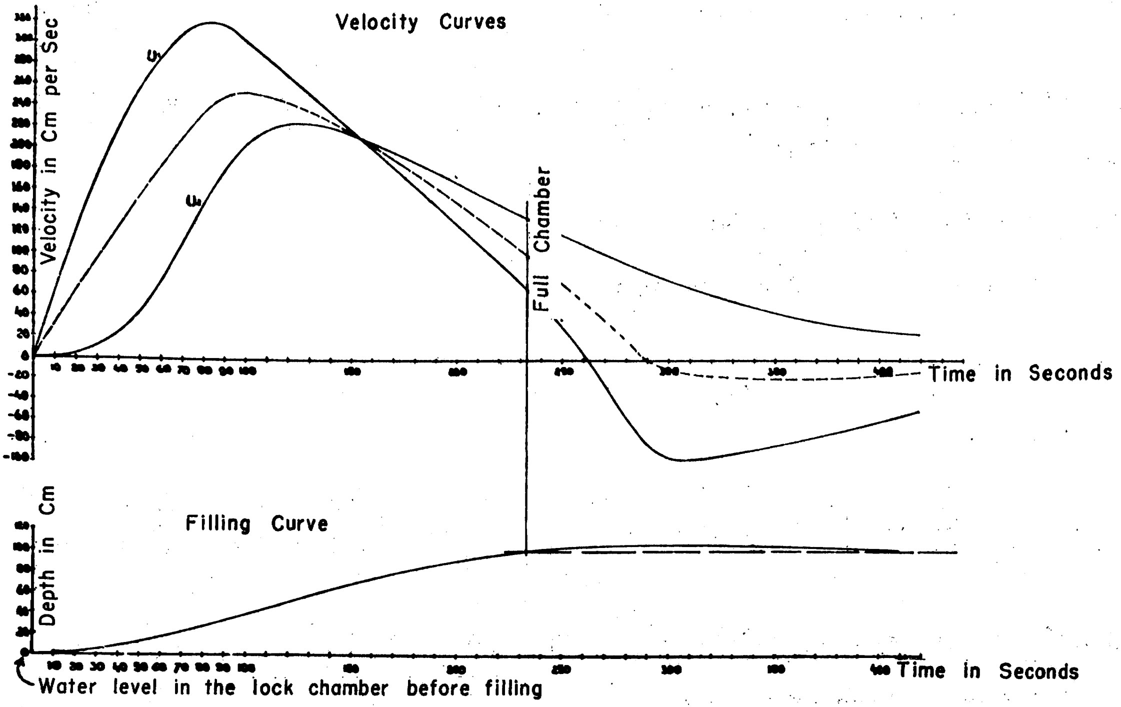
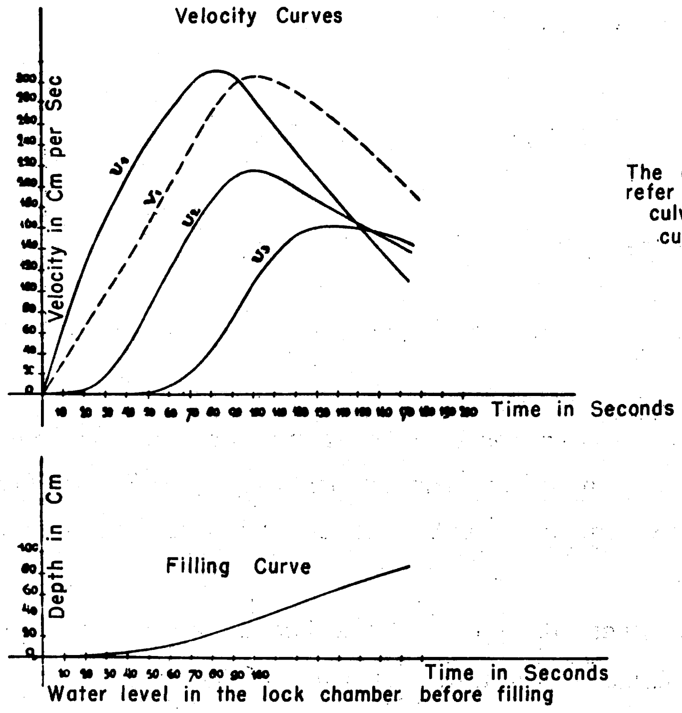


Fig. 30 – Velocity and Filling Curves at Filling Through a Culvert with Two Laterals



The dashed curves in Figs. 30 and 31 refer to the flow velocity in the first culvert section, the other velocity curves refer to the flow velocity in the laterals.

Fig. 31 – Velocity and Filling Curves at Filling Through a Culvert with Three Laterals

## C. Relation Between Velocity Curves and Filling Curves

The quantity of water flowing into the lock chamber in a time dt is

$$dq = -O\,dz$$

in which O is the surface area of the lock chamber and $-dz$ is the rise in water level in the chamber during dt ($z$ is taken positive downwards). In addition,

$$dq = F\,v\,dt$$

in which F is the combined cross section of the culverts and $v$ is the flow velocity in the culverts. Thus,

$$-O\,dz = F\,v\,dt \quad \text{or} \quad -\frac{dz}{dt} = \frac{F}{O}\,v \qquad (33)^{*}$$

If the filling curve is given, the value of $-dz/dt$ at each instant can be found because $-dz/dt$ is the tangent of the angle formed between the abscissa and the tangent to the filling curve at this instant. Thus, if the filling curve for an existing lock chamber is experimentally determined, the velocity curve for the flow in the culverts can be derived from the filling curve. (In the case of culverts with laterals, this procedure yields the velocity curve for the flow in the first culvert section).

At the same time, formula (33) indicates that the filling curve is an integral curve of the velocity curve.

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[*] Equation (33) yields $d^2z/dt^2 = -(F/O)\,(dv/dt)$ or $dv/dt = -(O/F)\,(d^2z/dt^2)$. Substitution into Eq. (29) and simplification, under consideration that $v = -(O/F)\,(dz/dt)$ and $h - (F/O)\int_0^t v\,dt = z$, yield

$$\frac{d^2z}{dt^2} = -\frac{F}{O}\frac{g}{\ell}\,z + (\eta^2 + \delta)\,\frac{O}{2F\ell}\left(\frac{dz}{dt}\right)^2 \qquad (34)$$

This formula can be regarded as known (compare formula 199a, page 349 of Hydraulik by Forchheimer). When $dz/dt$ is determined from this formula (approximately, because $\delta$ is variable; for the rest, compare Forchheimer), $v$ is obtained and in this way the velocity curve can be plotted.

# CHAPTER IV

# THE PRACTICAL NECESSITY OF KNOWING THE FLOW IN THE CULVERTS DURING FILLING OF THE LOCK CHAMBER

## A. Introduction

As already stated in the beginning, the design of a lock depends to a great extent on the choice of the filling system for the lock chamber. This choice should be made in accordance with the following objectives:

(a) The construction of the lock must be cheap, hence simple.

(b) The filling period must be as short as possible.

(c) The forces acting on the ships in the chamber, caused by the inflowing or outflowing water, must be small, in other words, the ships in the chamber should remain at rest and safe during the filling operation.

The most common filling systems are:

(1) Filling through the gates (either valves in the gates or the gates proper regarded as valves).

(2) Filling through short culverts installed in the lockheads only (loop culverts).

(3) Filling through culverts with laterals distributed along the entire length of the lock chamber (in abbreviated form, culverts with laterals).

In the case of filling through the gates the direction of the inflow is generally along the lock axis, while in the case of filling through culverts this direction is generally normal to the lock axis.

In order to facilitate determining the satisfactory filling system for a given case, on the basis of the requirements presented under (a) and (b), the aspects involved will be discussed in the following with respect to filling time and the forces exerted on the ships in the lock chamber. A discussion of the factor mentioned in (a) is outside of the scope of this work.

## B. Filling Period

### 1. Filling Through the Gates

The familiar formula for the filling period

$$V = \frac{2\,O\,h}{mF_0\sqrt{2gh}} \tag{35}$$

is valid only for filling through valves in the gates and, moreover, only for instantaneous valve opening. This formula is based on the fact that the velocity of the water flowing into the lock chamber corresponds at any time to the available head; hence, it involves neglecting the mass of water in the passage connecting the upper pool to the lock chamber.

If the valve is opened slowly (valve opening time T), the size of the inlet opening is not constant during operation of the valve. If $F_t$ denotes this inlet area, the quantity of water flowing into the chamber during a time interval dt at time t after the beginning of valve operation ($t < T$) is:

$$dQ = mF_t \sqrt{2gz}\, dt$$

If the valve is opened with uniform speed and the corresponding inlet opening increases linearly with time during the valve operation, then $F_t = t/T\ F_o$ ($F_o$ is the area of the opening after the valve is fully open). Thus,

$$dQ = m \frac{t}{T} F_o \sqrt{2gz}\, dt$$

In addition, $dQ = -O\,dz$ (the head z is taken positive downwards). Accordingly,

$$m \frac{t}{T} F_o \sqrt{2gz}\, dt = -O\,dz \quad \text{or} \quad t\,dt = -\frac{OT}{mF_o\sqrt{2g}} \frac{dz}{\sqrt{z}}$$

Assuming that h' is the head which is still available at time T, the following obtains:

$$\int_0^T t\,dt = -\frac{OT}{mF_o\sqrt{2g}} \int_{h'}^{h} \frac{dz}{\sqrt{z}}$$

or

$$\frac{1}{2} T^2 = \frac{2\,OT}{mF_o\sqrt{2g}} \left(\sqrt{h} - \sqrt{h'}\right)$$

Hence

$$T = \frac{4O\left(\sqrt{h} - \sqrt{h'}\right)}{mF_o\sqrt{2g}}$$

The head h' vanishes in a time $V' = 2\,0\sqrt{h'}/mF_o\sqrt{2g}$. Accordingly, the total filling period becomes

$$V'' = T + \frac{2\,0\sqrt{h'}}{mF_o\sqrt{2g}} = \frac{1}{2}\,T + \frac{2\,0\sqrt{h}}{mF_o\sqrt{2g}} = \frac{1}{2}\,T + \frac{2\,0\,h}{mF_o\sqrt{2gh}} \tag{36}$$

or in words, in the case of uniform motion of the valve and linear increase of the inlet opening, the filling period is equal to the sum of half the valve-operation time and the filling time at instantaneous valve opening.*

It should be noted that in the preceding calculation m is assumed to be constant during opening of the valve, while in actuality this is not quite the case.

## 2. Filling Through Culverts Without Laterals (Loop Culverts)

The filling-time formulas (35) and (36) may be used to determine the time required for filling a lock chamber through loop culverts only if the virtual length, pertaining to the exit cross section, is negligible (see page 74). If this is not negligible, the notion of a definite filling time is no longer applicable because the water level in the chamber will in reality proceed to fluctuate with respect to the level of the upper pool for some time (see page 89).

The best method for determining the filling time in the case of filling through long loop culverts is to plot the corresponding filling and velocity curves. Nevertheless, it is permissible to apply formulas (35) and (36) [m is the discharge coefficient] as an approximation, although they are entirely arbitrary and are not based on theoretical considerations.

If the culvert is of such type that the mass of water in it is negligible, then the following two different cases must be considered: the valve is installed at the downstream end of the culvert or the valve occupies such a position in the culvert that the flow refills the entire culvert profile after passing through the valve (see page 74).

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*See also the articles by F. Lüdecke and by Dr. R. Winkel, published in Zentralblatt der Bauverwaltung of 1917 and 1925, respectively.

Both formulas (35) and (36) are applicable to the first case, while only formula (35) is applicable to the second case. If in the second case the valve is opened slowly, then, in order to determine the portion of the filling time, $T_s$, corresponding to the period during which the valve is in motion, it is necessary to evaluate m for successive periods of several seconds each by utilizing Weisbach's values of $\delta$ (page 91) and to plot the velocity and filling curves. After the valve is fully open, the discharge coefficient m remains constant, so that the usual filling-time formula can be used to determine the remaining portion of the filling time, $T_r$. The total filling time is, therefore, $T = T_s + T_r$.

It should be noted that the second case is generally prevalent in practice. The discharge coefficient must be determined in all cases where the virtual length, pertaining to the exit cross section, is negligible.

### 3. Filling Through Culverts with Laterals

The velocity curves and filling curves can be utilized to determine the filling time in cases involving culverts with laterals. Formulas (35) and (36) may be applied as an approximation, although they are entirely arbitrary and are not based on theoretical considerations.*

## C. The Forces Exerted on the Ships in the Lock Chamber During Filling Operation

The forces exerted on the ships in the lock chamber during establishment of the water level in the lock chamber can be classified as: (1) longitudinal forces, and (2) transverse forces.

The designations indicate that the first category acts in the direction of the lock axis, while the second category acts in the direction normal to the lock axis. The actual force acting on a ship at a given instant is the resultant of the longitudinal and transverse forces.

### 1. Analysis of the Longitudinal Forces

#### a. Filling Through the Gates

Already several years before the European War, the heads of the Berlin-Charlottenburg Hydraulic Laboratory realized the urgent need to

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*Whitehead lists several values of the discharge coefficient m in his book (mentioned previously). The value of m, measured at the existing large lock at IJmuiden, was 0.72 [from formula (36)]. It should be noted that the culvert inlets were sharp edged, and that baffles were installed in front of the inlets, which contributed to the resistance.

investigate the forces exerted on the ships in the lock chamber during lockage. Since there the investigations involved primarily filling through the gates, whereby preponderantly longitudinal forces occur, only these forces are analyzed in detail.

In connection with the experiments conducted in this laboratory, Dr. H. Blasius and Dr. H. Krey published the analyses of the occurrence and magnitude of the longitudinal forces in Glaser's Annalen für Gewerbe und Bauwesen of 1912 and in the Zentralblatt der Bauverwaltung of June 1914, respectively. These publications are based on results of filling and emptying operations during which the inflow and outflow velocities corresponded every time to the still available head; in other words, the mass of water in the conduit connecting the upper pool to the lock chamber was neglected (hence, filling through short culverts or through valves in the gates).*

According to the publications, the principal longitudinal force is the force which arises when the ship is subjected to the impact of the wave occurring due to the inflow of the water into the lock chamber and propagating in the longitudinal direction. If during filling operation, for example, the valve is instantaneously fully opened and a quantity of water $\underline{Q}$ flows into the chamber in the first second, the longitudinal velocity of the water in the chamber must become $u = Q/bd$ and the admitted water will spread over the lock chamber. In this formula $\underline{b}$ and $\underline{d}$ are, respectively, the width and depth of flow in the lock chamber.

The initial velocity of the water in the chamber is zero; the inflow must produce the velocity $\underline{u}$. Thereby a rise in level $\eta$ must occur and must be of such magnitude that the water at rest would acquire a velocity $\underline{u}$. A simple calculation indicates that $\eta = (Q/b)\sqrt{1/gd}$ and that the velocity of the propagating wave is $c = \sqrt{gd}$ (g is the acceleration of gravity).

The wave advances towards the lower lockhead and strikes the lower gates where the velocity $\underline{u}$ is reduced to zero. Hereby there occurs a rise in level which again can be computed with the aid of the above formulas. This rise in level is propagated in the direction of the upper lockhead, reducing

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*In these publications the assumptions are that the inflow is uniform and parallel to the lock axis and that the presence of the ship in the lock chamber does not disturb the condition described.

to zero the velocity of the water in the chamber everywhere along its path. Having reached the upper gates, the water in the chamber again acquires velocity and, consequently, a new wave is being propagated in the opposite direction.

The formula $\eta = (Q/b)\sqrt{1/gd}$ shows that the greater the depth of the water in the chamber, the smaller is the wave height. At the beginning of the filling operation, however, $\eta$ is largest not only because of this factor but also because $Q$ is largest then.

When the wave strikes a ship having a submerged beam area $D$, the force exerted on the ship is

$$K = \eta D$$

However, the rise in level is further increased by the recoil of the wave from the ship.*

From the preceding it follows that the lock chamber is filled in successive layers and that the ship is subjected to a force acting alternately in the one and the other direction.**

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*In Die Bautechnik of August 3, 1923, Dr. R. Winkel proved that this recoil has a great effect on the magnitude of $K$ and that the effect depends on the ratio of the submerged beam area of the ship to the wetted cross section of the chamber. The author notes that, when the ship obstructs the entire chamber, the entire wave is reflected from the ship, so that the resulting force is $K = 2\eta D$. When the ship is merely a raft, the force is $K = \eta D$. In the case of an arbitrary ship, the magnitude of the force ranges between $2\eta D$ and $\eta D$ or, in general,

$$K = k\eta D \quad \text{where} \quad 2 \geq k \geq 1$$

With regard to the evaluation of $k$, reference is made to the publication. The result of the evaluation is:

$$K = \sqrt{\frac{2F}{f} + \frac{1}{4}\left(\frac{F}{f}\right)^2} - \frac{F}{2f}$$

in which $F$ is the wetted cross section of the chamber and $f = F - D$. However, there are still secondary effects which change the magnitude of k. Because of the arriving wave, the fore part of the ship becomes lifted and the aft part becomes submerged deeper. This causes the wave near the bow to become flattened, while a rise in level occurs near the stern of the ship. Therefore, the force acting on the ship becomes smaller than $K$ (further information is available in the publication cited).

**The numerical examples presented previously did not deal with the stepwise filling of the lock chamber because the propagation of the waves proceeded so rapidly that its effect on the flow velocity in the culverts was small ($c = \sqrt{gd}$).

In contrast, if the valve is opened slowly, the discharge into the lock chamber increases slowly to a maximum magnitude. During a time interval dt the wave covers a distance c dt, so that a hydraulic gradient $J = d\eta / c\,dt$ occurs in the chamber. Since $d\eta = (d\,Q/b)\sqrt{1/gd}$ and $d\,Q = d\,b\,du$, then

$$J\,c\ \ dt = du\,\frac{b\,d}{b}\sqrt{\frac{1}{gd}} = du\,\frac{d}{c}$$

or

$$J = \frac{du}{dt}\,\frac{d}{c^2} = \frac{1}{g}\,\frac{du}{dt} \tag{37}$$

This formula shows that the hydraulic gradient is proportional to the rate of change of the flow velocity in the lock chamber and, therefore, proportional to the rate of discharge into the chamber if <u>d</u> may be considered as constant.

Assuming that <u>J</u> is constant along the ship's length $\ell$ and that $\ell < c\,T$ (<u>T</u> is valve opening time), the longitudinal force exerted on the ship before the reflected wave has reached the ship is $K' \equiv J \ell D\,k$.*

Except for the fact that the head decreases continuously during opening of the valve, $K'_{max} < K_{max} = \eta_{max} D$. The slower the valve is opened, the smaller are <u>J</u> and $K'_{max}$.

b. Filling Through Culverts Without Laterals (Loop Culverts)

When the lock chamber is filled by means of loop culverts, the rate of inflow, <u>Q</u>, will increase slowly even if the valves are fully opened instantaneously. The rate of increase in inflow, $d\,Q/dt$, is equal to $F\ (dv/dt)$, so that $du/dt = (F/b\,d)\ (dv/dt)$. Introducing into formula (37) yields:

$$J = \frac{F}{g\,b\,d}\,\frac{dv}{dt} \tag{37'}$$

According to this formula, the variation of <u>J</u> during the filling operation can be traced if the velocity curve (dv/dt) and the filling curve (d) are known.

If (1/d) (dv/dt) is considered constant during the time required for the wave to traverse the length of the ship (this is often the case at

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*With regard to <u>k</u>, reference is made to the footnote on the preceding page.

the beginning of filling the chamber, when dv/dt is maximum; (see Fig. 29, for example), then the magnitude of the longitudinal force acting on the ship is

$$K' = J \ell d k = k \frac{F \ell D}{g b d} \frac{dv}{dt}{}^{*} \qquad (38)$$

Thus, K' is maximum when (1/d) (dv/dt) is maximum. Since the magnitude of d at any time is known from the filling curve, the maximum value of (1/d) (dv/dt) can be readily found by trial (d is to be regarded as constant during the time required for the wave to traverse the length of the ship).

In normal cases of filling the lock chamber, 1/d as well as dv/dt is maximum at the beginning, so that the largest longitudinal force occurs then. In this case, these can be calculated directly from formula (29a), so that it is unnecessary to plot even a part of the velocity and filling curves.

It should be noted that the longitudinal force usually is maximum before the reflected wave has reached the ship (thus, before a longitudinal force of opposite direction has arisen).

### c. Filling Through Culverts with Laterals

In order to furnish a clear picture of the longitudinal forces occurring during filling through a culvert with laterals, analysis will be made of the case in which the lock chamber is filled through a culvert with two laterals (page 77 on) and which is specifically illustrated in Fig. 30.

At the beginning of the filling operation, $du_1/dt$ is maximum and only the first lateral is active. Appreciable discharge from the second lateral begins later. Therefore, the longitudinal force at the beginning of filling, that is, as long as this force is maximal, depends on the discharge from the first lateral. The discharge from the second lateral not only becomes effective later, but $du_2/dt$ is also smaller than $du_1/dt$. Thus, the discharge from the second lateral produces a wave which strikes the ship only after the wave produced by the discharge from the first lateral has traveled back and forth one or more times.** Under certain conditions, therefore, the discharge

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*Reference to k is made in the footnote on page 104. If it is desired to obtain a more accurate value of K', the hydraulic gradient line can be plotted from the velocity and filling curves.

**The velocity of wave propagation is $c = \sqrt{gd}$.

from the second lateral may reinforce the wave produced by the discharge from the first lateral; yet, on the other hand, by the time the wave due to the discharge from the second lateral becomes important as far as the magnitude of the longitudinal forces is concerned, the wave occurring due to the discharge from the first lateral is no longer of corresponding importance.

Considering a culvert with laterals, such as mainly occurs in practice (many laterals fairly uniformly distributed along the length of the lock chamber, each having a small cross section in comparison with the culvert cross section), the longitudinal forces generally are of minor significance because the rate of discharge from the laterals which function first is small on account of the small lateral cross section.

It is possible to reduce the longitudinal forces by opening the valve slowly. In this way the flow velocity in the first lateral as well as in the following laterals will increase more slowly than in the case of rapid valve opening.

## 2. Analysis of the Transverse Forces

### a. Filling Through the Gates

As stated previously (page 103), the transverse forces are not of paramount importance in the case of such a filling system. Therefore, they will not be discussed herewith any further.

### b. Filling Through Culverts Without Laterals (Loop Culverts)

The principal transverse forces exerted on a ship in the lock chamber are due to the impact of the water jets entering the chamber upon the ship or locally upon the calm water alongside the ship.

At first the analysis will deal with filling through one culvert (one-sided filling). When the water flowing from the culvert strikes the side of the ship, the force $\underline{P}$ exerted on this side can be approximately calculated in a simple way from the momentum formula $P\,dt = mv$, in which $\underline{m}$ is the mass of the water acting during the time interval dt, and $\underline{v}$ is the velocity of this water. If the cross section of the water jet at the point of impact is $\underline{F}$, then $P\,dt = (F v\, dt/g)(v)$ or $P = F v^2/g$.

This formula is valid only if the ship's side involved is located normal to the water stream. In the case of an arbitrary direction of this side, a coefficient $\gamma$ ($\gamma < 1$) must be introduced into the formula. Thus, the formula becomes $P = \gamma (F v^2/g)$. The ship is pushed by the force P.

If the water jet does not strike the ship, but streams under it, the momentum is absorbed by the water alongside the ship on the side opposite the culvert. In case the lock is so wide that the water jet does not directly strike the opposite wall, it is necessary to compute approximately the difference in water level between the water in the chamber immediately in front of the culvert outlet and at the point where the velocity of the water is practically zero. If s denotes this difference, d denotes the depth of the water in the chamber immediately in front of the culvert outlet, and B is the breadth of the water jet, then

$$P = \frac{1}{2} B \, (d + s)^2 - \frac{1}{2} B d^2 = \frac{1}{2} B \, (s^2 + 2 s d)$$

If s is small in comparison with d, then $P = 1/2 \, B \, (2 s d) = B s d$. Hence, $B s d = F v^2/g$ or $s = F v^2/B d g = H v^2/dg$, in which H is the height of the culvert outlet.

In this calculation it is assumed that the culvert outlet is rectangular, the breadth of the water jet is constant, and the pressure distribution of the water in front of the outlet and at some distance from it is hydrostatic. Since these assumptions are neither general nor theoretically entirely true, it is judicious not to attribute too much validity to this calculation. Moreover, the width of the lock will generally be not so large that no direct impact of the water jet against the opposite wall would occur. In practice, however, this impact would have a minor effect because the velocity of the water at the opposite wall will be small on account of the increase in cross section of the water jet.

When B is regarded as constant and the water jet from the culvert diverges prismatically, the value of s at any distance from the culvert outlet can be computed and it is obvious that a constant hydraulic gradient is formed in the direction transverse to the lock axis. If a ship is located in front of the culvert outlet, it is possible in this case to calculate the transverse force exerted on the ship, which is dependent on the breadth of the ship. Also this evaluation is highly indefinite because the manner in which the flow from the culvert will diverge is not known. For this reason it is essential to make model tests.

In the preceding case the ship is drawn towards the discharging culvert, as it were.

The above forces, which act directly on the ship, are termed primary transverse forces. They do not readily admit of evaluation, even those considered at first. Firstly, because it is not known how the water jet from the culvert diverges and, secondly, a portion of the water will generally stream under the ship or flow alongside the ship, so that the pushing force will be reduced by a pulling force. Thus, both types of transverse forces will act together.

The maximum transverse force that can occur is $P_m = F v^2/g$, in which $\underline{F}$ is the cross section of the culvert outlet and $\underline{v}$ is the velocity at that point. If the computed value of $P_m$ has an allowable magnitude, it is known for certain that the case verges on the unfavorable.

The magnitude of this primary transverse force at any instant can be approximated from the velocity curve. The primary transverse force is maximum at the instant when the flow velocity in the culvert is maximum. In contrast with the longitudinal forces, the direction of this force is generally constant; in a special case, the direction is reversed only once (see the following subsection c).

The secondary transverse forces constitute a third category of forces, related to the longitudinal forces as well as to the primary transverse forces. These occur primarily when the water flows instantaneously into the chamber (loop culverts) and the ship is located outside the direct sphere of the water jet.

If only one culvert discharges (one-sided filling), the hydraulic gradient outside the direct sphere of influence of the culvert, transversely to the lock, will not remain constant. Therefore, beyond the zone which is directly under the influence of the culvert, a transverse wave will deflect the longitudinal wave from its direction parallel to the lock axis. Thus, the longitudinal wave will cause a transverse force in addition to a longitudinal force. This transverse force is designated now as a secondary transverse force.

The largest secondary transverse force results from the longitudinal wave which is most deflected from its longitudinal direction, that is, from the wave which arises at the instant when the primary transverse force is maximum. Of course, the secondary transverse forces occur simultaneously with the longitudinal forces, hence periodically. They do not admit of evaluation. All that can be stated is that at any instant they will not be greater than the corresponding primary forces. Thus, if the greatest possible primary transverse force has an allowable calculated magnitude, then it is unnecessary to take into consideration the secondary transverse forces as far as magnitude is concerned. However, because of their variable direction, the secondary transverse forces usually have a greater effect on the calm position of the ships in the lock chamber than the primary transverse forces having uniform direction.

If a ship is located entirely or partly in the direct sphere of the water jet, then naturally no secondary transverse forces will act on the part of the ship in this sphere. Therefore, it is needless to emphasize the secondary forces in the region of the primary transverse forces.

The presence of the ship will likewise affect the magnitude of the secondary transverse forces because the water in the lock chamber will recoil suddenly upon passage of a longitudinal wave.

The primary forces will generally be smaller at filling through two loop culverts opposite each other (two-sided filling) than at one-sided filling. However, if the water from the culvert streams very close against the ship's surface and the ship is situated in the transverse hydraulic gradient formed by the flow from the other culvert, then the transverse forces produced separately by the two culverts act in the same direction. In the case of two-sided filling, the highest water level in the chamber in the sphere of the two culverts will occur at the point where the two water jets stream towards each other. Since it is permissible to assume that the difference in level transverse to the lock axis is the same for one-sided and two-sided filling, the hydraulic gradient at two-sided filling will be approximately twice as large as at one-sided filling. Accordingly, the secondary transverse forces at two-sided filling will be approximately twice as large as at one-sided filling. However, the problem becomes extremely complicated due to interference phenomena.

### c. Filling Through Culverts with Laterals

The magnitude of the largest possible primary transverse force exerted on a ship can be approximately evaluated for the case of a culvert with laterals at one-sided filling if the velocity curves for the flow in the laterals are known. In order to obtain this largest primary transverse force, it is sufficient to plot the rising section of each of the velocity curves.

In the case of a culvert with laterals, such as used in practice (numerous small laterals distributed along the entire length of the chamber), the largest primary transverse force is of minor consequence if the ships are located merely in the direct sphere of a portion of the laterals. If a ship is so long that it lies in the direct sphere of all the laterals, the primary transverse force would be of greater importance. It should be borne in mind, however, that the various laterals do not have simultaneously a maximum discharge, so that the individual water jets from all the laterals do not cause simultaneously a maximum transverse force.

Since the primary transverse forces generally are of uniform direction (their direction changes once at most; see page 109), a ship subjected to their effect will lie calmly in the lock chamber.

One-sided filling will be analyzed first. If the laterals are installed so high that the water pushes against the ship, then the primary transverse forces are pushing forces. If the ship is situated at the wall containing the culvert, the hawsers become tense and it is essential to know whether or not the pushing forces are excessively large because snapping of a hawser would cause serious damage. If the ship is located at the opposite wall, the tension in the hawsers would be relieved by the direct impact of the water, but they would be stressed by the transverse hydraulic gradient. Either a pushing force or a pulling force will prevail, depending on the ship's breadth, the chamber breadth, and the elevation of the laterals.

If the laterals are installed so low that the water streams under the ship, the ship will be drawn towards the culvert (compare page 109). If the ship is moored to the wall containing the culvert, the primary transverse forces will relieve the tension in the hawsers during the filling operation (safe berth of the ship[*]), while if the ship lies at the other wall, the hawsers will be stressed (less safe berth).

If the laterals are installed low and the water initially pushes against the ship and subsequently streams under the ship because of the rising water in the lock chamber, the primary transverse forces will change in direction once.

The secondary transverse forces, which continually change in direction, will not arise in the region of the primary transverse forces (see page 110). Merely on account of their variable direction it is essential to make provisions that the entire lock chamber becomes the region of the primary transverse forces during the time when much water flows into the chamber.[**] Accordingly, concentration of laterals is undesirable. Nor is it advisable to arrange a culvert in such a way that a given group of laterals dominates. It is essential, for example, to see to it that the discharge from the first laterals does not gradually become shut off in such a way that the water flows mostly from the last laterals (Panama Canal). Moreover, concentration of laterals should be avoided because the primary transverse forces acting on the section of the ship within the sphere of these laterals will be large.[***]

When the chamber is filled through two culverts with laterals opposite one another (two-sided filling), a pushing force will always occur if the laterals are at high elevation and the ship is moored close to a wall. This pushing force usually is greater than that which would occur at one-sided filling, because the water from each culvert separately will frequently produce a pushing force in the same direction. If the laterals are located so low

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[*] In a filling system in which the hawsers are slack and, consequently, the ship is pressed against the wall, the disadvantage is the friction occurring between the ship and the wall during rising of the ship, while the advantage is that the eventual longitudinal waves maintain no grip on the ship due to the friction. (Compare the article by C. T. C. Heyning in De Ingenieur, No. 34, 1925, page 735).

[**] Small longitudinal forces during this time.

[***] Large longitudinal forces may arise then also. At a given rate of valve opening, the longitudinal forces will be larger when the concentration of discharge from the laterals occurs near the upper lockhead than when the concentration is near the lower lockhead (difference in culvert length). In the Panama locks the concentration is at the downstream end of the culvert. According to Whitehead's publication, this is the reason why the ships there have not been subjected to stresses from longitudinal forces (see page 10).

that the water streams under the ship, the resulting force always is a pulling force.

The preceding discussion furnishes the reason why it is advisable to install the laterals as low as possible if the design specifies application of two-sided filling. In this case the berth of the ship in the lock chamber is more secure than in the case of laterals at high elevation (slack hawsers).

If, at two-sided filling, the ship is located along the longitudinal axis of the chamber and is moored to both walls, the primary transverse forces caused by the discharge from both culverts will counteract one another. The resultant transverse force obviously will be smaller than in the case of one-sided filling; yet the position of the ship in the chamber will be less stable (but not unsafe) in the case of high lifts and rapid filling, as the transverse force would frequently change its direction--the ship would roll back and forth. This will be due to the fact that not all the laterals would continuously have a uniform discharge (as expounded on page 125), with the result that the transverse forces caused by the flow from the two culverts separately generally are not precisely equal to each other simultaneously.

### 3. Comparison Between Longitudinal and Transverse Forces

It is evident from the preceding that the longitudinal forces and transverse forces are entirely different in character from each other. In the case of filling through culverts, the largest longitudinal forces occur when the velocity curve is steepest ($dv/dt$ is maximum), thus, in normal cases, at the beginning of filling,* while the largest primary transverse forces occur later, when the flow velocity in the culverts or laterals is maximum ($dv/dt = 0$). When culverts are used, the maxima of both types of forces theoretically never occur simultaneously. In practice they occur simultaneously only when the culvert length is negligible and the valve is fully opened instantaneously, as then both $\eta$ (page 103) and $\underline{v}$ are maxima simultaneously.

The largest secondary transverse forces likewise always occur later than the largest longitudinal forces because their origin is the same as that

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*The value of $dv/dt$ is not maximum at the beginning of filling in abnormal cases such as, for example, when the culvert is short and the valve is opened at a uniformly accelerated rate, or when the shape of the culvert cross section at the location of the valve is such that the portion of the culvert passage opened by the valve initially increases very gradually and at a given instant expands suddenly.

of the primary transverse forces. They occur somewhat later than the largest primary transverse forces. The phase difference depends on the propagation velocity $c = \sqrt{g\,d}$ of the longitudinal waves in the lock chamber. At slower rate of valve opening the magnitude of the longitudinal forces decreases more rapidly than that of the transverse forces; this is due to the fact that at slower increase in velocity of the water (smaller longitudinal forces) the flow velocity in the culverts will rise during a longer time interval than at a more rapid increase (at slow increase the head drops slower than at rapid increase), so that the maximum velocity naturally will occur later at slower increase than at rapid increase, although it cannot be stated a priori that this maximum will be smaller. Therefore, when a transverse force is too large, it is more difficult to reduce it than it is to reduce a longitudinal force.

It is obvious, therefore, that transverse forces should be avoided as much as possible when loop culverts are used. Primary transverse forces in the case of loop culverts can generally be avoided by making provisions that the ships never lie in the direct sphere of the culverts, which can be achieved if the lock chamber is made so much longer than the length of the largest ship undergoing lockage that it is not necessary to moor the ship in front of the culvert outlets, and by arranging that no primary water jets reach the ship. It is recommended to satisfy the latter condition by bending the culverts in such a way that the water jets are directed not towards the chamber but in the opposite direction, namely, towards the gates of the lock-head supplying the water.*

## D. Comparison Between Filling and Emptying of the Lock Chamber

As far as the effect on the safe berth of the ships in the lock chamber is concerned, the essential difference between filling and emptying the chamber is that the primary transverse forces occur during filling and do not occur during emptying (primary pulling forces are of no consequence, as soon as the ship is located centrally before the culvert outlet, because then the velocity of the water at the ship surface would be practically zero).

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*This principle is applied to the design of the lock which is currently under construction at IJmuiden. In order to prevent the ships from approaching too close to the gates, so as to assure the safety of the gates, a section of the lock chamber always remains between the ship and the gate, and the culverts discharge into this section (see Figs. 22 and 24).

Secondary transverse forces, however, occur during filling as well as emptying, and primarily during emptying because the water flowing in the culverts deflects the longitudinal wave from the direction parallel to the lock axis.

Moreover, the longitudinal forces occurring during the emptying operation are smaller than during the filling operation, as the largest $\eta$ (page 103) or $\underline{J}$ (page 105) is smaller (during filling and emptying the largest longitudinal forces occur in normal cases at the beginning of the operation, but the flow depth $\underline{d}$ of the water in the lock chamber is then minimum in the first case and maximum in the second case). Therefore, the filling operation involves the most concern.

If the filling operation is not detrimental to the ships in the lock chamber, the emptying process is definitely not any more detrimental.[*]

## E. The Hydraulic Design of a Filling System for Locks[**]

### 1. General Analysis

In designing a filling system for a lock, the first step is to prepare a rough estimate of the required flow cross sections in accordance with the filling time and the assumed desirable opening time of the valves. Then, in case it is considered to use culverts, the rising section of the velocity curve (or curves) is plotted and the magnitude of the largest forces anticipated is computed.[***] If the forces are too large, the rate of valve opening is reduced. When the rising section of the velocity curve (or curves) is plotted for three different rates of valve opening, the proper rate can be found by interpolation. If the resulting filling period is too long, the culvert cross section is increased. After several trials, the proper culvert cross section and rate of valve opening are finally obtained.

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[*] Therefore, only the filling operation is discussed in greater detail. This is also the reason why in the third lock of St. Marys Falls the culvert system used for emptying was different from that used for filling (culverts without and with laterals, respectively; see page 6).

[**] The construction aspects of the design of a filling system are outside the scope of this work.

[***] In the design of the IJmuiden lock, the maximum allowable hawser force was assumed as 13.5 tons for a ship of 45,200-ton displacement (see page 51).

Should the desirable culvert cross section be too large, in view of the corresponding excessive dimensions of the valves, it is necessary to narrow the culvert at the location of the valve and to enlarge its outlet.* However, the divergence must be of such type that the water would not separate from the culvert walls; test results show that this will be the case if the angle of divergence is less than 10°.**

In the case of long culverts, moreover, it is essential to determine whether the continuing rise of the water level in the chamber after the level of the upper pool has been reached for the first time (termed residual flow) will not hinder the opening of the gates. Of course, this rise in level cannot be expected ever to constitute a hindrance in the case of a single set of miter gates because these gates would open of their own accord due to the water pressure on the inner edge. If a roller gate is used, such a mode of opening the gate is out of the question and the rise of the water in the lock chamber must necessarily be taken into consideration.

In the case of the normal type of culverts with laterals, such culverts naturally being long, the rise in water level of the chamber is a lesser factor than in the case of loop culverts of similar length. The residual flow would practically last not much longer than in the case of loop culverts of the same length and cross section as the first culvert section. The dimensions of the remaining culvert sections and of the laterals have little effect on the duration of the residual flow, as these sections and laterals will discharge into the lock chamber during the residual flow when such discharge through the first lateral is prevented as soon as the flow direction in the first culvert section is reversed. The water in the last laterals will then enter the lock chamber, while the water in the first lateral will partly return into the culvert and partly flow towards the upper pool (see Fig. 10).

If calculations indicate that a detrimental rise in chamber water can occur, the rate of valve opening should be reduced in order that the flow

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*This procedure was used in the design of the IJmuiden lock under construction. The opening time of the valves is very long there--10 min. If the culvert outlets were smaller, it would have been possible to open the valves faster and achieve the same filling period. This would practically not affect the longitudinal forces, but the transverse forces would become larger.

** Therefore, rounding the edges of the outlet is of no benefit. If the outlet occasionally serves as an inlet, then such rounding would be appropriate for the purpose of the inflowing water.

velocity in the culvert would be as small as possible at the instant when the chamber first becomes filled to the level of the upper pool. In this case, moreover, it is recommended to design the culvert not for minimum resistance to flow, as is generally recommended in standard designs, but for large resistance; the flow velocity would thus be retarded more rapidly. Yet no large increase in filling time would result because at high culvert resistance it is permissible to open the valve faster than at low culvert resistance without causing any increase in the forces exerted on the ships. The section of the velocity curve, corresponding to the period during which the valve is in operation, can be made similar for both cases; the shape of the subsequent section, however, depends solely upon the remaining resistances, so that it is always dissimilar in these cases.

The anticipated detrimental rise of water level in the lock chamber would be the determining factor in the choice of the gate system.

If small locks are to be designed with short loop culverts or short culvert sections, the inertia term in the equations of motion may be neglected, especially in the case of high lifts, so that the resulting calculation becomes greatly simplified.

The question arises now as to the culvert length at which the inertia term may be neglected. By plotting the rising section of the velocity curve, corresponding to sudden complete opening of the valve, it becomes possible to verify whether the length of the loop culverts is such that the inertia term may be neglected. It can readily be noticed then whether or not the rising section rises nearly vertically. In the first case, the inertia term may readily be neglected. It can be established, in a similar way, whether the inertia term may be neglected in the case of culverts with laterals. Of course, if this term is neglected, the successive beginning of functioning of the laterals will not be indicated, but this is anyway no criterion for the suitability of the filling system in the case of short locks, since the most hazardous forces involved are the primary transverse forces, and the largest of these forces occurs not at the beginning of filling but only after all the laterals are functioning. The maximum anticipated primary transverse force can be determined with approximately the same degree of accuracy whether or not the inertia term is neglected.*

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*The inadequacy of the filling system for the Panama locks is readily evident from the calculations presented by Whitehead and derived on the basis of neglecting the inertia of the water.

With regard to the design of locks for inland waterways or small navigation locks, therefore, the inertia term of Eqs. (29), (11), (17), etc. may generally be neglected, which greatly simplifies the hydraulic aspect. If the locks are long, however, the inertia term may not be neglected in the case of investigating the magnitude of the longitudinal forces due to culverts with laterals.

In the preceding calculations, no consideration was given to the possible difference in specific weight of the water in the lock chamber and outside. It is needless to explain any further that this factor should be allowed for in a simple way. During the filling operation, for example, the specific weight of the water in the lock chamber will continually vary. This variation in specific weight should be taken into consideration by computing its periodic values. When the chamber is filled, only a layer of water continues to flow in, so that the specific weight of the water in the chamber does not vary much (depending on the ratio of the water layer involved to the total quantity of water in the lock chamber).

If the gates are opened then, the water will suddenly stream into the chamber, which could still exert fairly large longitudinal forces on the ships. If the gates remain closed, residual flow will occur in the culverts and continue until the specific weight of the chamber water is the same as that of the outside water.

## 2. Further Analysis of Culverts

### a. Analysis of Loop Culverts

In designing a culvert system, it is essential to endeavor to use such a shape and outline of the culverts that the forces which might act on the ships in the lock chamber would be as small as possible. As far as the longitudinal forces are concerned, it is not necessary to be apprehensive. They can be kept small by very slow valve opening.

It has already been pointed out that, in order to reduce the transverse forces, it is advantageous to bend the culvert outlets towards the gates (page 114). Further, in order to reduce the primary transverse forces, it is recommended to direct the culvert outlets slightly downward, so that a portion of the water jets issuing from the culverts would stream underneath the ship, with the result that only a portion of the water jets would strike the ship and, at the same time, a transverse force would occur which would counteract the force caused by the direct impact against the ship. In order additionally to reduce the transverse forces, care must be taken that the exit velocity of the water is as small as possible, which necessitates making the culverts as wide as construction considerations permit and greatly reducing the flow velocity by means of slow valve opening. It is obvious that use of the smallest valves possible is advantageous because it facilitates narrowing the culverts at the location of the valves and gradual divergence towards the outlet.

An advantage of narrow culverts with wide outlets is that the mass of water in such culverts is smaller than in culverts having a constant cross section equal to that of the enlarged outlet, at approximately the same filling duration, so that when roller gates are used, for example, the resulting hazard of detrimental rise in water level in the lock chamber above the upper pool level is less (page 116). Although the surface friction in culverts with diverged outlets is greater than in the above culverts of constant cross section and, moreover, losses occur in the diverged outlet (as computed by Fliegner, page 71), yet the unfavorable effect of these factors upon the filling time vanishes when the valves are opened a little faster.

Another advantage of using diverged culvert outlets is that during filling of the lock chamber the water jets will continue to diverge outside the culvert, so that the velocity of the water at the point of impact against the ship is smaller than at the culvert exit (smaller transverse force), while proper shaping of the divergence makes it possible to direct a portion of the water underneath the ship, with the result that a transverse force would arise which would counteract the force caused by the direct impact.

A disadvantage of using a diverged culvert outlet is the hazard of entraining air through the valve shafts, whereby the discharge capacity would be reduced to an extent that could not be determined in advance and the water would discharge from the culverts in surges.* It is necessary, however, to determine from calculations whether this hazard exists, for which purpose the rising section of the velocity curve must be plotted. If the hazard might

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*The latter was ascertained at Hansweert. The filling curve, obtained there at the third lock, evidenced distinct surges when the outside water was so low that the culvert outlets extended partly above this water.

exist, then the narrow portion of the culverts should be located lower or, when this is impossible, the speed of valve opening should be reduced, thus reducing the flow velocity of the water (thereby, however, the filling time would increase). Another means for overcoming this difficulty is to diverge the culverts to a lesser extent.

In designing a lock the question may arise whether it is advisable, in the case of unequal length of the culverts on opposite sides of the lock-head, to use culverts of unequal cross section or unequal divergence of the outlet for the purpose of equalizing the discharge from both culverts at any time. This case may arise when designing locks with roller gates, whereby one culvert passes around the gate recess and the other culvert is laid along a shorter path. The question should generally be answered negatively because the inequality of the discharge will not be large.

As far as the longitudinal forces are concerned, the inequality of discharge is of no importance because it makes no difference whether at a given instant more water flows into the lock chamber at one side than at the other. The important aspect in this case is only the rate of total discharge from both culverts.

As far as the primary transverse forces are concerned, an unequal discharge is generally of no more importance. Equal discharge from both culverts is essential only when the ships are moored along the lock axis during filling and the lift is very high, as in the case of the Panama locks.

According to the discussion presented on page 110, it is obvious that unequal discharge from both culverts is no more unfavorable with respect to the magnitude of the secondary transverse forces than with respect to the magnitude of the longitudinal forces or the primary transverse forces.

### b. Analysis of Culverts with Laterals

It is noted on page 112 that concentration of laterals is undesirable and that the domination of a given group of laterals (factually a concentration) must be avoided. The question arises as to how the latter can be achieved. In the case of low lifts, it would suffice to use a large number of laterals of small cross section (combined cross section of the laterals equal to 1.5 to 2 times the culvert cross section). Of course, the first laterals begin to function before the other, yet the resulting longitudinal forces will never be large if the valves are opened slowly.

If high lifts are involved (10 m, for example, as in the case of the Panama Canal locks), various means are available to prevent the last laterals from discharging the most water at the time when the primary transverse forces are maximal (thus, at the hazardous stage of the filling operation). Only the following means are listed here: arranging the first laterals in a direction deviating from the normal to the culvert axis towards the lower gates and arranging the last laterals in the opposite direction, in addition, increasing the cross section of the first laterals and decreasing that of the last laterals. (It should be noted that these means would fail if the lock operates in both directions and the lift is high in both cases, but this case is merely theoretical). Using simple means,* however, it is never possible to avoid the first laterals beginning to discharge first, yet this factor need never produce any detrimental results on the ships in the lock chamber (slow valve opening).

In connection with the construction aspects of the structure, however, it is generally recommended to use the simplest possible design of a culvert with laterals. Excessively large longitudinal forces can be avoided by using slow valve opening, hazardous primary transverse forces can be avoided by installing the laterals at low elevation (see page 113) and, if the ship undergoing lockage is moored along the lock axis and the lift is high, by making provisions that the discharge from both culverts at each instant is as much equal as possible, during which the rising section of the velocity curve, in the case of unequal culvert outline, for example, can be achieved by means of unequal opening of the valves.**

As far as the magnitude of the transverse forces is concerned, a small height of the lateral is more favorable than a large height (see formula on page 108).

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*It is possible, for example, to install a culvert connected in the middle of the chamber to the main culvert containing the laterals; however, this method is never necessary.

**According to Whitehead's publication (mentioned previously), this fault was regarded at Panama as highly detrimental. Improvement was achieved by incomplete opening of the valve in the culvert discharging the most water. Equality of discharge during the entire filling period was obtained in this way.

### 3. Further Analysis of Filling Through the Gates

In place of loop culverts, valves can be installed in the gates. Primary transverse forces would not occur then, but secondary forces would. The reason is that if the inflow is quite nonuniformly distributed along the entire chamber profile, then secondary transverse forces would arise because the sudden recoil of the water from the ship in the lock chamber will cause the flow parallel to the lock axis to deviate from its original direction.

Longitudinal forces similar to the primary transverse forces occur then if the water strikes the ship directly. On the other hand, a drop in level will occur in the immediate vicinity of the gate; this drop is essentially equal to s, as computed on page 108. The corresponding force is a pulling force* which, therefore, counteracts the force mentioned previously. If the ship is located at some distance from the gate, the drop in level s is practically absent, but then also the primary water jet has a lesser effect on the ship.

In order to fill the lock chamber, it is better to open the gates proper than to open the valves in the gates. This system is used in the Gröschel lock near Breslau, among others, whereby the gate is a segment gate which is revolvable about a horizontal axis and can be lifted.** The advantage of this filling system is that the inflow occurs along the entire width of the lock (small secondary transverse forces), while the energy of the water jet can eventually be dissipated by means of installed baffle piers. Moreover, because of slower opening of the gate, the filling time may become longer than in the case of using valves in the gates, since in the first case the gate is opened during the filling operation and in the second case the ships must wait until the gates are opened after the filling operation.

The lock at Södertalje (Sweden) is also filled by means of opening the gates.*** In this lock the gates are sector gates revolvable about a vertical axis. During the opening of the gates most of the water flows into the lock chamber approximately perpendicular to the lock axis and a small

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*See H. Krey, Zentralblatt der Bauverwaltung of June 1914.

**See Engelhard, Kanal und Schleusenbau.

***See, among others, De Ingenieur No. 46, 1924.

portion in the direction of the lock axis. The advantage of this system is that primary transverse forces do not occur even when the ships are located at the gates.

In principle, it is better to use a system in which the gate is completely lowered or raised. Then the inflow proceeds along the entire width of the chamber and in the direction of the lock axis, so that the resulting transverse forces are of minor importance. The dynamic force of the inflow can be partly dissipated by means of installing baffle piers, if necessary (see the article by Dr. Burkhardt in Bautechnik of January 14, 1927). This system is highly promising for locks with very high lifts.

In Der Bauingenieur of 1925, Krey presents a design of a lock in which filling occurs through the gates and the ships do not have to wait at all. The gates of one lockhead are shut behind the ship and afterwards the gates of the other lockhead are opened, while the ship proceeds to pass through the lock. Naturally, the lock must be very long and the water loss during lockage is very great. Application of this system has not been taken into consideration as yet.

## 4. Conclusion

It can be concluded from the preceding that, regardless of the arbitrary filling system used, slow opening of the valves always makes it possible to achieve a condition in which the forces exerted on the ships are not of such a nature that would constitute a hazard to the ships during filling of the lock chamber. For this purpose, it is always necessary to determine the optimum opening time of the valves. However, often the filling period at this opening time will be too long, and another filling system must be found. With the aid of the preceding it is possible to determine, from the hydraulic standpoint, which filling system will result in the optimum economical construction of a lock in each practical case.

It is generally unnecessary to use the filling system of culverts with laterals (often the costliest installation). If the lift is such that, in accordance with analysis, use of no other system can be considered, then the system of culverts with laterals will always yield good results. In certain cases, however, instead of using the above system, satisfactory results can be achieved by establishing the water level in the lock chamber by means of opening the gate, as discussed on the preceding pages.

However, the fact that the actual magnitude of the transverse forces is unknown makes it advisable to conduct model tests in case the calculated maximum possible primary transverse force proves to be still too large. It will be evident then that the transverse forces will be smaller than the calculated ones. Therefore, model tests should be conducted before it is concluded that culverts with laterals are to be used in a given case.

If it is decided to proceed with conducting such tests, it is essential to establish, with the aid of the results of the previous discussions, the precise aspects that must be tested. Should the work commence injudiciously, it may be found that the design, in accordance with which a definite model is prepared, is totally unsuitable, with the result that both time and money would have been wasted.

It is obvious that the coefficient of skin friction in the prototype will be smaller than in the model (page 30), yet its influence on the evaluation of the magnitudes of the prototype forces will not be appreciably affected. The forces obtained will thus be slightly too small, and the filling time somewhat too long.

# CHAPTER V

# EXPERIMENTAL VERIFICATION OF THE THEORIES DEVELOPED

Although it has been shown in Part I that the results of the tests conducted on behalf of the new IJmuiden lock agree with the theory developed in Part II, the relation between the two will be briefly recapitulated herewith.

## A. Tests on the Existing Large Lock at IJmuiden

The tests conducted on the existing large lock at IJmuiden are described in Chapter III of Part I. It is described how the diagrams shown in Fig. 10 are obtained. The curves of these diagrams represent transverse-force curves because the ordinates are proportional to the square of the velocities of the discharge from the laterals. In order to obtain the velocity distribution, it is necessary to plot the roots of the ordinates. When the scale of the ordinates is modified, the velocity curves represent also the discharge curves of the laterals.

The graph shows clearly that the laterals begin to function successively also in prototype structures. The irregular undulations of the curves may be attributed partly to the resistance to which the water is subjected upon entering the laterals and the magnitude of which is not constant because of formation of eddies, and partly to the irregularity of the eddy region in which the small cylinders are suspended. These undulations are noticeable mainly when the increase or decrease in flow velocity with respect to time is small, that is, near the end of the rising section or along the descending section of the velocity curves, respectively. If the culvert sections are so long that the inertia term of the equations of motion of the water in the culvert has a great effect on the magnitude of the flow velocity, then the irregularities of the resistance would have little effect on the discharge of the laterals.*

The irregular resistance to which the water is subjected when entering the laterals accounts also for the fact that similar laterals yielded unequal discharges under the same conditions during various tests (established also by Whitehead). It was impossible, therefore, to combine the observations made on the odd and even laterals at the same lift for the purpose of determining

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*Established by the Berlin tests.

the actual discharge of all the laterals at this difference in level.* Also calibration of the instruments appeared impossible for the same reason.

## B. Laboratory Experiments

Introduction. As described in Part I, the following filling systems were investigated at the Berlin-Charlottenburg Hydraulic Laboratory, among others:

(1) Filling through laterals installed low in the lock-chamber walls and concentrated exclusively in the middle of the chamber (termed: filling through laterals in the middle).

(2) Filling through laterals installed at low elevation, concentrated near the two head locks, and interconnected by a conduit.

(3) Filling through the culverts in the lockheads (termed in abbreviated form: loop culverts).

Although the test installations are adequately described in Part I, a very concise description is presented herewith in order better to understand the aspects involved. The test filling systems were installed in one model (Fig. 11). System (1) could be tested by opening only valves B and B', and system (2) could be tested by opening only valves A, C, A', and C'. System (3) was separately installed in the model (the dashed lines). The ships were elastically moored to both lock walls in the model. Due to the motion of the water in the lock chamber, the ships moved back and forth. As soon as the forces acting on the ships ceased, the ships resumed their equilibrium position. With the aid of pencil points attached to the foremast and aftmast, the motions of the ship were recorded on a sheet of paper having a fixed position with respect to the ship (Fig. 15a). The diagrams obtained in this way were subsequently designated as force diagrams because they were representative of the magnitudes of the forces acting on the ships (a given force produced a given elastic deformation which is proportional to the force). In the equilibrium position of the ship, the pencil points are at the intersection of the axes. Thus, each diagram begins and ends at the intersection of the axes. The scale of the diagrams is obtained by means of calibration.

During the tests the water level in the lock chamber is recorded on a revolving drum. Filling curves are obtained in this way (curve JK of

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*See page 15.

Fig. 17). The motions of the ship are again recorded on the same drum, the longitudinal and transverse motions separately. This was desirable because the force diagrams had a very compact shape, so that it was impossible to detect at which instant a given force occurred during the filling.

The validity of the previously developed theory will be briefly proved in the following on the basis of the experimental force diagrams.

### 1. Filling Through Laterals in the Middle (Fig. 16a)

When the ship is located in the middle of the lock chamber 1.50 m from the south wall (position A), the forces are almost exclusively transverse forces. The longitudinal forces become leveled out because waves proceed from the middle of the chamber simultaneously in both directions and are reflected from the gates. The discharge from the south culvert streams underneath the ship. As a result, the ship is drawn towards the south wall. This pulling force is still absent only at the beginning of filling, as long as the velocity of discharge from the laterals is still small. (The direction of the primary transverse force thus changes once; see page 109). The pattern of the primary transverse force is shown in Fig. 16i* (transverse-force curve). Naturally, the transverse-force curve conforms well to the velocity curve.

The concave course of the descending section is due to the fact that the transverse-force curve has ordinates which are proportional to the square of the ordinates of the velocity curve. (In the case of short culverts in which the inertia of the water is negligible, the ordinates of the transverse-force curve at sudden valve opening will at all instants be proportional to the still available head. Hence, the transverse-force curve has a concave course then). The fact that the experimental transverse-force curve has fewer undulations than the curves of Fig. 10 (which are transverse-force curves as well) is attributable to the large inertia of the water in the culverts and of the ship (compare page 125).

Primary transverse forces (Fig. 16ℓ) do not occur during emptying the lock chamber.

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*This curve is essentially the same as the curves of Fig. 10. If the drum had not been revolving during the recording of this curve, the first diagram of Fig. 16a would have been obtained.

### 2. Filling Through Laterals near the Lockheads, Connected by a Conduit (Fig. 16c)

If the water discharges exclusively from the laterals near the upper lockhead (only valves A and A' of Fig. 11 are open), the resulting diagrams have the shape of Fig. 16b when the ship is situated in the direct sphere of the flow from the laterals. If valves C and C' (Fig. 11) are also open (filling through laterals near both lockheads, connected by a conduit), the resulting diagrams are as shown in Fig. 16c when the position of the ship is the same.

Comparison of Figs. 16b and 16c shows that the diagrams of both are in fair agreement. This is due to the fact that in the last case the discharge occurs first from the laterals near the upper lockhead, and only later from the laterals near the lower lockhead. Therefore, the first longitudinal displacement of the ship is not affected by the discharge from the laterals near the lower lockhead. It will have occurred before these laterals are practically functioning. The discharge from the laterals near the lower lockhead has little effect on the further displacements because this discharge has small acceleration, so that it produces small longitudinal forces.

This phenomenon is still more improved when the chamber is filled through all the laterals simultaneously (valves A, A', B, B', C, and C' are opened). If the prow of a ship of ± 180 m actual length is situated in front of the laterals near the upper lockhead, the stern of the ship is situated in front of the middle laterals. The first longitudinal displacement of the ship is due to the discharge from the laterals near the upper lockhead. Simultaneously with the first longitudinal displacement there begins the first transverse displacement of the forward part of the ship, recorded by means of the foremast, as shown in the diagrams of Fig. 16d. The discharge from the middle laterals occurs relatively later; this is evident from the fact that the transverse displacement, caused by the discharge from these laterals and affecting the stern of the ship, begins only after the ship has undergone a longitudinal displacement (back and forth).

When the stern of the ship is situated in front of the laterals near the lower lockhead, the prow is situated in front of the middle laterals. The primary transverse displacement of the foremast begins, therefore, after the first longitudinal displacement has occurred (due to the discharge from the laterals near the upper lockhead), while that of the aftmast begins only after the ship has undergone its second longitudinal displacement in the direction of the upper lockhead (Fig. 16e).

The diagrams clearly manifest that, at slow valve opening, the transverse forces decrease in magnitude to a lesser extent than the longitudinal forces.

If the chamber is filled only through the laterals near the lower lockhead (only valves C and C' of Fig. 11 are opened) while the high water is turned through the upper lockhead (this case is termed: filling through the laterals near the lower lockhead), then the longitudinal displacements are small even at very rapid valve opening, as shown in Fig. 16f. This fact is attributable to the extreme culvert length (± 400 m in the prototype). In this case, a relatively large transverse force occurs only at part of the ship located in the direct sphere of the effective laterals (primary transverse force).

### 3. Filling Through Loop Culverts* (Figs. 16g, 16h, and 16k)

Figures 16g and 16h show that the longitudinal and transverse forces at one-sided filling are approximately half as large as at two-sided filling. In addition, Fig. 16g shows that the magnitude of the secondary transverse forces and the longitudinal forces do not vary much with the position of the ship in the lock chamber (positions A and C).

According to the experimental diagrams (position B), the primary transverse forces at two-sided filling are approximately twice as large as at one-sided filling (see page 110).

Under otherwise similar conditions, the forces during emptying the lock chamber are smaller than during filling the lock chamber (compare Figs. 16g and 16k).

IJmuiden, March 29, 1927
J. P. Josephus Jitta

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*During these tests the culvert outlets were not bent towards the gates.

# THE DESIGN OF THE VREESWIJK LOCK SYSTEM

## (Het ontwerp van het schutsluizencomplex te Vreeswijk)

by

J. P. Josephus Jitta

Reprint from De Ingenieur, No. 32, 1935

# ABSTRACT

This article contains a description of the design of the lock system, related to W. H. Brinkhorst's article in De Ingenieur, No. 36 of 1934 and to the design of other large navigation locks of the Amsterdam-Rhein Canal. The mode of arrangement and construction of the system is motivated. The following aspects are discussed successively: (1) general data, (2) type of gates, (3) general discussion of the lock design, (4) individual construction details, (5) exchanging the gates; lift gate storage, (6) the footbridge, (7) arrangement of the gates in connection with filling and emptying the lock chambers, (8) tests at the Delft Hydraulic Laboratory, (9) experiments to determine the actuating power for the valves in the gates, (10) design of the lift gates, (11) mechanical and electrical equipment, and control of the lock system, (12) the approaches, (13) details pertaining to navigation, maintenance, and traffic in the lock system.

## LIST OF ILLUSTRATIONS

# THE DESIGN OF THE VREESWIJK LOCK SYSTEM

## I. GENERAL DATA

Two adjacent navigation locks were constructed, each 18 m wide, with an effective length of 225 m and a maximum lift of 6.4 m, while a site was reserved for a third lock to the west of the other locks.

The lock system is not limited strictly to the locks proper. Spacious approaches with mooring facilities for ships were designed in order to achieve effective lockage operation (Fig. 1).

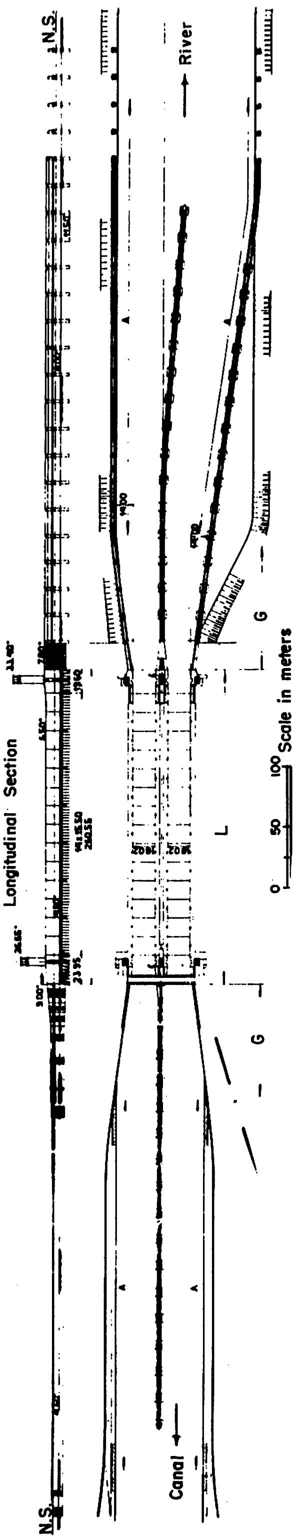

Fig. 1 - Layout of the Lock System

A. Mooring stations for ships. G. Approaches. L. Lock structure. N.S. Normal stage. Bumpers partly omitted; the last mooring posts in the river approach are not equipped with such bumpers or with foot bridges.

## II. TYPE OF GATES

Since it was essential that the gates could turn water in both directions and could be opened at some head in order to empty the water, lift gates were assigned in this special case, although this type of gate usually increases the cost of the structure. The gates are equipped with valves for the purpose of establishing the level in the lock chambers.

## III. GENERAL DISCUSSION OF THE LOCK DESIGN (Fig. 2)

The advantage of using lift gates is that the shape of the locks below deck elevation (thus, of the rougher concrete structure) can be readily exploited.

The locks are supported on concrete piles. This was desirable because it made it possible to limit the foundation depth and because, by appropriate distribution of the piles, the floor thickness likewise

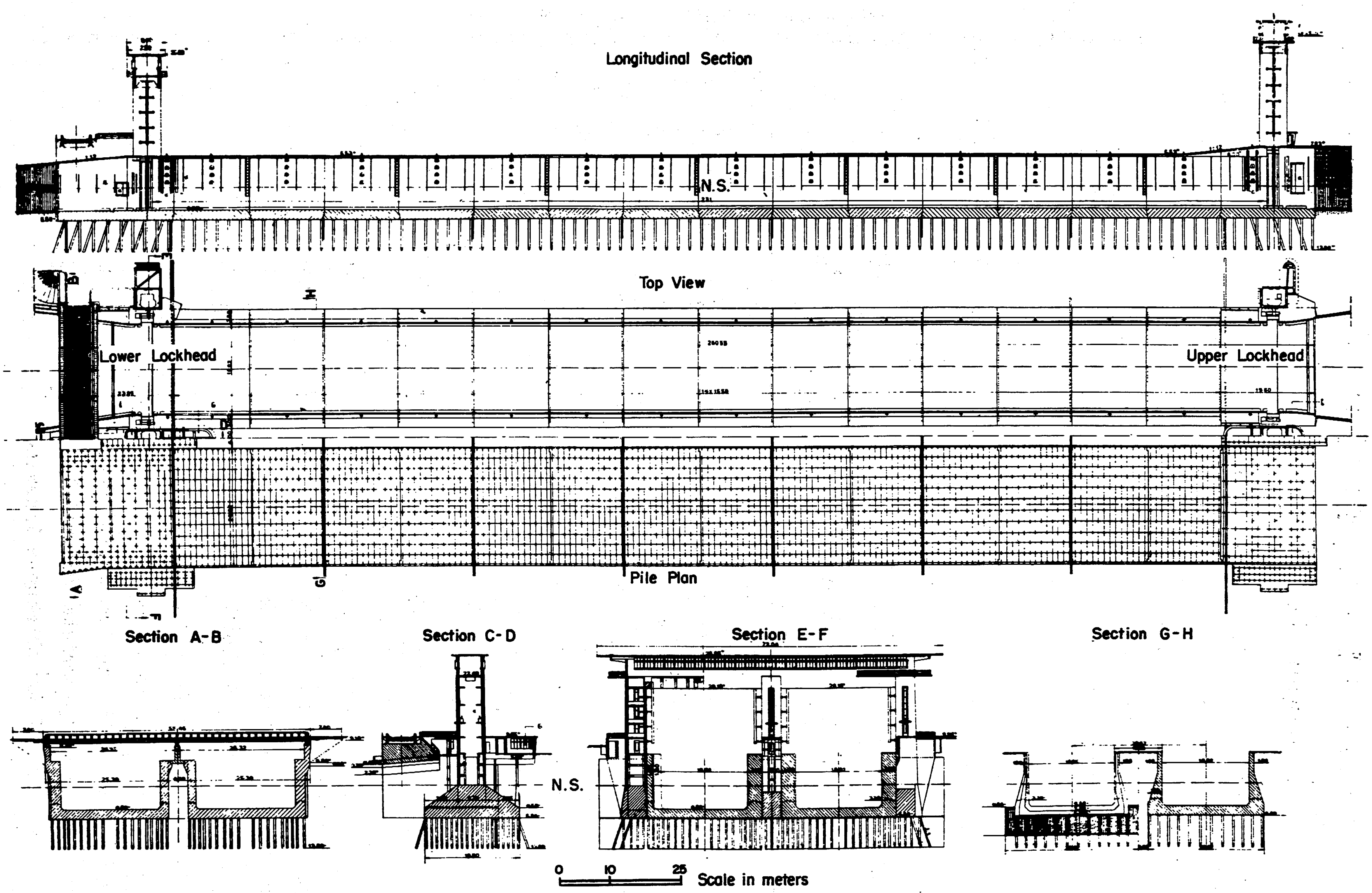

Fig. 2 - Details of Lock Design

**Legend :** ▬ Steel bulkhead. ▬ Wooden bulkhead. + Vertical Pile. ⊢ Buttress Pile. N.S. Normal stage.

resulted in adequate rigidity and the required overall weight could be kept as small as possible in connection with the uplift pressure. The largest number of piles per unit area occurs beneath the heavy walls. Buttress piles are used beneath the lockheads in order to take care of the horizontal pressure exerted by the gates on the lockheads in the direction of the approaches. The horizontal pressure in the other direction is absorbed by the lock-chamber floors. For this purpose, these floors fit closely against each other, are poured successively (narrowing of eventual expansion joints), and are continually kept under water after completion.

The vertical piles remain detached from the floor so that they would not heave during elastic deformation of the floor. The buttress piles are connected to the floor by means of reinforcing bars in order to prevent possible sliding. The piles are about 6.50 m long, have a square cross section of 0.35 m by 0.35 m, and carry a maximum load of 45 tons.

The two locks are constructed separately; this results in smaller structural units and more uniform construction elements (simpler construction operations). Moreover, it involves economy in concrete and reinforcing steel.

As a result of using a pile foundation, large spaces occur under the lock, as the soil, loosened by the pile driving operations, settles under the structure, so that a clearance is formed there (observed during construction of the north lock at IJmuiden). The main bulkheads are located under the lockheads. They are placed in such a way that the upward pressure under the latter depends on the water outside the locks; a smaller load on the piles is achieved in the case of the upper lockheads, while a sufficiently large overload on the piles is obtained at maximum head in the case of the lower lockheads in connection with the thrust on the buttress piles designed to absorb the horizontal pressure against the gates.

The gate portals are designed separately from the lockheads. The resulting advantages are:

(a) The heavy towers are supported by the piles in the most effective way.

(b) The lockhead floor is less heavily loaded, not only due to the adequate support of the lift towers, but also because large forces never act on the walls when the gate portals are stressed.

(c) The foundations of the lift towers may extend partly outside the lockheads; thus, the gate can be installed near one end of the lockheads.

(d) The vertical settings and movements of the gate portals are independent of those of the lockhead walls.

(e) Smaller construction units.

(f) Simpler wall profiles.

The disadvantages are unimportant.

The portals are to be made of concrete, because steel portals are not any cheaper and require additional maintenance. It is planned to erect three separate towers, then the gate portals shown in Fig. 2. The advantages of portals are in this special case:

(1) One gear system per gate for the gate operation.

(2) The bridge (upper beam) absorbs the stresses arising due to eccentric loading of the towers.

(3) With the aid of the catwalk, installed in the upper beam, the valves in the gates and their mechanical parts can be readily exchanged, and at the same time the catwalk can serve for mounting and renovating the gate gear system, the counterweights, etc.

(4) In case the electric power is interrupted, the gates can be operated by means of a Diesel motor.

(5) The upper beam can be utilized for suspending and exchanging the gates.

Except for the higher cost involved, the disadvantages are of no importance. Suspending the gates with the aid of floating pontoons was difficult in the present case because of the large weight of the gate (166 tons) and the presence of the traffic bridge.

## IV. INDIVIDUAL CONSTRUCTION DETAILS

Reinforcing. The reinforcing distribution in the construction units is designed to resist shear (Fig. 3). Thereby consideration was given to the fact that direct shear occurs only when there is resistance to expansion or contraction of the walls. During construction, the concrete below the construction joint, which has already set, will resist shrinkage of the fresh concrete poured above the joint and, after construction, the friction between the ground behind the walls and the wall proper will oppose any change in wall length due to temperature variations.

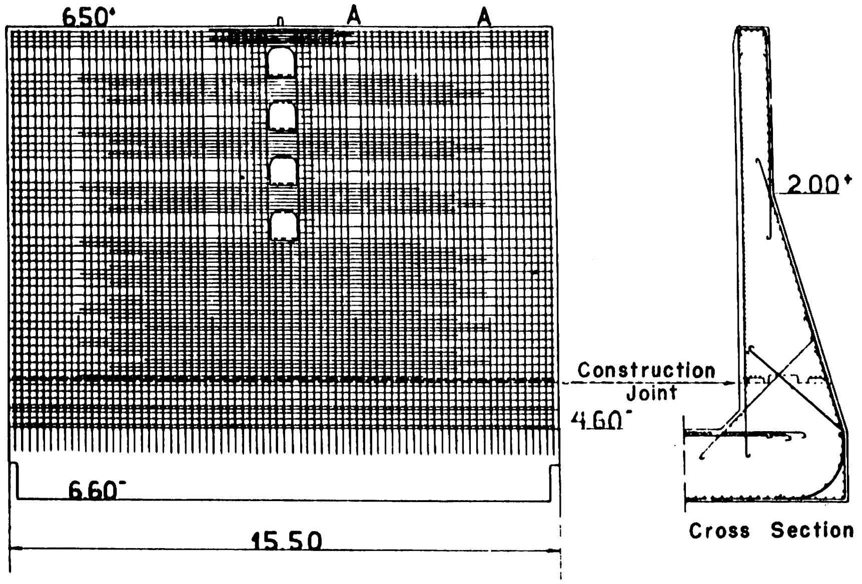

Fig.3 – Type of Wall Reinforcement
All horizontal bars are without joints. 'A' indicates location of steel bumpers.

In connection with the first factor, extra reinforcing is placed immediately above the construction joint, while in connection with the second factor, the reinforcing distribution is most concentrated in the middle and gradually decreases towards the ends.

Use of reinforcing against sliding in the gate recesses and portals is entirely avoided, except at the construction joints. No bracing occurs there, except in the gate portals. There is no danger that the upper reinforcing rods of the floors will straighten if they are located in the pressure zone; the weight of the concrete cover above the reinforcing is in itself sufficient to oppose the straightening. Moreover, there is at least some bond between the cover and the underlying concrete.

Projections, etc. Projections from the walls, such as supports for the mooring posts, are avoided because they make it difficult to use single forms. Use of recesses in the concrete should not be ruled out on this basis, but they facilitate the occurrence of shear. Therefore, the ladder recesses, for example, are located at the end of the wall sections.

Joints. The horizontal joints expose half a tooth. A whole tooth is not used because it is difficult to avoid air and foam beneath the tooth during pouring of the concrete. A water seal is obtained by using hemp rope

(7.5 cm in diameter) impregnated with asphalt (free imitation of the lock of the Twenthe Canals).

The joints between the walls and the foundations of the gate portals consist of asphaltic sheets 0.035 mm thick, which are fairly hard when dry and very soft when wet, without increasing in volume. In order to keep these sheets dry during pouring and hardening of the concrete, they are covered with felt free of tar. These sheets are omitted in some places, so that the concrete footings of the lift towers are effectively supported on the lock floors.

## V. EXCHANGING THE GATES; LIFT GATE STORAGE

To assure maximum operating effectiveness of the locks, the simple and rapid mode of exchanging the gates, after damage by collision, for example, is regarded as an aspect of primary importance to which attention is paid from the beginning of the design work. It involves replacing very heavy objects which necessitates the use of heavy equipment. The separate elements of this equipment which must finally be operated manually, such as the pin inserted into the gate prior to hoisting operation, for example, likewise are so heavy (180 kg) that normal handling is impossible. Therefore, the entire process of exchanging the gates is completely prepared in advance and all the necessary equipment is arranged in such a way that all operations could be performed in a simple and rapid manner and with minimum personnel, exertion, and hazard.

As stated previously, the advantage of gate portals above separate towers in the present case is that the upper beam can be utilized in the process of exchanging the gates. To facilitate suspension of the gates from the portals, a 27.5-ton hoisting winch, equipped with a 16.5-hp alternating current motor, is installed and anchored to one of the lock walls near the gate portal involved. This winch, which weighs nearly 20 tons, is movable on wheels with rubber tires, as a tractor cab. The wheels of the winch are removed prior to anchoring.

In the meantime the hoisting tackle, with a capacity of 190 tons,* is arriving by boat. It consists of an upper pulley and lower pulley, both

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*That is, the weight of the heaviest gate for the Amsterdam-Rhein Canal, namely, that of the Wijk lock at Duurstede.

of which have shafts rotating on supports. Each pulley contains five sheaves 900 mm in diameter, the outermost being located outside the webs in order to facilitate reduction of the shaft cross section (Fig. 8).

Subsequently the hoisting cable is clipped and fastened to the winch drum. Then the upper pulley of the tackle is hoisted up with the aid of the traveling crane mounted in the gate portal. For this purpose, the crane is attached to the top ends of the webs. After the brackets c, welded to the webs, have been raised above the floor of the upper beam, steel beams are placed under them and the pulley is lowered to these beams, after which the traveling crane is disconnected from the pulley. Then a grooved yoke j of cast steel is placed with the aid of the traveling crane on the web ends protruding above the floor in such a way that these ends protrude above the grooves. Afterwards the pulley is again lifted by the crane and heavy pins are inserted through the holes prepared in the webs. Finally the steel beams (mentioned previously) are removed and the pulley is adjusted until the pins fit properly into the surface of the yoke j.

When the upper pulley is in place, its shaft ends fit into grooves covered with cast steel and located on the underside of the floor stiffeners, so that the pulley can resist the horizontal thrust occurring during hoisting of the gate.

The next manipulation is the hoisting of the lower pulley with the aid of the winch for the purpose of attaching the gate. The latter occurs by inserting a loose bolt, attached to the lower pulley, between existing partitions in the gate in such a way that it becomes possible to insert the heavy pin weighing 180 kg. This pin is machined taperingly and is placed in advance, with the aid of the traveling crane, on an iron slide q which is attached to the gate structure (upper right of Figs. 6 and 8).

After the gate has been attached, it is hoisted so high that, after several guide rollers are pushed inward, the gate can be removed from the guides (Fig. 4a). During the hoisting operation the pulleys of the hoisting tackle are lubricated with the aid of high pressure grease pumps.

Subsequently the gate is lowered with the aid of the winch and set vertically on two specially constructed pontoons P for which, with the aid of the 5-ton hoisting mast located on one of the two pontoons, heavy I-beams are inserted through the extreme valve openings provided in the gate (Fig. 4b).

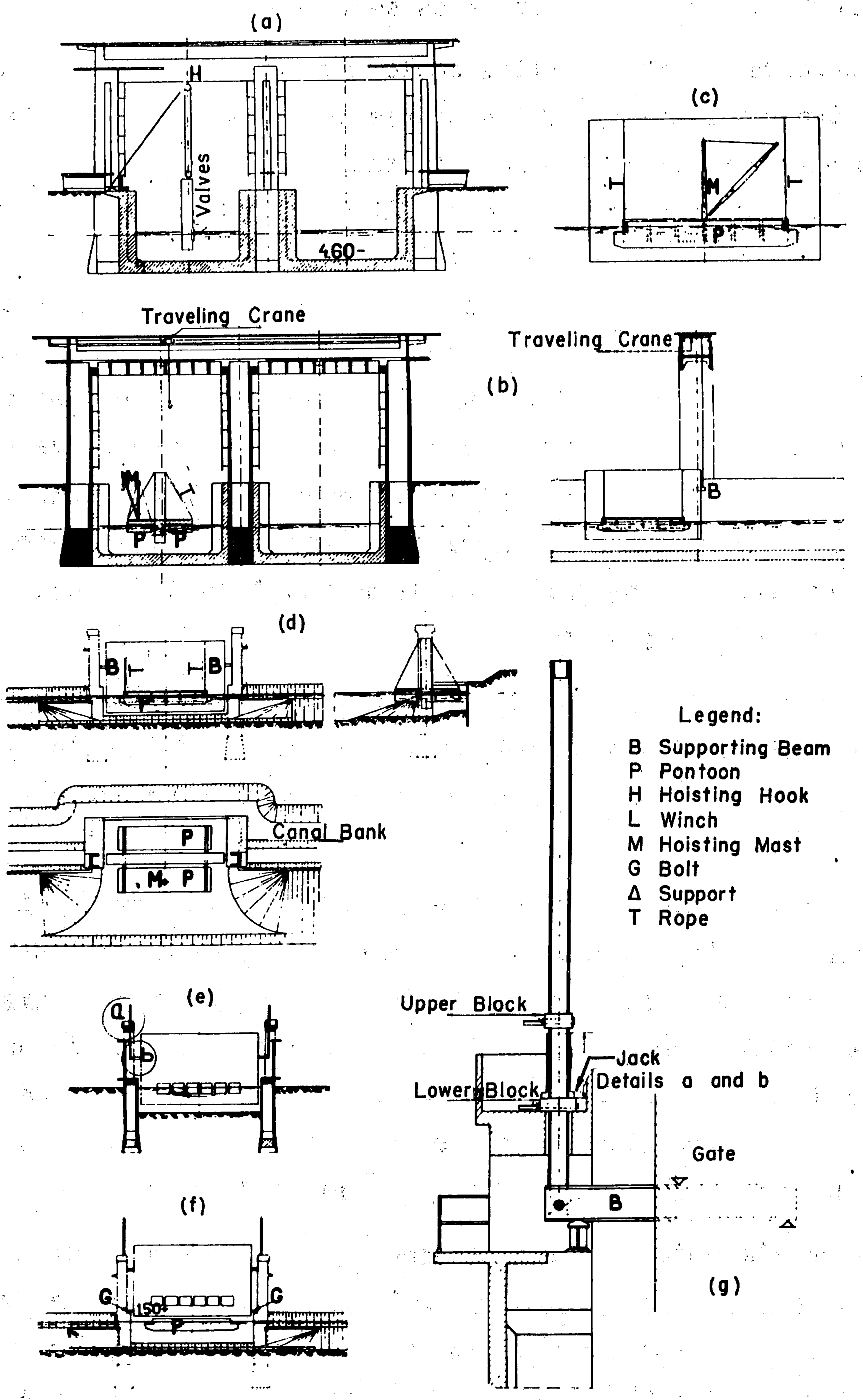

Fig. 4 – Diagram Showing the Process of Exchanging and Storing a Lift Gate

(a) Gate is lowered. (b) Left: gate is removed on pontoons; Right: one of the beams B is forwarded. (c) Side view of gate during transport. (d) Gate arrival at storage place. (e) Gate is jacked up. (f) Gate is in place. (g) Details of top of towers and jacking arrangement.

Then the tackle can be disconnected from the gate and the gate is moved as a float (Fig. 4c). Ropes are provided in order to prevent capsizing of the gate in the case of extreme tilting of the pontoons during storm or because of leakage.

While the gate is being removed from the lockhead, the new gate, resting on two other pontoons, can be forwarded and the process (outlined above) of the suspending operation is repeated in reverse sequence.

The gate which is removed from the lock can be stored, suspended in a vertical position, in the lift gate storage place prepared in the canal bank ± 1 km north of the locks (Figs. 4d, 4e, and 4f). This storage place consists of two concrete towers on foundation pits. A small harbor is formed in the bank between the pits by means of an enclosure of iron sheeting. The gate is brought into this harbor in such a way that it remains afloat with its longitudinal axis between the towers. Then the gate is jacked up until its lower edge is so high above the water that the pontoon landwards of the gate, which is not equipped with a hoisting mast, can pass beneath the gate. Thus, no floating pontoon is required for storing the gate.

The jacking operation can proceed in the following manner. With the aid of the traveling crane located in the horizontal beam of the gate portals, the beams B (Fig. 4b, right) are lowered into the gate, being rolled on rollers if necessary, and are placed in prepared cushion blocks in the interior of the gate. Upon arrival at the lift gate storage place, two heavy iron bars are fastened to opposite sides of the structure and pass vertically through holes in the high ledge of the towers (Fig. 4g). These bars move through the grooves of two cast steel blocks located above this ledge. A steel pin is inserted through the upper block and the corresponding hole in the bar; this pin is placed in advance on a slide attached to the block. A 120-ton hydraulic jack, having a displacement of 0.80 m, is placed on each tower between the two blocks and bars. After the hydraulic jacks have been pressed upwards, a pin is inserted through each of the lower blocks and the corresponding hole in the bar; then the jacks are released and, after the pins are removed from the upper blocks, these blocks are lowered to their original position. Subsequently the pin in each tower is reinserted through the upper block and then the pins are removed from the lower blocks. Then the jacking operation is continued.

These manipulations are repeated until the gate is raised sufficiently high. Then a roller is placed on one side of the gate under the end of the beam B which is attached to the bar, and a stiffened I-beam is placed on the other side of the gate, so that the gate finally rests on a roller and on a fixed support. The bars can then be removed and the jacks can be stored. Finally the gate is bolted below to prevent swinging due to strong winds (G, Fig. 4f).

The valves of a stored gate are located on the canal side, so that they are within reach of the hoisting mast of the pontoon and are available as reserve valves for the other gates. Storage of a gate can be effected in a workday of 8 hr. Since facilities are available for storing only one gate, it is essential to have four pontoons available, namely, two pontoons to transport the gate for repairs and two pontoons to transport the reserve gate. Thus, two pontoons take the place of a second lift gate storage place.

To assure stability, each pontoon contains watertight partitions, both longitudinally and transversely, in case it is filled with ballast water. The partitions do not extend to the deck. The hoisting mast is supported at the center of the partitions, at the point of their upper surface, and in the deck.

The hoisting winch, the hoisting tackle, and the pontoons are designed to serve all the lift gate locks of the Amsterdam-Rhein Canal, so that their cost is not attributed to the Wreeswijk locks only. In addition, the pontoons are necessary for exchanging the miter gates of the Ravenswaay lock system.

Since the elevation of the bridges across the canal section north of the Lek River is not the same as that of the bridges south of this river and since the canal depth at the section mentioned above is not constant, it is necessary to support the gate at various elevations with respect to the pontoons. The dissimilar elevation of the upper beams of the gate portals of the various locks of the canal with respect to the water below the portals and the dissimilar height of the gates involved some difficulty in designing the drum of the hoisting winch because the required cable length differed in each case.

The simplest solution would be to make the winch drum so large that it could accommodate the longest cable involved (it was regarded unsatisfactory to wind the highly stressed cable in additional layers around the drum). However, such an arrangement would require a larger and wider drum than the one already designed at the time, and therefore, would result in a heavier winch. In connection with transporting the winch to the destination, moreover, the winch width is limited to a definite maximum, while the weight of the winch, even without a larger drum, has practically exceeded the allowable maximum. Therefore, upon recommendation of J. G. Snip, engineer of the Waterways Department who assisted in the design, the drum side was provided with a depressed section in which the variable excess of the cable length was stored prior to hoisting the gate. Afterwards this section was covered with lids which formed a continuous surface with the drum after installation and were provided with grooves just as the drum proper. Prior to lifting the gate, the cable was wound two or three additional times around the drum in order to prevent excessive stressing of the stored cable section during hoisting.

Since during initial operation of the hoisting winch the lower pulley of the hoisting tackle (weight ± 4 tons) is raised to about the upper edge of the gate, the first portion of the cable may be much thinner than the rest of the cable (respective diameters 16 and 44 mm). The entire thin portion is always stored in the deepened section of the drum.

In addition to the functions mentioned previously, the pontoons can be used for the following purposes: to transport safely the gates, for every lock of the Amsterdam-Rhein Canal, as well as the corresponding bridges from the factories where these objects are prepared to the locks; to erect or place the gates and bridges in their appointed places; to perform various maintenance purposes. Two pontoons can be coupled together by means of heavy I-beams in order to increase the stability for hoisting heavy loads.

## VI. THE FOOTBRIDGE

The footbridge is a sheet steel bridge on three supports. The footpaths are located outside the main beams, so that the path facing the locks is used also for servicing the locks.

Transport of the bridge occurs with the aid of the pontoons described previously. The bridge must pass under an existing traffic bridge; therefore, its elevation above the pontoons is limited. Raising of the bridge occurs as follows (Fig. 5).

One of the bridge ends is attached to the hoisting tackle which in turn is fastened to the gate portal of one lower lockhead. Then the pontoons under this end are sunk by means of water ballast as deep as possible and a buffer is placed between the pontoons and the bridge. Afterwards the bridge is moved until its other end is under the hook and the same procedure is repeated. Then all the pontoons are pumped dry, whereupon the bridge floats higher above the water. These manipulations are repeated until the bridge floats sufficiently high to permit placing it in it's final position.

## VII. ARRANGEMENT OF THE GATES IN CONNECTION WITH FILLING AND EMPTYING THE LOCK CHAMBERS

As stated previously, the filling or emptying of the lock chambers occurs through valves in the lift gates. The other system under consideration, namely, complete lifting of the gate at full water pressure, was regarded as difficult from the construction standpoint because the maximum water pressure here amounts to approximately 900 tons and, moreover, the gate must be able to operate in both directions.

When a comparison is made between the two systems, it is found that the system used has the following advantages over the other system:

(a) During filling operation the inflow can be directed towards a favorable place in the chamber, so that it is possible to avoid the use of baffles or guide vanes in the concrete lock floor and the adjoining sections.

(b) During the water flow the gates rest on wheels that are not heavily loaded.

(c) Use of elastic or hinged sheets for sealing the gate sides can be omitted.

(d) The largest possible reserve can be obtained for the water inlet and outlet.

(e) Lighter actuating mechanism of the gate.

Contrasting these advantages are the following disadvantages:

(a) Less simple and heavier gates.

(b) Larger developed leakage joint.

(c) Without special provisions, the gate cannot be closed in the flowing water, which may be necessary after serious damage of the operating gate.

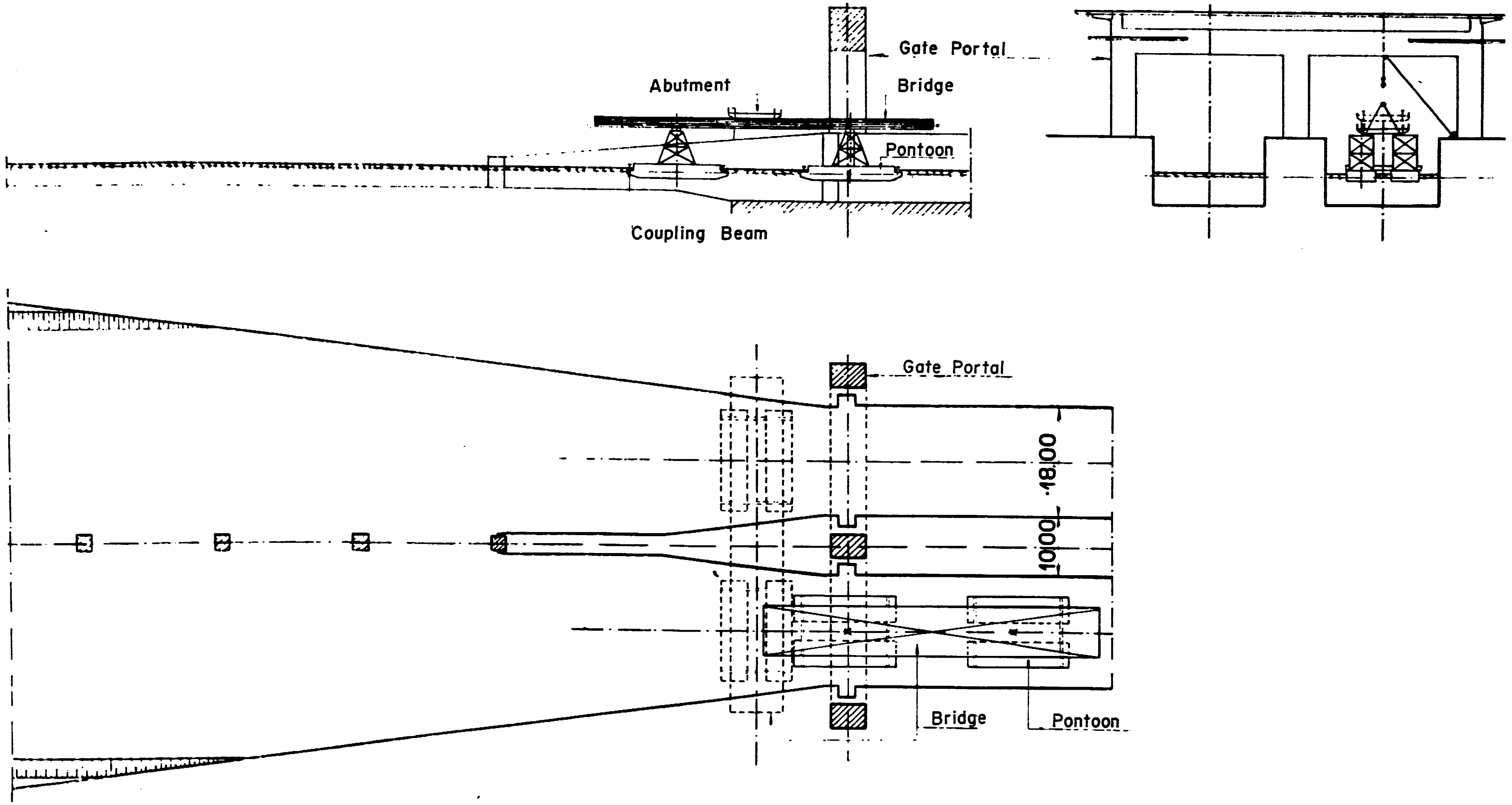

Fig. 5 – Diagram Showing Installation of the Bridge

(d) Without special provisions, the gate cannot be opened at water pressure, which may be necessary in order to shorten the filling period.

(e) The necessary presence in the gate of the valve-actuating mechanism and of the inflow.

In designing a filling system, it is endeavored to exploit these advantages and to mitigate the disadvantages. In order to overcome the disadvantages listed under (a), (b), (c), and (d), slide valves are used in the gates, together with a compensating device, as described in De Ingenieur, No. 36 of 1934.

By inserting a wedge, this compensator can be fixed with bearing wheels and an arbitrary gate can be readily closed after the other gate of the same lock has been damaged due to collision; this is also possible in the case of overloaded wheels.

## VIII. TESTS AT THE DELFT HYDRAULIC LABORATORY

The elevation of the valves is such that the inflow meets the chamber water approximately at midheight, so that a surface wave and bed wave, which counteract each other, occur in the chamber shortly beyond the gate.

According to tests conducted at the Delft Hydraulic Laboratory, the mode of filling the chamber was quite satisfactory in principle; but measures had to be taken against the detrimental drop in water level of the chamber immediately in front of the gate. These measures comprised installing baffles or guide vanes in the gate, the function of which was to direct the inflow specifically towards the low water forming in front of the gate.

If the guide vanes had not been installed, the ships could approach the gate at maximum lift to within 25 m, without subjecting the hawsers to excessive stresses. This distance is reduced to 4 m when the guide vanes are installed.

Since the valves occupy practically the entire breadth of the lock and the guide vanes produce proper vertical distribution of the water, it can be stated that this system satisfies also the general principle which must be observed in similar filling operations, namely, that the inflow become uniformly distributed over the entire wetted profile of the chamber as close beyond the gate as possible.

Since the ships in the canal never are located immediately near the lower gates during emptying of the lock chamber,* it was unnecessary to equip also these gates with guide vanes.

The lower edge of the valves is miter shaped in order to reduce the initial rate of inflow into the chamber. Thus, the rate of valve operation can be kept constant at 5 mm per sec. At maximum lift (6.40 m) the filling time is 8 min; this time can be shortened to 7 min by raising the gate when the head is reduced to 0.20 m. Premature raising of the gate proved not to be detrimental to the ships at any of the water levels in the chamber. However, a gradual increase in gate speed was found to be desirable. In the case of emptying the lock chamber, it proved advantageous not to raise the gates completely because the corresponding gates are not equipped with guide vanes. Nevertheless, the size of the valves had no relation to establishment of the level in the lock chambers. This size is determined in accordance with the discharge considerations and the desirable uniformity of all gates.

It was further established in the laboratory how far the partition wall (Fig. 1) of the locks must be extended in the direction of the canal in order to prevent the effects of emptying one lock chamber on the ships entering the other lock. Finally it was established whether elimination of the discharge from one valve is detrimental to the ships. It was found that the flow must be kept symmetrical continuously.

## IX. EXPERIMENTS TO DETERMINE THE ACTUATING POWER FOR THE VALVES IN THE GATES

The use of large slide valves (that is, six valves per gate, each closing off an opening of 5 sq m) is motivated only if the required actuating power is not excessive. It must not be forgotten that the actuating mechanism of the valves always moves up and down with the gate.

Since literature does not contain any adequate and agreeing information about friction coefficients of metals, tests were conducted on a metal strip 0.20 m long and 0.05 m wide, under a load of 5 to 20 kg per sq cm,** and sliding back and forth over another metal strip in a container with water, the distance between the two strips being about 0.25 m. The attraction force at the contact surface of the metals can be evaded by applying a bending moment.

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*See Fig. 1, for example.

**The highest pressure occurring in the canal (the Wijk lock at Duurstede).

Earlier tests, conducted by Koning and Bienfait in Amsterdam on behalf of the north lock of IJmuiden, showed that rust greatly increases the friction coefficient. Therefore, it was decided to use strips of stainless steel. It was hoped that use of hard metals would decrease the friction coefficient, as the molecular attraction between the contact surfaces of the two metals would be smaller.

It was found that strips of stainless steel of various composition were not satisfactory for sliding over each other. Soon the adhesion became so strong that it destroyed the contact surfaces by forming deep and wide grooves in the strips. Bronze, composed of 87 per cent copper and 13 per cent phosphorous tin, on stainless steel was not satisfactory, probably because the bronze layer seemed to contain microscopically small serpentine irregularities which increased the friction in the long run. Moreover, the motion became rather jerky after a shorter or longer time, depending on the type of metals. After the contact surfaces had been cleaned, the friction coefficient was repeatedly reduced to a great extent and the jerkiness no longer occurred.

The most satisfactory results were obtained by using stainless steel of strength exceeding 100 kg per sq mm (Brinell hardness greater than 300) and cast bronze composed of 88 per cent copper, 8 per cent tin, and 4 per cent zinc, which is hard and forms a powdery layer. The jerkiness did not occur, but the friction coefficient remained fairly high, yet fairly constant (maximum 0.3 to 0.5, depending on the type of steel and the load).

Hardwood on iron or bronze was definitely unsatisfactory. Finally bronze strips lubricated with grease and sliding over stainless steel strips were used. It was found that the two metals stuck to each other after some time interval. In order to reactuate the bronze strip, it had to be just pulled loose, which required a force that never exceeded 18 per cent of the load. Immediately after the strip was freed, the friction coefficient again decreased to its normal value (less than 0.08). The type of bronze or stainless steel was found to be of minor importance when grease was used.

The presence of some sand in the grease between the strips, which is likely to occur in actuality, did not affect the results. The grease used was waterproof, so that excessive lubrication was unnecessary.

The tests have made no contribution to the scientific field. The practical results were:

(a) There exist metals which may be used for valve surfaces in the case of lubrication exclusively with water, but a high maximal friction coefficient should be anticipated, namely, 0.3 to 0.5, depending on the type of metals which slide over each other and on the load involved.

(b) The friction coefficient at small loads is generally higher than at large loads, although this fact does not imply any fixed law.

(c) The favorable results were obtained with types of hard stainless steel and types of hard bronze (cast in molds).

(d) Water lubrication has a favorable effect on durability and on quiet sliding motion.

(e) The wearing of metals which are not mutually corrosive is inconsequential in each case when the load does not exceed 20 kg per sq cm and water lubrication is used.

(f) In the case of nonlubricated metals or metals that are lubricated only with water, the friction coefficient at slow motion does not differ much from that at rest (the difference is generally less than 10 per cent).

(g) In the case of lift gates which are regularly raised above the water and, therefore, must always be controlled, the use of slide valves is quite justifiable if adequate grease lubrication is provided. Technical progress assures proper grease lubrication (high pressure grease pumps).

(h) When the drag exerted on a liberally lubricated slide valve amounts to 20 per cent of the load on the valve, there need be no fear that the valve could not be set into motion. Immediately after the valve is set into motion, the required actuating power decreases appreciably.

(i) Not every waterproof type of grease yields favorable results.

## X. DESIGN OF THE LIFT GATES (FIG. 6)

Introduction. The lift gates of the lower lockhead and upper lockhead differ only in height. The reserve gate fits into both lockheads: the low gates are readily converted into high gates by means of an additional section 1.30 m high. Figure 6 shows a high gate, while Fig. 8 shows a low gate.

The design of the lift gates is completely dominated by the six valves which each gate contains. The valves are located at the outer covering of the gates, so that they can be readily exchanged, and the interior of the gate serves as a distributing manifold for the water flowing into the lock

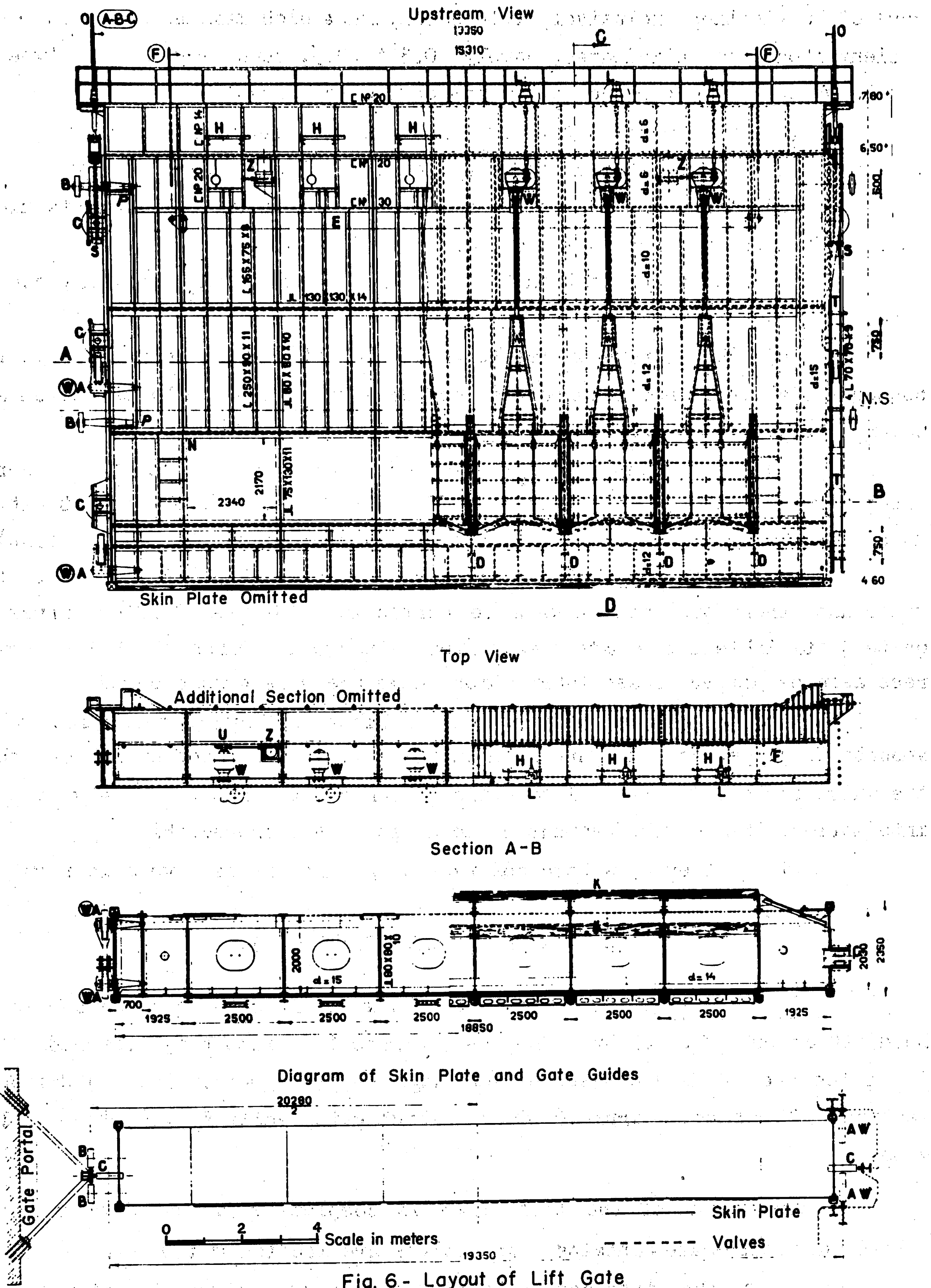
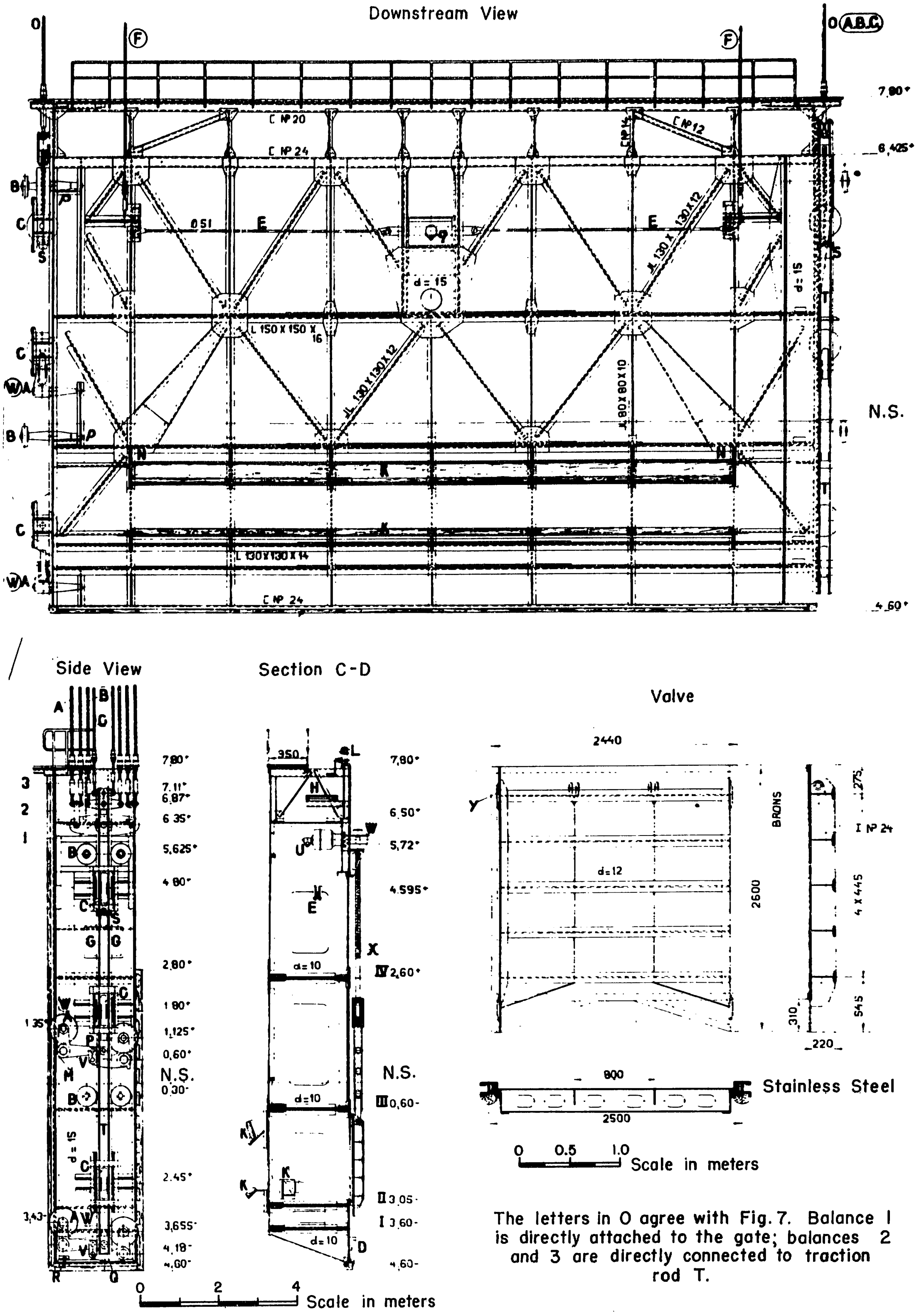


Fig. 6.- Layout of Lift Gate
The drawing shows a high gate; a low gate is obtained by removing the section between 6.50m + and 7.80m +.



The letters in O agree with Fig. 7. Balance I is directly attached to the gate; balances 2 and 3 are directly connected to traction rod T.

Fig. 6 - Layout of Lift Gate
The drawing shows a high gate; a low gate is obtained by removing the section between 6.50m + and 7.80m +.

chamber during filling operation. Since the interior of the gate serves as a turbulence basin, the chamber section which is subject to damage, and thus the lock chamber itself, can be shortened. Exchanging the valves can be effected with the aid of the traveling crane located in the gate portals, for which purpose holes are prepared in the floor of the machine room, centrally above the gates (A, Fig. 8, lower left), or with the aid of the hoisting masts of the pontoons.

In connection with the selected location of the valves, it was essential to make the outer covering waterproof. This would require a watertight side seal of either elastic or hinged sheets, or watertight headwalls. Since the headwalls would have to be very heavy in order to distribute uniformly the reactions of the members over the height of the gate, they may just as well be made watertight. This is effected in order that the elastic or hinged sheets, which are commonly less desirable, could be omitted.

Framework. The framework of the gates consists of sheet metal horizontal and vertical beams, designed as economically as possible. The economy was governed by the transverse force. Preference was given to sheet iron structural members over latticed beams because the former can be repainted more readily, have greater stiffness, and can be fabricated cheaply. In addition, latticed members would have had to be higher than the sheet iron members, which are merely 2 m high, so that the thickness of the gate as well as the length of the concrete structure would have become larger. An advantage of the latticed structural members is the numerous openings through which the water can circulate during the motion of the gate. In order to overcome the disadvantage that sheet iron members obstruct the circulation, large holes are provided in the webs of the members and, in addition, the upper-edge angle iron is omitted at the pervious gate side. During motion of the gate the water immediately above the horizontal members will be diverted especially across the edge, which it does most readily, and also through the large holes. The resulting achievement is smaller resistance to which the gate is subjected in the water.

Another result is that the water contained in a gate section, unlike in the case of previous lift gates with sheet iron members, cannot be diverted sufficiently fast when this section is being raised above the water level, so that initially the water is lifted together with the gate. (The reverse phenomenon occurs during lowering of the gate: insufficiently rapid inflow and, consequently, the initial crowding of the flow through the member of this gate section).

Omission of the upper-edge angle iron of the horizontal member immediately above the valve openings was found to be essential for the stable position of the ships in the lock chamber during filling operation. Due to the suction effect of the inflow beneath this member, a strong drop in level occurs above the member; initially this drop remains steady because the angle iron impedes the inflow from the chamber, but as the water in the chamber continues to rise the depression suddenly becomes inundated, which produces a force acting on the ship moored in the lock chamber in the direction of the gate.

The edge of the horizontal members on the pervious side of the gate has become unsymmetrical and is therefore disadvantageous as far as stresses are concerned. Because of the asymmetry, the stresses in the lower-edge angle iron are higher. Therefore, steel of type 52 (standard specifications) is used for this angle iron, while steel of type 37 is used for the other angle irons.

The web plates of the horizontal members (18.85 m long, 2 m wide, and 15 mm or 12 mm thick), the cover plates and angle irons, and the lower facing strip are of the same length.

Calculation of the Framework. Calculation of the gate framework proceeds on the assumption that the vertical members are supported on the horizontal members. Therefore, they are regarded as beams having several (that is, four) supports. It was endeavored as much as possible to obtain equal maximum support reactions of the vertical members, so that only one type of horizontal member would be sufficient. However, since the location of two horizontal members is established, namely, on opposite sides of the valve openings, this advantageous arrangement could not be achieved and two types of members were used (member I = member II and member III = member IV; the upper members are the heaviest). Besides the vertical members, the horizontal members are likewise directly subjected to water pressure.

The preceding mode of calculation is possible because the bottom section of the gate is not formed by a sill and, therefore, can deflect freely.

The allowable stresses are taken as 1400 kg per sq cm for the steel of type 37 and 2100 kg per sq cm for the steel of type 52.

Skin Plate. The skin plate consists of flat plates stiffened with bulb irons. The bulb irons are vertical in order to reduce the resistance during the motion of the gate. Buckled plates are not suitable because of the resulting lesser rigidity of the gate (particularly for suspending the gate during normal operation and during mounting), the higher cost due to excess weight and correspondingly heavier counterweights, and because water pockets occur between the buckled plates and the raised valves; these pockets can yield the water only very slowly, so that initially this water is raised together with the gate. The allowable stress was taken as 1000 kg per sq cm, whereby no allowance was made for rusting and the rivet spaces were not deducted.

A gutter is arranged below and along the skin plate; it forms one unit with the bottom section and does not protrude from it, in order not to increase the resistance during motion of the gate.

Latticed Struts. Latticed struts were used on the side of the gate not containing the skin plate; the struts were designed to support the gate during operation (at the ends) and during mounting (in the middle). Above the upper angles N of the valve openings, located farthest apart, the struts assume an irregular form designed to facilitate supporting the gates on the heavy I-beams (No. 80) during transport with the aid of the pontoons.

Valves (Fig. 6, lower right). The web plate of the horizontal member located immediately above the valve openings coincides with the lowest water level of the canal, while the upper edge of the valves is slightly below it.

The valves were designed as stiffened cast steel plates made of one piece, but due to circumstances of nontechnical nature they were fabricated as stiffened cast steel plates that were entirely welded. The valves have bronze slide surfaces 0.05 m wide (88 per cent copper, 8 per cent tin, and 4 per cent zinc; it was cast in molds). They slide over stainless steel strips mounted on the gates and having fairly high strength. The vertical stainless steel strips are lubricated at two points with grease that keeps well in water. Lubrication is effected by means of automatic high pressure grease pumps mounted on the gates and actuated by the valve-operating systems. The grease is pumped through copper tubes 7 mm in diameter and having a wall thickness of 1.5 mm.

When the valves turn water from the canal towards the river, some leakage is permissible because the heads involved are small. Then the cast steel outer edges of the valves slide unlubricated, perhaps like rusting steel. Although the resistance coefficient in this case would at least triple, no increase in actuating power is required because the head is less than a third of the normal maximum head.

Since lubrication is applied only to the vertical friction strips which are continually stressed during motion, it is essential to construct the valves in such a way that the pressure on the strips would be distributed vertically as uniformly as possible and that the water pressure on the closed valves would be taken up mainly by the strips. The latter is achieved by using flexible upper and lower ends of the valves and by spacing the horizontal stiffeners in such a way that the maximum deflection of the valves would be less than 1 mm.

In order to prevent touching of the horizontal bronze strips against the horizontal stainless steel, particularly during lowering of the valves when they are stressed by the water pressure, the horizontal strips are tapered on the long sides. In order to prevent oblique motion of the valves which are actuated merely by a spindle, bronze liners are installed to act as lateral guides (Y). Since these cannot entirely prevent jamming due to oblique motion, as the mutual distance is insufficient for this purpose, mounting of the valves is made in such a way that transverse stability is achieved by means of the lower liners and the actuating mechanism. For this purpose, the mounting arrangement of the valves consists of a triangular set of channels, stiffened by means of heavy welded pipes (heavy, to prevent grasping with boat hooks) and attached to the valves at two places by means of hinges; a spindle, which is much too heavy for proper motion of the valves, is rigidly attached to this system. The spindle is kept in its place by means of an adjustable nut as an accessory of the actuating mechanism. Thus, guiding occurs by means of guides located far from each other.

The guides between which the valves are moving are made in such a way that the stainless steel strips, which are attached by means of Muntz-metal bolts, can be readily replaced (Fig. 6, lower right). They require only a very small breadth (0.16 m for every two valves), so that the flow section could be as large as possible, and are finished with wood in such a way that the inlet losses in the valve openings are as small as possible. In case a gate might fall down, due to a mishap, it is stopped by the brackets D (Fig. 6) attached to the gate. The location of the brackets is such that arrangement of the valves in normal lowest position need not occur with great accuracy; this may be regarded as an advantage of these valves in comparison with valves which must be arranged in the lowest position.

Baffles. The baffles K, regarded as essential for the upper gates in order to distribute the inflow during filling of the lock chamber, are of creosoted Oregon pine and their most vulnerable corners are protected by a steel cover. Should the Oregon pine show rapid wearing, contrary to expectations, it would be replaced later by other wood. The greatest advantage of Oregon pine in the present case is its low specific gravity (0.6 in wet state).

A lower gate can be readily converted into an upper gate by installing the baffles and the additional gate section.

Compensator and Other Features. Several features are encountered in the gate headwalls. The most important pertains to opening the gates at a given head; it is a compensating device arranged as described in De Ingenieur No. 36 of 1934. The device is shown in Fig. 6. It is designed for a water pressure of ± 100 tons on the gate, yet the actual load usually is less than 50 tons, namely, for a head of ± 0.20 m, which is the head at which the gates will be opened at any water level in order to shorten the time of filling or emptying the lock chamber.

The wheels A of the compensator, which are not equipped with flanges, serve simultaneously as guide wheels in transverse direction during motion of the gate in the gate recesses. They gradually transfer their function to the wheels B which roll along the gate guides that are attached to the lift towers. These wheels are mounted on long shafts which can be pressed inward together with the wheels in order to free the gate from the guides, so that the gate could be removed from the lock. The slides p are installed for this purpose.

To guide the gate up and down, other flangeless wheels C are used. They are mounted on the gate and attached to the traction rod T of the compensator; in the gate recess they roll along a guide rail which is present there, and above the deck slab they roll along guides mounted on the lift towers. In connection with the gap between the guides (immediately above the deck slab), three rollers C are present on opposite edges of the gate.

All wheels are of cast iron (cast in molds). The shafts of wheels B and C are eccentric in order to facilitate initial adjustment of the wheels and adjustment after wearing. The wheels A can be adjusted by modifying the elevation of the stop S with the aid of washers and by shortening or lengthening the connecting rods V with the aid of eccentric shafts. Also the traction rod is adjustable in the direction transverse to the gate. Only its connection with the upper links P is fixed in this direction with the aid of washers; the connection with the lower links Q remains free to move in the direction transverse to the gate and adjusts itself properly.

In addition, provisions are made (holes G) for facilitating storage of the gate in the lift gate storage place by means of the inserted beams B (Fig. 4g).

An auxiliary partition is installed parallel to each end partition, where necessary, to support the shafts of the guide rollers, the shafts of the links of the compensator, and the beam inserted through the holes G. In addition, studs M are installed under the upper links P to support the gate on a beam placed above the gate recess, which may be necessary in order to replace the worn cables. Finally, point R (Fig. 6, side view) serves for bolting the gate in the storage place (G, Fig. 4f).

## XI. MECHANICAL AND ELECTRICAL EQUIPMENT AND CONTROL OF THE LOCK SYSTEM

The Gates. The operation arrangement of the gates is shown schematically in Fig. 7, and the corresponding definitive design is shown in Fig. 8. In each gate this arrangement consists mainly of a gear system located centrally above the gate in the horizontal beam of the gate portals, which is arranged as a machine chamber. This system actuates the sheaves which raise or lower the gate by means of cables. The gate is largely balanced by counterweights. Three counterweights are available at each edge of the gate--the small counterweight K and the double counterweight $G_1$ and $G_2$. The small counterweight hangs either from the sheaves or from the gate so that it is used for the motion of the gate. When the sheaves pull on the weight, the gate descends; conversely, when the sheaves pull on the gate, the weight hangs from the gate and constitutes the moving power or a part of it. When the gate is lowered, it is bolted by slight hoisting of the small counterweight. Then it is certain that the gate is actually closed.

The large counterweight normally hangs entirely from the gate by means of the cables A. The small counterweight K hangs from the sheaves by means of the cables D or is connected to the compensator of the gate by means of the cables C. When the gate is lowered and the small counterweight hangs from the sheaves for the purpose of bolting the gate, the compensator is released and the gate comes to rest against its sills at practically any water pressure. The wheels W then are free of the rails. If it is desired to discharge or admit water by raising the gate under a head, which would seldom be necessary, a greater pulling force than normal must be applied to the compensator in order to place the gate on the corresponding wheels. For this purpose, section $G_1$ of the double counterweight is readily hooked into the hook J (by means of inserting two wedges) which is connected to the compensator by means of cables B.

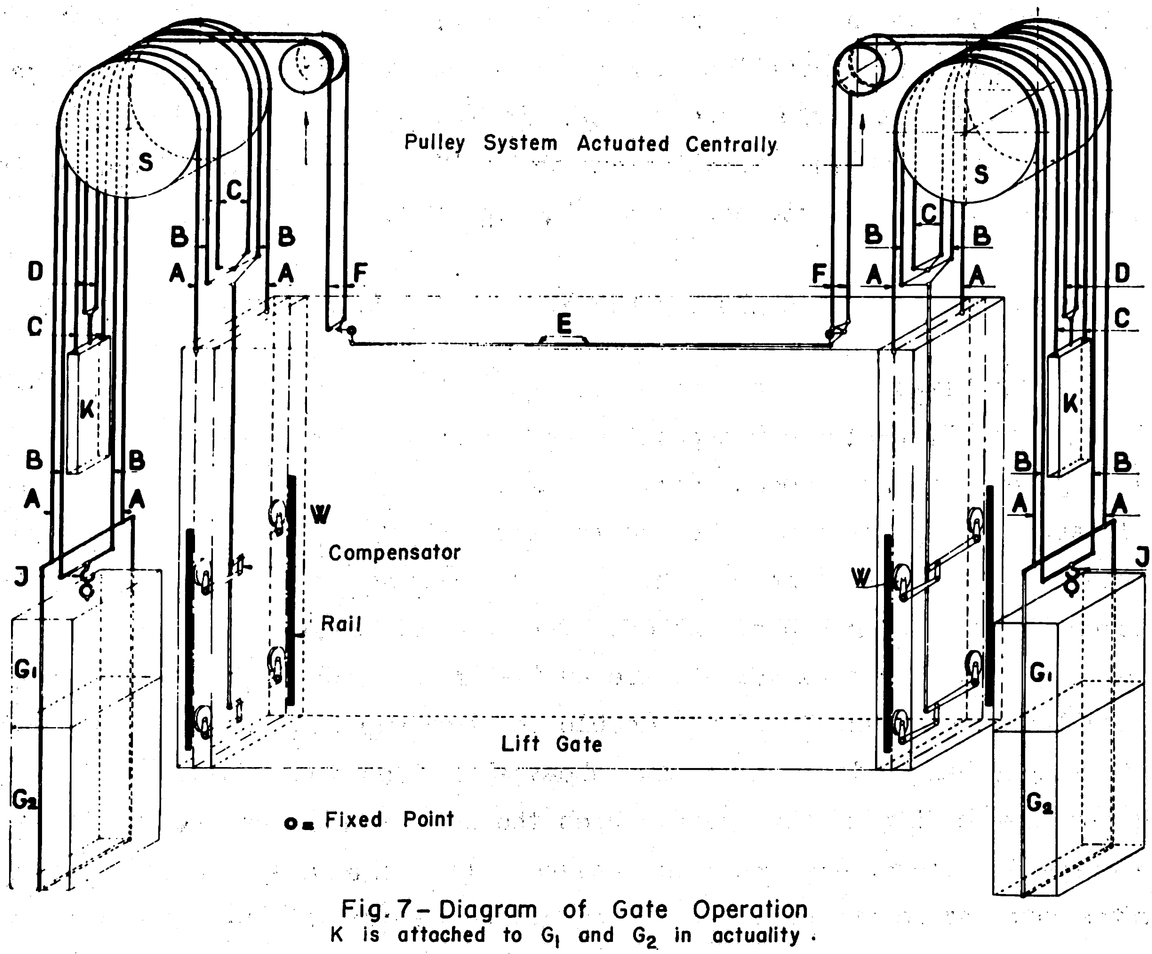


Fig. 7 - Diagram of Gate Operation
K is attached to $G_1$ and $G_2$ in actuality.

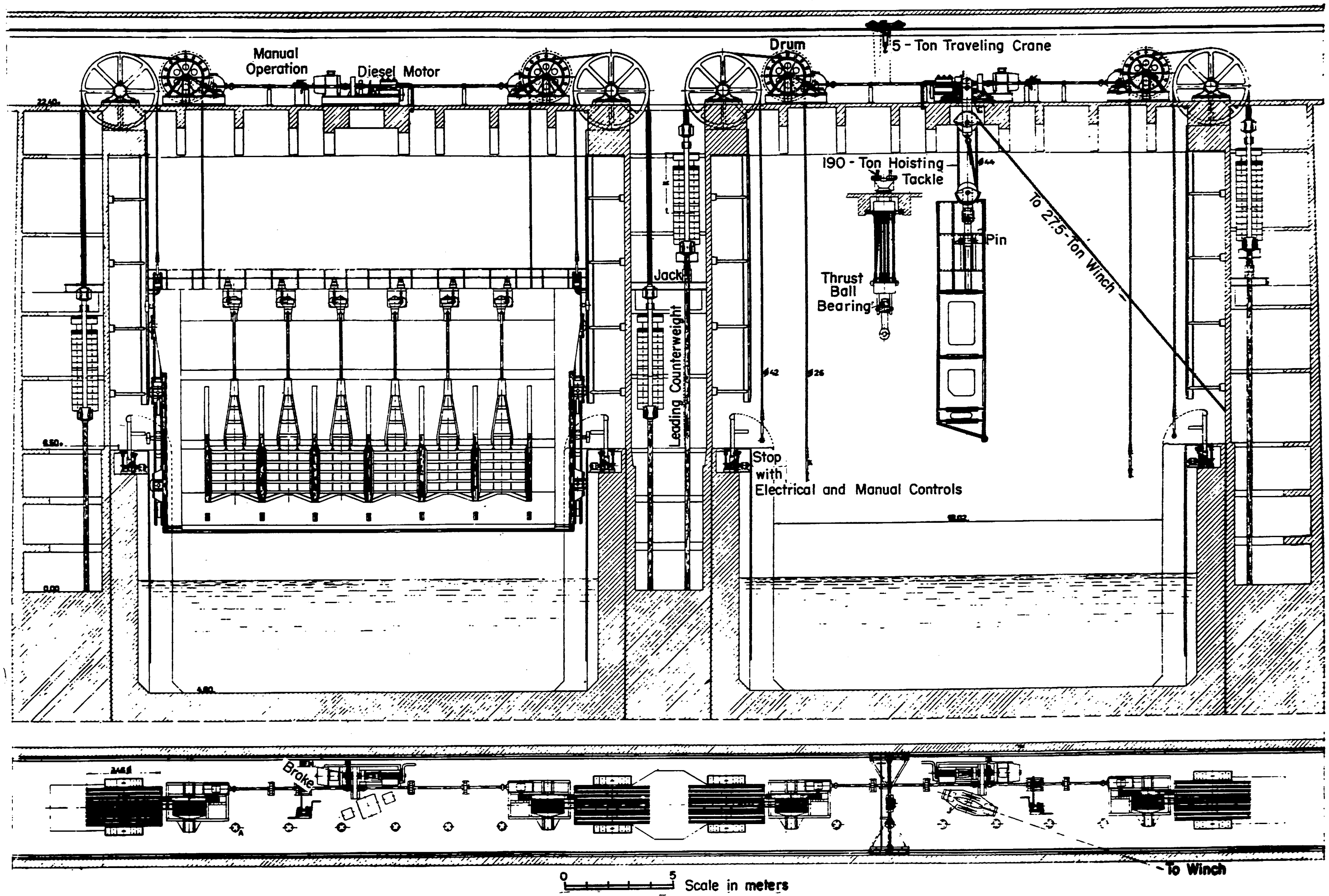


**Fig. 8** - Actuating Mechanism of Lower Gates

Left : Gate in motion. Right : Gate suspended; counterweights are temporarily supported. Below : Horizontal section through the machine room in the upper beam of the gate portal.

The cables involved move over sheaves S̲ of large diameter (3.46 m). These are more expensive than two sets of smaller diameter, but are more advantageous with respect to wear on the cables. The sheaves S̲ are mounted on the same shaft which rotates over roller bearing blocks. They are designed for 1.4 times the normal load. The outer sheaves are rigidly attached to the shaft, the other sheaves are movable on slide bearing blocks. The latter sheaves become slightly displaced with respect to the outer sheaves when the compensator is actuated or disconnected.

The speed of raising the gates is 0.175 m per sec when they are still in the water, and the subsequent speed is 0.35 m per sec. Since the water level at which the upper gates are raised varies between 0.20 m below normal stage and 5.80 m above normal stage, the level at which the speed of gate operation changes can be readily adjusted by means of controls. Opening of the lower gates will require approximately 1 min, while the maximum (at highest water level) for the upper gates is about 1.5 min.

The psychological factor that waiting always seems long has played a role in the assignment of fairly high speed of the gates. The opening time of the gates generally constitutes a very minor portion of the lockage time, as the latter consists mainly of the time required for passage of the vessel into and out of the lock. Therefore, increasing the speed of gate operation usually is of no value. In the present case, however, considerable time is saved during lockage operations. Firstly, most ships need not be moored outside the locks before entering the locks, as the lock capacity is large and, secondly, the arrangement of the lock system (Fig. 1) is such that the entrance into and exit from the locks can proceed very smoothly.

Use of direct current became advantageous because of the following factors: the variable speed of the gate motion, the lack of knowledge of the actual water level, and the necessity of moving the counterweight K̲ very slowly a distance of several centimeters at the end of the closing process or at the beginning of the opening process of the gates (bolting and unbolting the gate). The gate motors (85 hp) have Ward-Leonard switches. This makes it possible later to increase or to reduce the gate speed if it is found that the water resistance was calculated either too liberally or too skimpily.

The power required for moving the gate was determined on the basis of the following data:

| | Lower Gate | Upper Gate |
|---|---|---|
| Weight of gate, including balance, pulley system, etc. | 157 t | 166 t |
| Uplift at highest water level | 14 t | 26 t |
| Weight of counterweights per gate | 150 t | 156 t |
| $G_1 + G_2$ | 66 t | 66 t |
| K | 9 t | 12 t |

The distribution of the counterweights and the degree of balancing of the gate are such that the required work per second is the same at speeds of 0.35 m (above the water) and 0.175 m (in the water). The criterion for gate motion in the water is the lowering of the gate at highest water level, during which both the water and the uplift exert maximum resistance to the motion. During raising of the gate the resistance in the water is of no consequence because the uplift is of opposite direction. When the gate is bolted, the sill pressure is 10 tons at highest water level and is larger at lower water levels.

There are two converters which rectify the alternating current into direct current; they are located in the machine room G near the gate portal of the lower gates (Fig. 2). Each converter services one lock, and one is a reserve for the other. The gates can also be actuated by means of a 30-hp Kromhout KS-motor which is so constructed that it can be regulated manually. Then the speed of the gate is secondary. Finally, manual operation is possible (requires four men).

The Valves (W, Fig. 6). The gear systems of the valves consist of an actuated horizontal worm gear in the center of which is attached a spherical movable nut. Through the nut passes a spindle which is rigidly connected to the member from which the valves are suspended. The spherical shape of the nut makes it possible to minimize the free play of the valve in all directions during its motion. Lubrication of the spindle occurs centrally in the nut by means of two high pressure grease pumps attached to the worm gear. Packings, located at the point where the spindle leaves the worm gear casing, prevent dirt (for example, floating dirt at high water level) from entering the nut. Each gear system forms a single unit and can be readily installed or removed. These systems are mounted on the gate. The worm gear casing is made of cast steel because of the occurring bending stresses. Should the valve motors fail to actuate the corresponding limit switches, the spindle would continue to rotate until it emerges from the nut and packing, and the valve would fall down. It would then be stopped by the brackets mounted on the gate (D, Fig. 6). When the valve is in this position, the system from which the valve is suspended prevents the spindle from falling forward. During rising motion the screw threads of the spindle would emerge from the nut and simultaneously, because of a local break in the screw thread (X, Fig. 6, section C-D), from the upper packings, so that the valve could not rise any further.

The motor (a multi-winding alternating current motor) makes 500 and 1500 rpm during raising and lowering of the valve, respectively. Such arrangement is desirable because complete opening of the valve requires about 9 min, while a similar expenditure of time for lowering the valve is excessive on account of eventual waiting for new lockage. The motor terminals necessary for moving the valves can be energized only at highest and lowest position of the gate. The supply terminals are energized only when the motor terminals are opposite them. At highest position of the gate, the motion of the valve proceeds at high speed only, as in this position the valves never need be raised.

The valve motors have a capacity of 3 hp for rapid operation and a capacity of 2 hp for slow operation. They can develop a starting torque of 1.8 times the normal torque.

It is not necessary that the valves still be moving upwards when the lock chamber is filled so much that the gate may be completely raised. This is indicated by a light signal given by differential water-level meters (fabricated by General Electric on the principle of the electrical point gage) located in the lock walls. The valves are stopped prior to raising of the gate.

The manual operation (L, Fig. 6) of the valves is so arranged that overexertion is excluded. During the manual operation the operators stand on platforms H (Fig. 6). No valve is manually operated as long as its motor is connected to the power supply.

The high pressure lubrication pumps (Z, Fig. 6) are operated by rotational motion. For this purpose, worm gear casings U (Fig. 6) are attached to the valve motors, which reduce the speed to one-twentieth. The shafts driving the pumps are equipped with elastic couplings. Each pump is installed between two valve gear systems, so that it can be operated by one system when the other system fails, for which purpose the element U must be transferred.

The Control. Control of both locks is effected from the booths b (Figs. 1 and 2, top view) located on the partition wall. When traffic is heavy, an operator is present in each booth and remains continuously on the respective lockhead. In addition, a chief operator supervises the entire lock system. He generally stays on the partition wall and the adjoining guide walls, and supervises the entire lock operation.

When the traffic is light (during the night, for example), the entire lock operation can be supervised by a single operator if only one of the locks is in use. Therefore, the valves of one gate can be opened from the control room near the other gate. During the time in which the chamber is being filled or emptied, the operator can reach the other gate in order to open it. Thus, no time is wasted.

The lock operation proceeds partly automatically and partly by means of shifting control levers. Completely automatic operation would be too vulnerable; moreover, automatic setting of the gate into motion, thus at an arbitrary instant for the control personnel, is not advisable because prior to lowering the gate it is essential to make sure that no ship is present or can arrive under the gate, and prior to raising the gate it must be ascertained that no ship is at the gate. Closing of the gate-stops across the gate recesses (Fig. 8) and lowering of the valves in the gates at highest gate position occur entirely automatically.

In order to facilitate safe opening of the gate-stops (described in part XIII), without using the controls existing at that place, this operation is preceded by a bright, red light signal to warn the men who may perhaps still be on the gate-stop. In addition, the gate-stop initially moves very slowly.

The following is the compulsory sequence of lock operation, proceeding from the standpoint that the raised gate of a lockhead may become lowered.

(1) The signal "safe" for approach to the lockhead involved is changed to "danger."

(2) The gate-stops across the gate recesses beneath the raised gate are opened and the converter is started.

(3) The raised gate is closed and bolted in its lowest position by raising the small counterweights.

(4) The sound signal is given and the valves of the other gate are opened.

(5) The latter gate is opened, after the optical signal is given by the differential water-level meter, and the valves are stopped, after which the gate-stops in the gate recesses are automatically closed and the valves are automatically lowered when the gate is at its highest position.

(6) The converter is stopped.

(7) The signal "danger" for exit is changed to "safe."

Since the preceding manipulation must take place before the next operation can occur, any mistakes are excluded.

## XII. THE APPROACHES

The guide walls consist of steel bulkheads and concrete mooring piers and posts, between which are bumpers of Oregon pine and above which are concrete footbridges. The mooring posts have broad footings and can later be moved, as need arises, upon construction of the third lock. The bumpers are reinforced at the joints with brass Bulldog clamps. They can be removed by loosening the free ends of the longitudinal beams. The protection for the bulkheads consists exclusively of horizontal bumpers because the ships merely move along there and never cruise up and down.

## XIII. DETAILS PERTAINING TO NAVIGATION, TRAFFIC IN THE LOCKS, CONTROL, AND MAINTENANCE OF THE STRUCTURES

In working out the details of the locks, the following basic aspects were the determining factors:

(a) The traffic to, in, and from the locks must be safe.

(b) Handling of the hawsers along the water must be readily possible.

(c) Mooring of ships must be made easy.

(d) The lock parts must be so constructed that they could not be damaged by the users.

(e) None of the lock parts should result in damage to the ships.

(f) All parts that are subject to wear must be readily replaceable or repairable.

With regard to traffic over the lock system, use of changes in level by means of stairs was avoided. These transitions were formed from sloping surfaces under 1:12. As means against slipperiness, flat treads, 0.60 m wide, are installed along the slopes. In addition, sand boxes are provided for strewing with sand.

Steel ladders are present both in the mooring posts and the lock walls in order to facilitate communication between the ships and the shore. The vertical members of the ladders are stiff (angle iron) because practice proved that flexible uprights are bent by compression or tension with the aid of boat hooks. The rungs are riveted to the uprights in order to lessen the grip of the boat hooks on the uprights. The ladders in the lock are suspended on bars; one end of a bar is anchored in the concrete, while the other end is placed in a pipe in order to facilitate safe movements of the walls on opposite sides of the recesses relative to each other (expansion and contraction). The movable end was unnecessary in the mooring posts. Thus, the ladders are readily replaceable. In the lock chamber they extend to 1 m below the lowest water level. In the mooring posts they extend only to the lowest water level because deeper penetration through the bumpers is useless. In some locks several ladders extend in the lock chamber to the bottom because this facility is advantageous when the lock is drained. Such an arrangement was not made in the present case because there is absolutely no objection to lengthening the appropriate ladders with the aid of wooden extensions on most occasions.

The deck slab profile above the ladder recesses is rounded for the convenience of the persons using the ladders. This profile made it difficult to step on or off the ladders. Therefore, care was taken to provide adequate hand grips in the upper surface of the walls at the points involved. Two double hand grips were installed, for the convenience of both left-handed and right-handed persons. The runoff from the hand grips is diverted through zinc pipes in order to prevent formation of rust spots on the concrete.

The footbridges facilitate reaching the lock area from the mooring stations in the river approaches. At dark they are illuminated by electric lights located above glass tiles in the floor; the arrangement is such that the location of the mooring posts is indicated, while navigation is not affected by the lights. It is possible to leave the ships by means of the ladders in the mooring posts.

Electric bulbs are installed beyond milk glass tiles in the upper niches of all mooring posts and locks (Fig. 10a), in order to mark the locks and approaches and to indicate the rows of mooring bits. The milk glass tiles are so thick that they cannot be broken by boat hooks, and they are so shaped that these hooks do not catch.

The mooring bits of the locks and posts are installed in niches and are suitable for supporting the boat hooks. They are of the type used in the Twenthe-Rhein Canal and are designed for a hawser force of 15 tons in the present case (Fig. 10a). The spacing between the mooring bits in each row is 1.65 m at the locks and 2.00 m at the mooring posts. In the lock, the mooring bits in a vertical row must be used successively during establishment of water level in the lock chamber, while in the case of the mooring posts a given ship usually ties only to one mooring bit of the vertical row.

The lock operation is so arranged that the ship personnel can assist themselves. For this purpose the upper mooring bits, which extend above the concrete, are located close to the top of the locks. Meanwhile, it remains feasible later to locate mooring bits at some distance from the face of the walls. However, such an arrangement would involve the complication that the hawsers, which are fastened around the mooring bits, would extend across the footpath along the lock chamber (danger of stumbling).

Since the ship personnel must assist themselves during lockage operation, they are warned by sound signals, installed in the walls, about the beginning of filling or emptying of the lock chamber.

The deck slab facing is of a specially designed rounded profile (Fig. 10b). In designing it, consideration was given to the fact that the hawsers should not kink (radius of curvature 0.15 m) and that it should offer some support or guidance to the ship personnel that might happen to be on the walls. The profile of each wall section consists of one length, as much as possible. It is uninterrupted along the entire length of the lock, so that a hawser of a ship towed along the wall cannot snag anywhere. It passes even over the gate recesses of the raised gates, for which purpose steel gangways are present which bridge the recesses when the gate is raised. In open position these gangways are sufficiently separated from the lift towers to permit passage between gangway and tower. Then warning notices, mounted on the gangways, serve to indicate the presence of the niches (Fig. 8).

The deck slab profile extends along the waiting places for the ships in the canal approach; in the river approach it ends near the first mooring station and gradually changes into the shape of a quarter circle which is present also at the outer side of all bridge railings. To prevent snagging of towed hawsers, the ends of the bridge railings are rounded and the corners of the mooring posts, protruding outside the bridges, are cut off (Fig. 9).

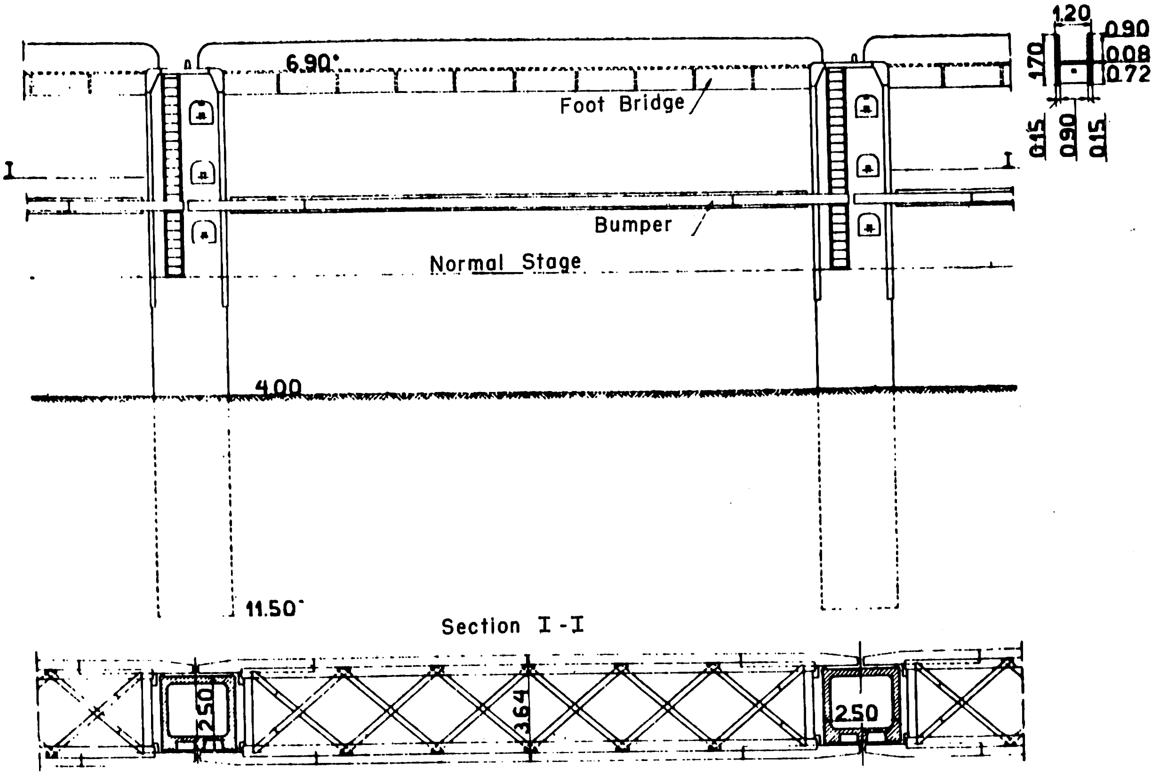


Fig. 9 - Layout of Mooring Posts with Bridges and Bumpers

The deck slab profile nowhere protrudes beyond the facing of the walls or bulkheads, in order not to damage the skin plates of the ships. For this reason the bulkheads have a concrete top forming a continuation of the deck slab profile.

Within the locks the deck slab profile is protected to some extent against collision with ships, in that the surface of the walls at the upper

0.70 m (that is, above the highest water level) is slightly depressed.* In this way, moreover, the ships bump at a suitable place against the walls.

Vertical layers of glazed brick are installed in the lock walls near the lock gates; in each wall the layer is colored red and white at 2 m and 4 m from the gates, respectively (c, Fig. 2, longitudinal section). The function of the white bands is to indicate the limit beyond which no ship may moor, while the red bands indicate the point beyond which it is dangerous to position the ships; these provisions are on account of the protruding sections of the gates and the probable motion of the ships during filling operation.

In order to assure a good view of the lock system and the adjacent canal section, as well as unimpeded traffic along the walls (towing of hawsers, for example), the lower gates are raised slightly higher than is necessary for clear passage, namely, 2.35 above the deck slab elevation at the place. For the same reason the lower edge of the traffic bridge is also located at that level.

Damage to the lock walls, due to the ships in the lock chamber, is limited by means of stiff steel bumpers in the walls (Fig. 10c, and d, Fig. 2, longitudinal section). The half-round steel bars, which are welded to the bumpers and subjected to wear, can be readily replaced either locally or completely. The greatest wear is likely to occur above canal level, which is the level that will mostly prevail in the lock chamber.

The disadvantage of the bumpers seemingly is that they require a concrete cover of 0.15 m, but practice proves that such a cover is quite satisfactory if the concrete structures are constructed carefully (no setting of the forms along the front side of the walls during pouring operation).** The advantage of the thick concrete cover is the greater allowable wear. The half-round steel bars have a 1:10 taper at top and bottom, in order to prevent snagging by the ships during lockage operation.

All the rails in the locks, on which wheels roll (gate recesses and gate guides along the lift towers), are made in such a way and are equipped with welded or bolted connectors, wherever necessary, that complete or local replacement is feasible.

Final Remark. All parts of the lock system were manufactured in the Netherlands, with the exception of some details which were made abroad and of which most were listed in the preceding.

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*The principle was applied at the north lock of Bremerhaven.

**The Eefde lock of the Twenthe-Rhein Canal, among others.

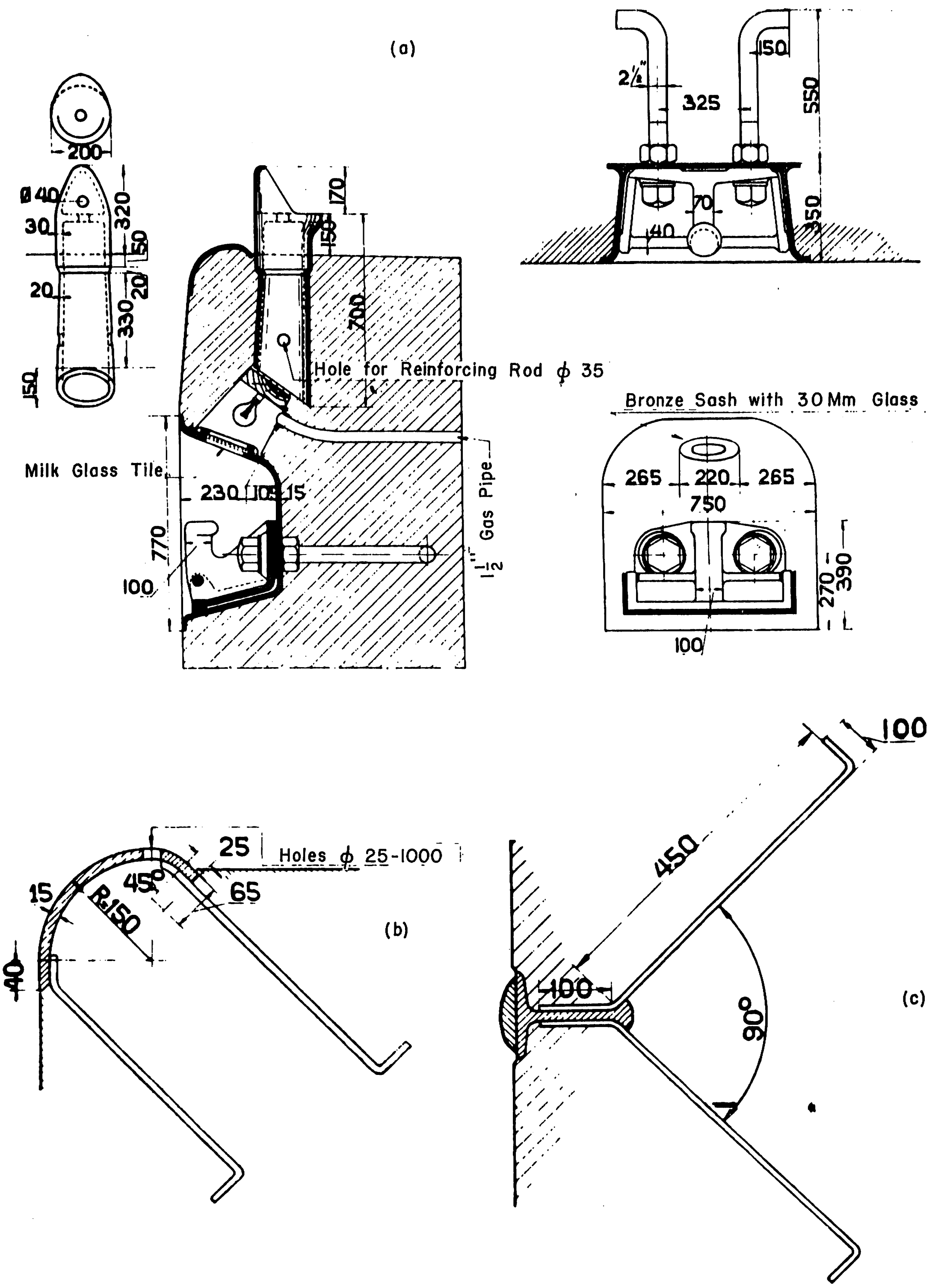

Fig.10 - (a) Mooring Bits and Niches; (b) Rounded Deck Slab Profile; (c) Steel Bumpers

# THE DESIGN OF THE LOCK NEAR TIEL

(Het ontwerp van de schutsluis nabij Tiel)

by

J. P. Josephus Jitta

Reprint from De Ingenieur, Nos. 49 and 50, 1949

# LIST OF ILLUSTRATIONS

# THE DESIGN OF THE LOCK NEAR TIEL

## I. INTRODUCTION

The design of the lock near Tiel was completed in 1938-39. It constitutes the final of a series of designs which were published during 1935 to 1938, inclusive.*

Had there been no war, a report on this design could have been readily prepared by referring to the previous publications. At the time when the opportunity to describe the design became available, however, it was necessary to take into consideration the fact that a new generation of young engineers had arisen in the interim period, who were not acquainted with the previous publications and who could not readily consult these publications without being subjected to excessive exertions. In addition, technical literature 11 to 14 years old will be regarded as dated. For these reasons, the design of the Tiel lock is presented here in relative detail, in accordance with the request of the editors of De Ingenieur; the older readers, in particular, may justly accuse the author of presenting old data alongside new data.

Firstly, the question arises whether the design, carried out at this time, still is up-to-date. This question can be answered in the affirmative. Nothing was accomplished in the field of lock design during the war years, and subsequent construction proceeded on the basis of results obtained prior to the war.

Meanwhile, the Beatrix lock at Vreeswijk, described in 1935, was put into operation on March 23, 1938, so that the corresponding experience could be taken into consideration only in 1938/39; at present, however, this experience is more qualified. In connection with this, some of the less important sections of the lock, which will be referred to subsequently, were designed somewhat differently from the original plans.

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*See the following references: De Ingenieur, No. 32 of 1935 (Lock System at Vreeswijk, Beatrix Lock), No. 14 of 1937 (The Wijk Lock at Duurstede), and No. 21 of 1938 (Lock System near Ravenswaay); in addition, see the book entitled Locks and Other Hydraulic Structures in and along Canals, by the author of these articles, published at Haarlem by de Erven F. Bohn.

## II. GENERAL DESCRIPTION OF THE DESIGN

### A. General Arrangement of the Lock Design

The effective length of the lock is 350 m, and the effective breadth is 18 m (Fig. 1a). The lock extends on the canal side to two piers, each of which is designed to accommodate three two-way bridges for highway traffic (two for main highway No. 15 and one for a secondary road), in addition to a single-track railroad bridge.

These piers form the guide walls for the ships. Provisions were made at the lower lockhead subsequently to erect piers for a second single-track railroad bridge near the other bridge. The bridge piers, which form an extension of the lock, parallel each other for the purpose of uniform bridge design, so that divergence of the approach bays begins beyond the piers.

The divergence of the guide walls of the river approach can begin fairly immediately outside the upper gate; therefore, the concrete entrance walls that are connected to the lockhead are designed divergent in plan view. These walls contain the terminals of two culverts, each having a cross section of 11.50 sq m, one in each lock wall. These culverts serve exclusively for passage of water from the Waal River to the Lek River and, therefore, are not connected with the lock chamber. Accordingly, passage of the water can occur even during lockage operations. The culverts extend from the south end of the entrance walls to the north end of the piers connecting to the lower lockhead (length nearly 455 m). To assure the largest capacity possible, the culvert outlets (in the piers) are gradually enlarged; the enlarged outlets are divided into two by a vertical partition (Fig. 1a, section A-A).

Spacious mooring stations are arranged outside the lock for the ships awaiting lockage. They are located outside the wake of the ships emerging from the lock. The distance between the ends of these guide walls is more than 1440 m.

Two adjacent locks are designed; they differ merely in that the culverts are installed only in the lock which is currently under construction. However, such an arrangement involves preparing the bridge piers connecting to the future lock. Later these piers can be attached in a simple way to the guide walls for the ships, without hindering land traffic (Fig. 2).

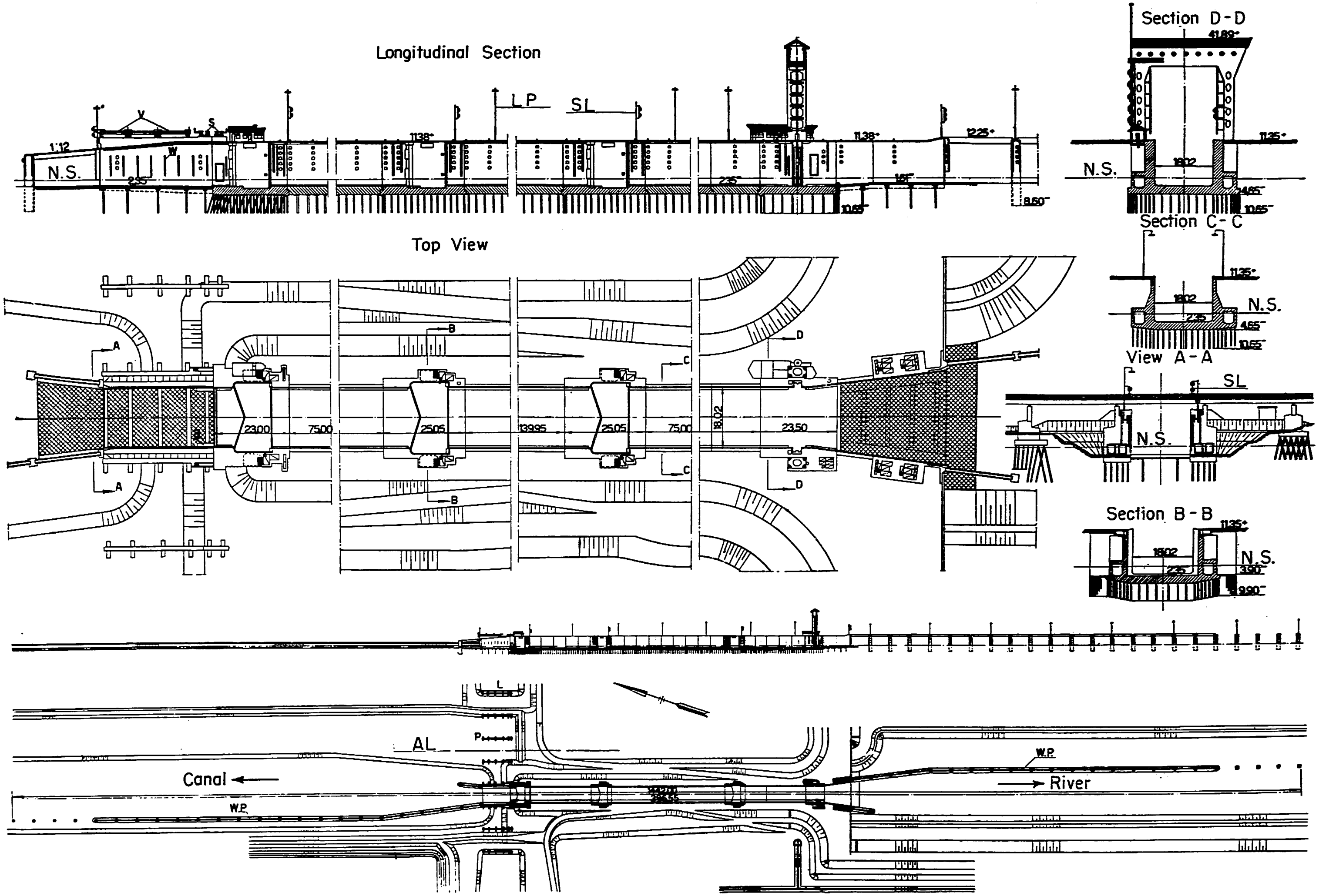

Fig. 1a - Layout of the Lock

AL. Axis of second lock. B. Pier footing. L. Abutment. LP. Light pole. N.S. Normal stage. P. Pier. S. Railroad bridges. SL. Signal light. V. Highway bridges. W. Steel bumpers. WP. Waiting places for ships.

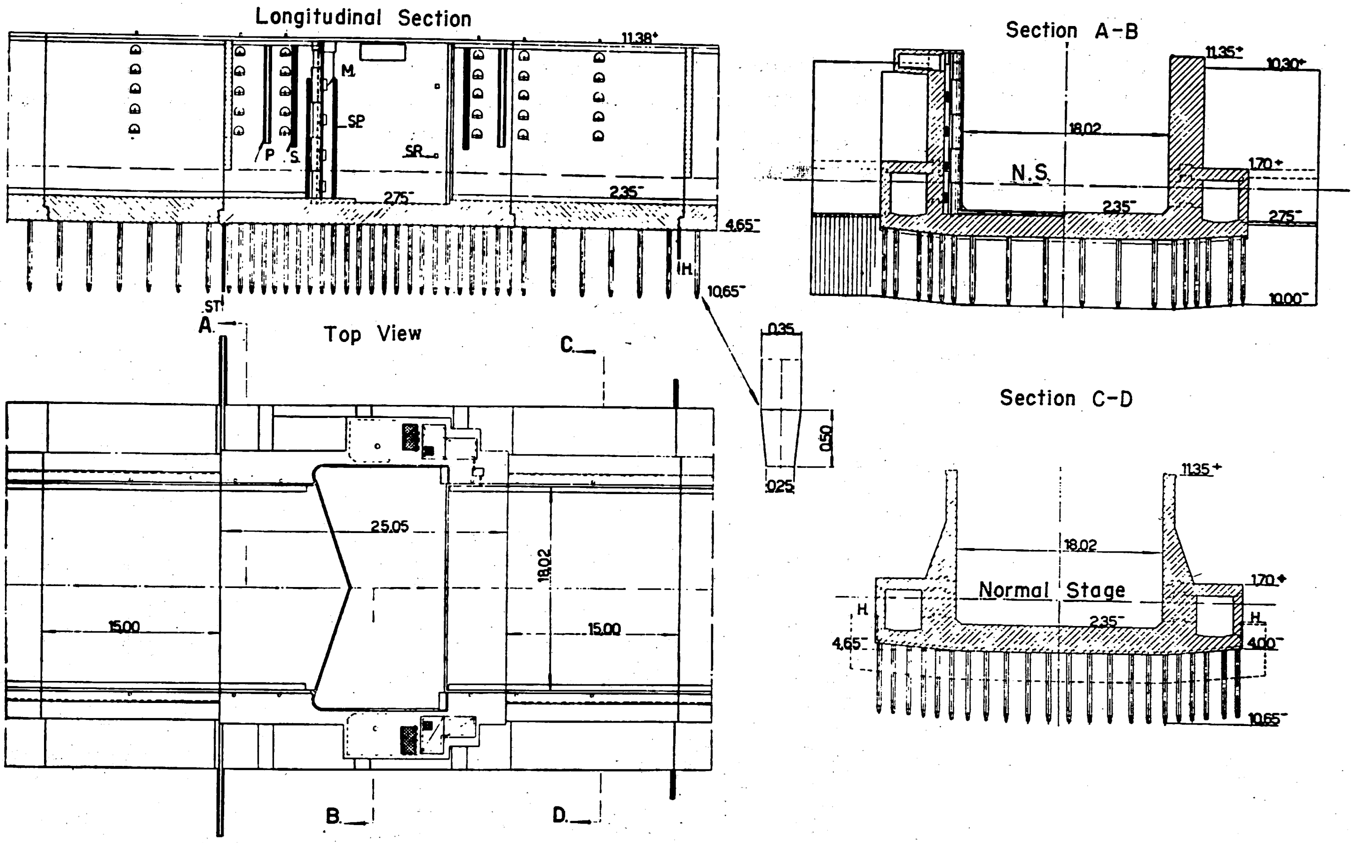

Fig. 1b - Layout of an Intermediate Lockhead and Adjacent Chamber Sections
H. Wooden bulkhead. St. Steel bulkhead. S. Stop strip. SP. Groove for pintle socket.
SR. Steel bumper. M. Wall trunnion.

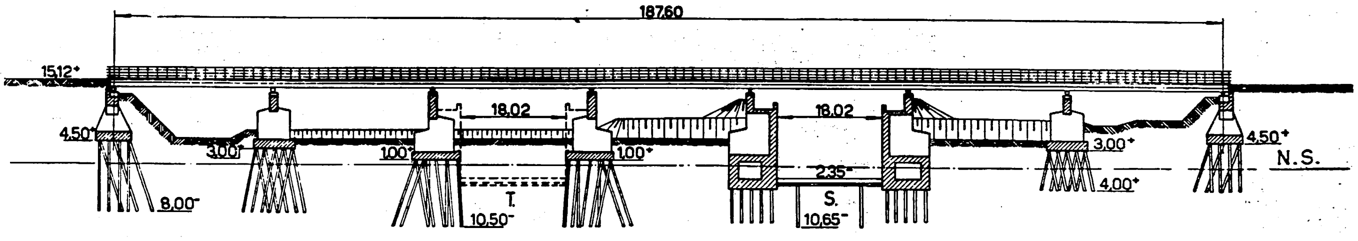

Fig. 2 - Cross Section Through Bridge Piers and Abutments
S is the lock under construction and T is the future lock.

Upon the initiative of the engineer G. C. Krayenhoff van de Leur, affiliated with the Waterways Department and in charge of the plan for the corresponding canal section, the lock was divided into three by means of two intermediate lockheads. The outer lock chambers are 85 m long. Division of the lock chamber has manifold objectives. Firstly, lockage of a ship or a group of ships passing into the 85-m chamber can proceed faster and with lesser complication of the water aspect for the Betuwe pool of the canal. This aspect is troublesome only when the Betuwe pool must be drained, which lasts on the average 20 days per year, namely, when the water level of the Lek River is 5.55 m above normal stage and the Ravenswaay lock, which is located at the north end of the canal pool and is normally open, is closed.* Secondly, division of the lock chamber results in formation of a valuable reserve when the gate (or gates) of a lockhead must be inactivated. Whichever lockhead is involved, there remains an effective chamber length of about 260 m, which is practically equal to the chamber length of the locks of the Maas canal system, of the Maas-Waal Canal, and of the Ravenswaay lock; these locks pass or have passed a large portion of the ships which undergo lockage at Tiel. Thirdly, by scheduling navigation in one direction, the ships moving in the same direction can be rapidly passed through the lock: as soon as the first lock chamber is full of ships, lockage of these ships proceeds, while the adjacent lock chamber is being filled with ships, and so on. Such an arrangement would facilitate, for example, the sailing of ships, destined for Zuid-Limburg or Germany and the Lek River, with the tide mainly in the back, instead of following the Waal River along a longer path and against the current.

Many engineers are skeptical regarding the advantages of the numerous lockheads. They consider the division too theoretical. These engineers are of the opinion that the only advantage of the four lockheads is the valuable reserve. The author of this article claims that division of the lock chamber offers the advantages listed previously, and he is of the opinion that such division will facilitate very rapid lockage operations. Naturally, satisfactory operation will depend to a great extent on the lock master.

The lock gates are steel miter gates, except for the upper gate which is a steel lift gate. Use of the latter gate was considered desirable in order to facilitate shutting off the flow that might occur if a set of miter gates were seriously damaged. Such a flow would never cease of its own accord

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*Use of pumping is anticipated to reduce the canal level by 0.50 m (formation of water storage).

because the water level in the Waal River at the location of the canal is always higher than that of the Lek River. In case the Rhein becomes canalized in the distant future and, consequently, the lock near Tiel can remain open a large part of the year, the lift gate lends itself excellently for closing or opening at the time when the lock must again be used for lockage operations or when the lock must be inactivated as such, while flow possibly exists there because some head still is available.

The lift gate is the same as that used for the Wijk lock at Duurstede. In order to make this possible, the deck slab is built 0.10 m higher than is strictly necessary. Of course, the gates at Wijk near Duurstede are designed for a higher lift (8.60 m as compared with 5.30 m), yet this factor was insufficient to necessitate making a special, somewhat lighter gate for the Tiel lock.

At present the lift gates of these two locks (the lock near Tiel and the lock at Wijk near Duurstede) are reserves for each other. The mutual reserve gate will be kept in a storage place prepared near the Ravenswaay lock.

### B. Filling and Emptying the Lock Chambers

The filling and emptying of the lock chambers occurs through valves in the gates. During filling operation the interior of the lift gate constitutes a turbulence chamber 2 m long; baffles are installed in this chamber and downstream of it.

The turbulence chamber is much smaller in the case of the smaller miter gates (1.10 m versus 2 m); moreover, no baffles or guide vanes can be installed outside the gate because they would protrude into the exposed space of the lock when the gate is open. Therefore, in order to make the miter gates suitable for establishment of water level in the lock chambers, whereby the water entering the chamber, moreover, does not flow parallel to the lock axis, greater care was required than in the case of the lift gate. After an extensive investigation, the Delft Hydraulic Laboratory succeeded in finding a satisfactory solution. Large holes were made in the members bounding the gate section containing the valves (Fig. 3a, section A-B); during filling of the lock chamber a portion of the water is forced to flow through these holes, so that the water entering the lock chamber is fairly distributed. A wooden grill is installed on the downstream side of the gate; this grill facilitates

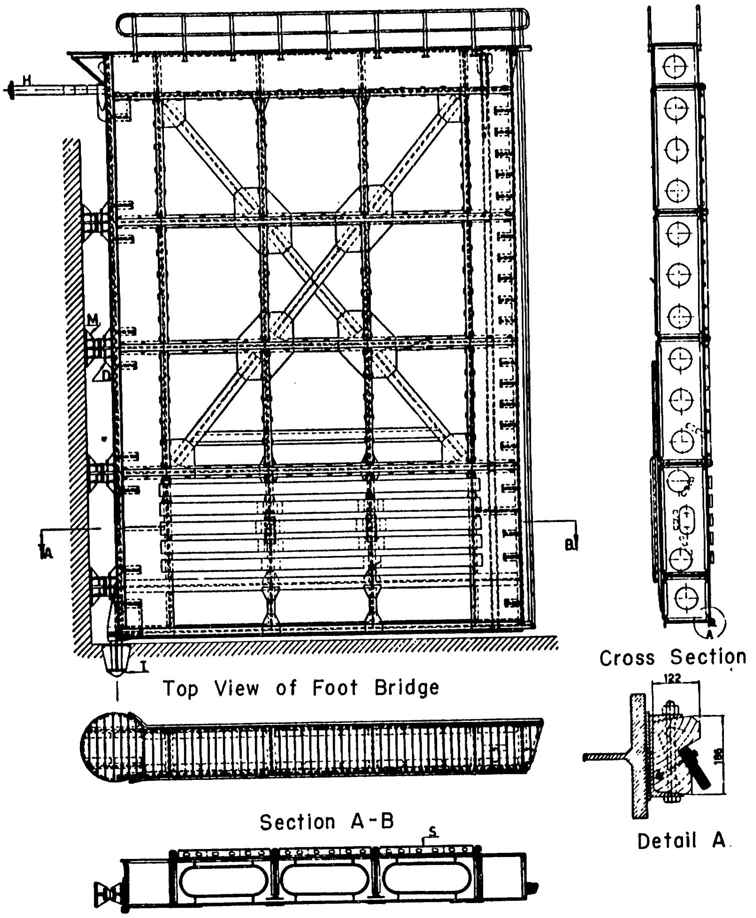
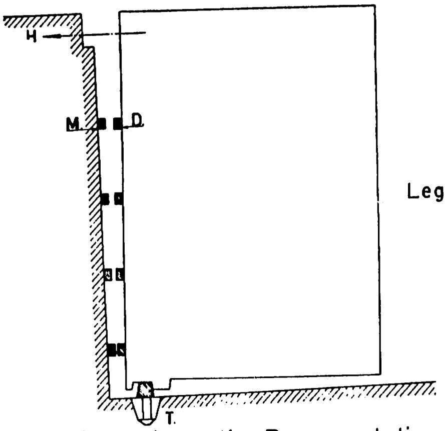


Fig. 3a – Design of Miter Gate



Legend for Figs. 3a and 3b:

| | |
|---|---|
| D | Gate Trunnion |
| H | Trunnion |
| M | Wall Trunnion |
| S | Valve |
| T | Pintle |

Fig. 3b – Schematic Representation of a Miter Gate Offset by Water Pressure

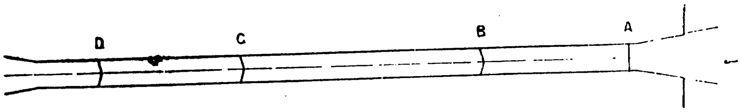


Fig. 4 – Diagram of the Lock

further energy dissipation and uniform flow distribution over the entire wetted profile of the chamber. The grill can be replaced, if necessary, without lifting the gate (Fig. 3a).

According to the investigations of the Delft Hydraulic Laboratory, the valves must be operated with variable speed corresponding to a definite schedule. Thereby, it makes quite a difference in the case of the lockheads for the miter gates, whether the chamber is emptied or filled through a given set of gates, and whether an 85-m chamber or a longer chamber is emptied through the lower gate.

Thus, the valve operating schedule, which is under automatic electrical control, is different for filling and for emptying and, in addition, is different for emptying a small chamber through the lower gate and for emptying a large chamber.

The question arises as to how the motors actuating the valves in the gates should be connected. The answer is as follows. If the gates are designated by A, B, C, and D (Fig. 4), beginning with the lift gate, then the following remarks are valid:

when filling occurs through B, A is open or absent;
when emptying occurs through B, A is closed;
when filling occurs through C, D is closed;
when emptying occurs through C, D is open or absent;
when the 85-m chamber is emptied through D, C is closed; and
when a larger chamber is emptied through D, C is open or absent.

Accordingly, the desirable opening schedule for the valves in the gates is achieved by connecting the motors actuating the valves to the mechanisms actuating the gates in the following manner: motor B to mechanism A, motor C to mechanism D, and motor D to mechanism C. In the case of the upper lockhead, it makes no difference whether a small or large chamber is being filled.

## C. Exchanging the Gates

### 1. Lift Gate

Exchanging the lift gate is carried out as in other lift-gate locks of the new canal. First a 200-ton tackle is suspended from the horizontal upper beam of the gate portal with the aid of a 6-ton traveling crane located in this beam. Then the hoisting cable is fastened to a 27-ton electrical hoisting winch located on one of the lock walls. With the aid of this winch, the gate to be removed is detached from its counterweights and is lowered to above the deck slab elevation. By pressing inward the shafts of several guide rollers, the gate can be turned 90°. Then the gate is lowered between special pontoons designed for gate transportation and, after I-beams (No. 80) are inserted through the outer valve openings, the gate is placed on the pontoons (Fig. 5) and is ready to be hauled away.

Meanwhile, the reserve gate is brought, supported between two other pontoons. This gate is fastened to the hoisting tackle, raised to above the lock walls, turned through 90°, fitted into the steel guides attached to the lift towers (after the shafts of several guide rollers have been shoved outward), attached to the counterweights, disconnected from the tackle, and is finally lowered with the aid of the actuating mechanism.

## 2. Miter Gates

The miter gates can be transported by the same pontoons used for transporting the lift gate. For this purpose, two pontoons must be placed near each other and rigidly coupled by means of a steel beam. A steel frame, designated as the gate-transport member, is placed on the set of pontoons. This frame contains two fixed shafts about which the gate, suspended in a box, is turned from a vertical position into a horizontal position. The gate is equipped with suitable hooks which fit around the shafts.

During the turning operation the two pontoons would tend to become submerged. To avoid that, a third pontoon is rigidly attached to the other two pontoons (Fig. 6). After the gate is laid down, the third pontoon is removed and the gate is taken to the storage place located north of the lock near Wijk at Duurstede. By admitting water into the pontoons, the gate is lowered onto the storage place, after which the pontoons can be removed (Fig. 7).

The reason that the storage place for the miter gates is located north of the lock near Wijk at Duurstede, while all the miter gates occur south of the Lek River, is due to the fact that the level of the canal north of the Lek River is fairly constant, whereas south of this river the level varies between 1 m and 5.55 m above normal stage, so that it would be impossible to deposit or remove the gates at all times with the aid of the pontoons.

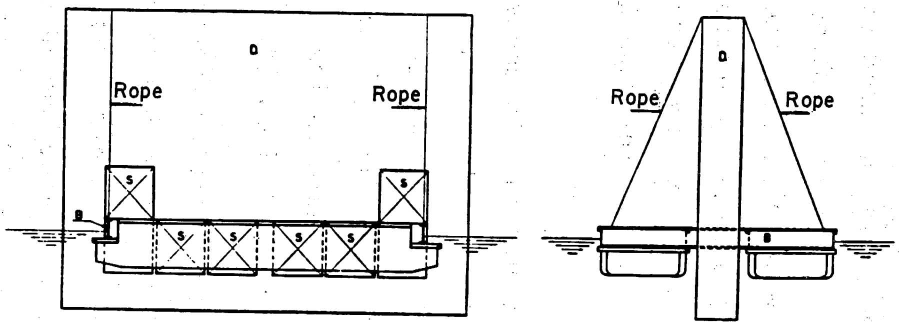


Fig. 5 - Diagram Showing Transport of Lift Gate

Legend for Figs. 5 and 6:

- A I-Beam (No. 40)
- B I-Beam (No. 80)
- D Gate
- O Gate-Transport Member
- S Valve

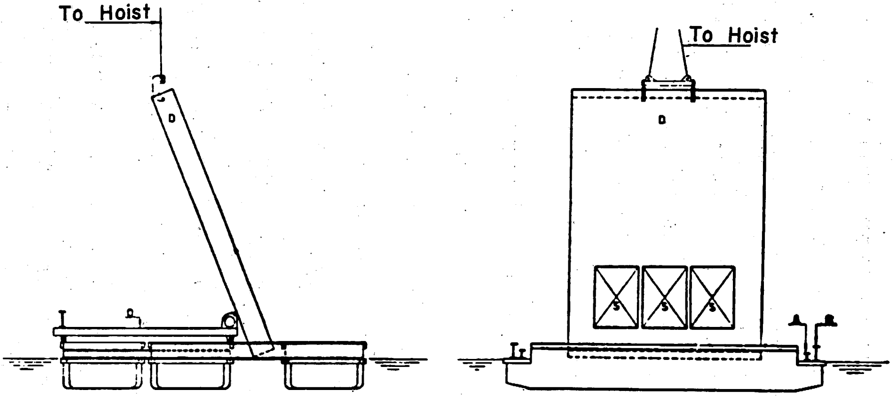


Fig. 6 - Diagram Illustrating Removal of Miter Gate

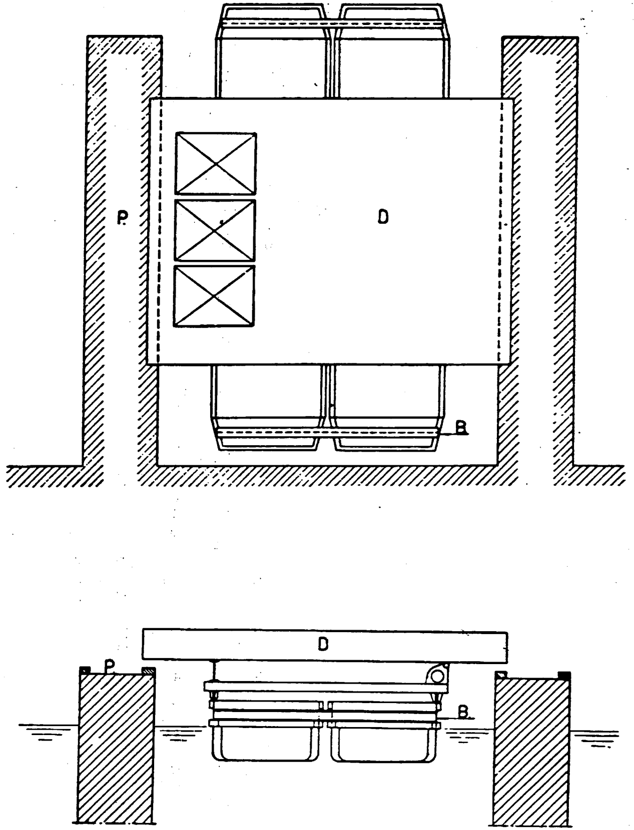


Fig. 7 - Diagram Illustrating Transport and Storage of Miter Gate

B. Coupling beam. D. Gate. P. Piers.

### D. Draining the Lock

In order to carry out repairs, it may be necessary to drain the lock fully or partially. Complete drainage can be effected by means of needles installed in the outer lockheads and resting against a hollow beam which is floated to the place and installed. During drainage through the needles the ends of the beam are set in grooves. The beam is suspended from the lock walls.

Adjustable holes are made in the upper and lower surfaces of the hollow beam; the function of the lower holes is to admit or discharge water, while the function of the upper holes is to discharge or admit air. Thus, in case the water rises while the needles are installed, the beam would not tend to rise. During drainage of the lock the hollow beam automatically empties the water which it eventually accumulates. The needles are I-beams filled with wood. They do not extend above the level that is allowable during drainage operations, so that errors are excluded.

Partial drainage may be necessary for the purpose of repairing the lift gate bearings (in which case a pontoon can be floated to the place and set against the walls), repairing the pintle or miter gate bearings (pintle socket), or repairing the walls at any point (pontoon suspended from the walls, with watertight sidewalls, bottom, and longitudinal partition). All the drainage installations are designed to serve all four 18-m locks of the canal.

## III. FURTHER DESCRIPTION OF THE LOCK

### A. The Concrete Structure

The lock is a boxlike structure resting on concrete piles. Since the direction of the original drop is from south to north, and later it will be primarily such (the negative head is always small), buttress piles are required only under the lower lockhead. These piles resist the horizontal water pressure (Fig. 1a).

The bridge piers connected to the lock walls and the entrance walls containing the culvert intakes are based exclusively on vertical piles; they are interconnected by concrete beams, resting on piles, on which the flooring is poured. The remaining bridge piers and walls are based on buttress piles

(Fig. 2). The concrete piles have a cross section of 0.35 m by 0.35 m and their maximal load is about 50 tons.

The upper edge of the lock walls and the lock floor are designed at constant elevation. The transition from the lock floor to the bottom of the approach bay, which is at higher elevation, is obtained by means of a concrete bulkhead based separately from the lock. The advantage of being able to lower this bulkhead if the water level in the river becomes lowered (a drawback peculiar to rivers) has already been utilized in the design. During the ten years after completion of the design, the low water levels were selected in such a way (the years 1947 and 1949 were particularly unfavorable in this respect) that at present the bulkhead is designed lower than originally.

The upper lockhead (Fig. 1a) is equipped with a set of vertical recesses for the lift gate. A gate portal was constructed to facilitate motion of the gate; it consists of fairly flexible towers and a covered upper beam housing the machine chamber. The towers are supported over the culverts and form one unit with the lockhead. They are made fairly flexible in order to prevent shearing of the upper beam due to movements of the lockhead walls. These movements may result from a difference in pressure head in front of and behind the walls or from a temperature difference between the front and rear edges of the walls. In the summer the front edge is warmer than the rear one, while the reverse occurs in the winter. In addition, the upper beam itself may expand or contract due to temperature variations, whereas the distance between the lower sections of the towers is constant.

Figure 8 shows the section through the gate recesses. The heavy anchor block serves for rolling the gate in the case of complete damming, for instance, in order to stop the flow arising due to failure of a set of miter gates. The notches k serve to accommodate heating elements which must keep the bearing surfaces free of ice. The highly troublesome ice growth is due to the water dripping from the newly raised gate. The icing tends to make the gate recess too narrow for the gate.

In the case of the Beatrix lock at Vreeswijk, where no heating elements could be installed, the gates once became quite stuck in the accumulated ice. Since then the ice was continually chipped away during the cold season, which is a time-consuming job that always had to be carried out under unfavorable conditions (in a duct and, moreover, during fierce cold).

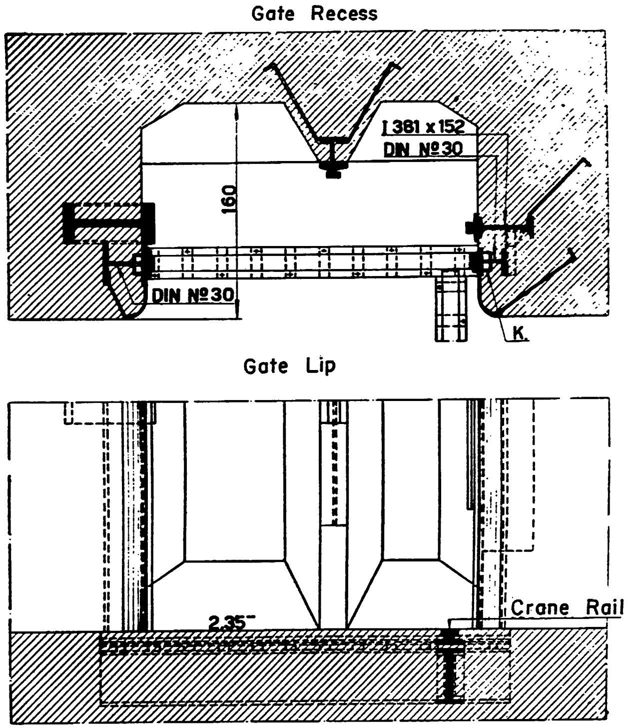


Fig. 8 - Cross Sections Through Gate Recess and Lip

K shows the channels for the heating element. Below the lowest water level they are in contact with the outer water.

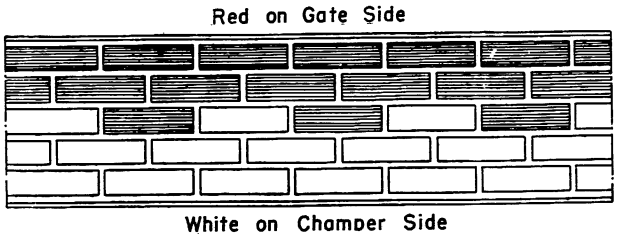


Fig. 11 - Stop Strip

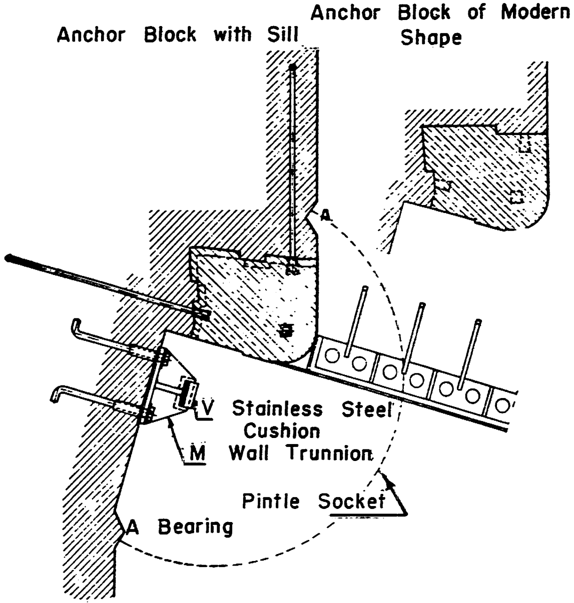


Fig. 9 - Horizontal Section Through an Anchor Block of a Miter Gate

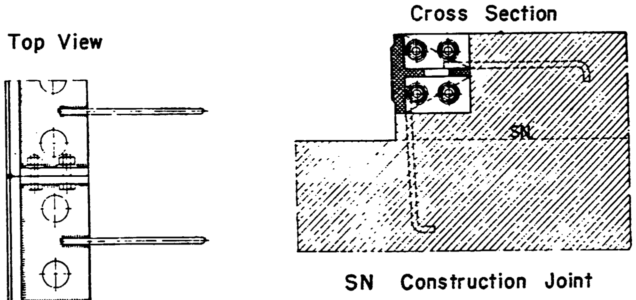


Fig. 10 - Cast Steel Sill for a Miter Gate

The lip of the gate was formed from a heavy rail stiffened with heavy channels (Fig. 8). The reinforcing steel (spaced reinforcing) is placed parallel to the lock axis, between the rail and stiffeners.

The remaining lockheads contain miter gates (Fig. 1b). The impervious section of the anchor blocks is made of granite, just as in the Ravenswaay lock system. Because of the excessive height, a steel structure would have been too complicated. The granite, which was delivered just prior to the outbreak of the war, did not have the shape which would have been given to it at present (Fig. 9, upper right) and whereby it would have made an inseparable unit with the concrete structure, independently of the anchors.

The concentrated force is resisted by steel trunnions in the wall, corresponding to similar trunnions in the gate which are connected to the rear vertical member of the gate at the location of the horizontal members. The function of the wall trunnions is to distribute the concentrated pressure in such a way that the load on the concrete would not exceed 50 kg per sq cm.

All trunnions are equipped with stainless steel cushions. The cushions are not made of ordinary steel because it rusts readily; rusting and continuous scour of the rust during motion of the gate would cause excessive wear, such as occurred in the locks of the Panama Canal. The sills are of cast steel and are connected to the granite as if it involved granite on granite (Fig. 10).

Each of the entrance walls on the river side of the lock contains the recesses for the two operating valves and the recesses for two reserve valves which are used when the operating-valve recesses are being drained (Fig. 16). Since they are banked up over the entire height, there is only a back wall present at the location of the culverts and the valve shafts. This results in a considerable economy in concrete.

The bridge piers (Fig. 2) along the extension of the lock walls are walls that are based low and contain the culverts. They are provided with a reserve-valve recess. The other piers are based high. They consist of a footing supporting vertical columns carrying a heavy concrete beam which accommodates the bridge supports. The piers which will later be installed along the extension of the walls of the second lock, and which can be based high because they are not scheduled to accommodate any culverts, can be extended to the guide wall. The piers at the exposed side of the future lock are dammed off by a concrete bulkhead below the lowest water level; the bulkhead passes through the footing under the north headwall. A vertical wall must be erected later at the future exposed side of the lock, connecting to the vertical columns (Fig. 2, dashed lines), for which purpose reinforcing steel has already been prepared in the columns and can later be readily extended after removal of the concrete cover. The future footpath along the lock will be located between the face of the future wall and the face of the pier section that will extend above the wall. The bridge abutments are basically similar to the piers having high foundations.

Wingwalls occur only near the upper lockhead. They are superfluous at the canal side of the lock because the soil can be banked against the bridge piers in order to obtain the transition from the lock plateau to the canal profiles. The wingwalls near the upper lockhead, consisting of anchored steel sheeting, fit to the south end of the entrance walls. The bulkhead there, however, is parallel to and fits to the south end of the lockhead.

This design has been selected in view of the following two considerations: subsequent excavation of the construction pit for the second lock near the lock under construction and subsequent presence of the completed second lock near the first lock. The higher cost of the steel walls is balanced by the economy in the concrete of the entrance walls.

The wingwalls on the side of the future second lock are of constant depth along the entire length and the lower edge does not follow the rough outline of the ground profile, as on the other side; this design was motivated by consideration of the required construction pit for the second lock (cited previously) and by the fact that the ground profile for the wingwall cannot be maintained after completion of the lock.

The entrance walls are not provided with bulkheads in the longitudinal direction of the lock; therefore, they are not impervious. The outer bulkheads form a separate element, as stated previously; near the upper lockhead on the side of the future second lock, they consist exclusively of steel sheeting, while otherwise they consist of steel sheeting extended to 1 m below normal stage and topped by a thin screen of reinforced concrete, erected on the sheeting and forming one unit with the lock wall. An outer bulkhead is installed also near the intermediate lockheads, normal to the wall (Fig. 1b).

The inner bulkheads consist primarily of steel sheeting. They are located mainly on the lock chamber side of the outer lockheads. These locations were selected for the following reasons: in the case of the upper lockhead, it is desirable that the ground water pressure against the floor should constantly correspond to the high water, in order to economize on piles; in the case of the lower lockhead, on the other hand, it is desirable that the pressure should exactly correspond to the canal water, in order to achieve a greater weight of the lockhead, so as to utilize the capacity of the buttress piles to absorb the horizontal water pressure in the direction of the lock axis.

In the case of the lower lockhead, the inner bulkhead directly corresponds to the outer bulkhead; in the case of the upper lockhead, the two bulkheads are connected by an outer steel wall along the walls, hence parallel to the lock axis. This arrangement, which does not imply the most economical use of bulkheads, had to be used because of the future doubling of the lock.

In addition, each intermediate lockhead is provided with an inner bulkhead which joins the outer bulkhead (Fig. 1b) and, finally, inner bulkheads consisting of short wooden walls are installed about the two wall sections (H, Fig. 1b). The primary function of the latter bulkheads is to close off the clearances under the structure, which occur due to settling of the ground between the piles. The wooden bulkheads are designed in such a way that the ground water is subjected approximately to the same resistance upon passage in any direction.

## B. The Wall Installations

Rows of mooring bits are installed in the walls, partly located in niches and partly standing on the walls near the front edge. After the Beatrix lock at Vreeswijk had been put into operation, it appeared desirable to install, in the remaining locks under construction, an extra vertical row of mooring bits near the gates at ± 4 m from the row nearest the gates. The function of the latter row is to facilitate mooring of ships moving in the direction of the closed gates, that is, ships scheduled to lie at the end of the lock chamber, while the other row serves for mooring ships scheduled to lie at the entrance of the lock chamber, else they would touch the closed gate (gates). This aspect was incorporated in the Tiel design; the greater part of the other lock designs was already realized when attention was drawn to this aspect

(Figs. 1a and 1b). In addition, several mooring bits were installed in the walls of the upper lockhead upstream of the lift gate, for the purpose of mooring the vessels during operations on the gate (exchanging, etc.).

The deck slab consists of a specially rounded steel profile, designated concisely as the deck slab profile. It is essential that this profile follow perfectly straight lines. It protrudes slightly above the concrete in order to offer some footing, even though mainly psychological, to the men moving along the front edge of the walls. The radius of curvature at the front is 0.15 m, so that the steel hawsers do not kink across the deck slab profile. The hawsers never drag on the concrete of the walls because the profile protrudes above the concrete. The deck slab profile passes over the granite anchor blocks which, accordingly, do not quite extend to the upper surface of the walls.

Vertical steel bumpers were designed originally in order to minimize wearing of the walls due to friction of the ships along the walls (spaced at ± 4 m)--these were installed, therefore, in the case of the lower lockhead constructed at the beginning of the war (W, longitudinal section, Fig. 1a)--but they are omitted in the portion of the lock currently under construction. An investigation conducted on existing locks after the war has proved that concrete of good quality in straight vertical surfaces does not wear off due to ships rubbing along or bumping against the walls. It was found, on the contrary, that the vertical surface of concrete of poorer quality, such as lean concrete that is not watertight, becomes damaged owing to the presence of the steel bumpers.

The damage should be attributed to the following factor: in lean concrete the water penetrates inward, so that the concrete becomes shattered during severe frost (numerous very severe winters occurred during the war years). Therefore, the damages occurred between the levels of the pools on the opposite sides of the locks.

Damage of the concrete due to lengthwise rubbing of ships can be readily expected in the case of unprotected protruding corners such as in the transition from the normal lock section to the divergent lock section at the upper lockhead. A wooden framework is present at that place, however, designed to fill the recesses for the hollow beam which will be used for draining the lock (see part II-D).

The gates cannot bang against the gate-recess wall parallel to the lock axis, in such a way that their valves might become damaged, because they are equipped with wooden buffers mounted along bearing surfaces provided in the walls and formed from vertical I-beams of which the outer edge of one flange fits to the concrete surface (SR, Fig. 1b).

Vertical stop strips are installed in the walls in order to prevent mooring of ships too close to the closed gates (S, Fig. 1b). In the case of the already completed locks, these strips consist of vertical bands of glazed bricks, red and white, spaced several meters apart. In the present case, the strips are combined into one band (Fig. 11). The advantages of the new system are prevention of mistakes and better visibility in the case of sodium vapor lights which make it difficult to distinguish the red brick from the surrounding concrete.

### C. The Mooring Stations for Ships and the Guide Walls (WP, Fig. 1, bottom, and Fig. 12)

The mooring stations for ships are designed in such a way that the waiting ships are located outside the wake of the ships emerging from the lock. They consist of concrete mooring posts above which are concrete footbridges (0.90 m between railings) and between which are wooden bumpers that move up and down with the water (Fig. 12). The mooring posts are square, 2.50 m each side. The function of the bumpers is:

(1) To form a straight alignment on which the ships would have no grip.

(2) As a soft and chiefly elastic buffer between the mooring post and ship.

(3) To prevent rotation of a ship, located along a mooring post, about the mooring post, so that the ship faces in the wrong direction (loss of time in the case of entrance into the lock, and danger of collision with ships coming from the lock).

(4) To protect the posts and footbridges against collision.

The mooring posts are provided with mooring bits, niches, and steel ladders. The corners are covered with vertical, rounded steel shapes. A concrete plug is installed on the bottom under the water. Drainage holes are present below the lowest water level for the purpose of removing the water; behind the holes is a layer of gravel. Guide walls of the same construction connect the mooring stations to the lock structure or to the portion of the guide walls forming one unit with the lock structure.

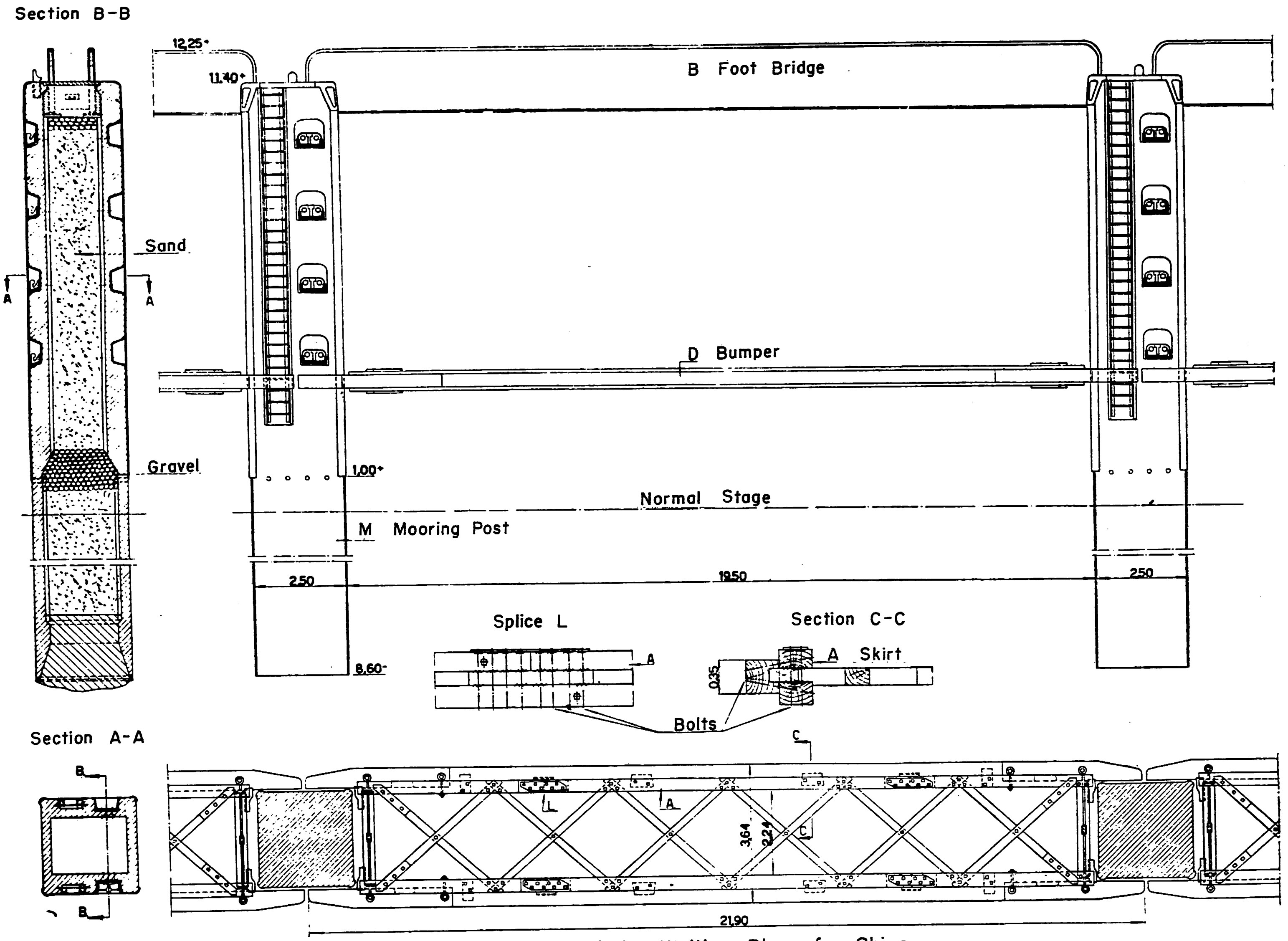


Fig.12 - Details of the Waiting Place for Ships

The splices L were introduced because it was impossible to obtain the skirts A from one length. Wood with clamps was used on one side and galvanized steel with staples at the bottom on the other side.

The bumpers are of the same construction as that used in the Beatrix lock at Vreeswijk, namely, a wooden latticework of which the tension occurring in the diagonals is transmitted to the longitudinal members by means of bulldog clamps (Fig. 12). Each bumper contains 14 sq m of wood. Not a single repair was found necessary in the nearly 12 years during which the bumpers were in use at Vreeswijk. Damaging collisions did not occur; the ships have no grip there. The bumpers, which come in contact with shipping only on one side, can be turned three times in order to expose sound wood on the side above the water. The wood that is not continuously under water is creosoted. It is not known whether the Tiel bumpers will last as long as those prepared prior to the war, since it was impossible to obtain Oregon pine during the postwar trouble period and it was necessary to be satisfied with European pine of shorter length (Fig. 12, splice L).

During the occupation, one of the bumpers at Vreeswijk was rammed by a German vessel with a drunken crew--an abnormal case. Recently the bulldog clamps (copper) were found, after dismantling, to be not as good as new. The clamps at Tiel consist of heavily galvanized steel plates, in order to economize on cost and foreign exchange.

The footbridges on the north side of the lock were prepared during the war. They are of classical design. The footbridges on the south side will be of prestressed concrete, while retaining the external shape.

## D. The Lock Gates

Prior to and during the war, the gates were designed as economically as possible, but in the case of the miter gates involved it was not readily possible to obtain the desirable profiles. For this reason the original gate weight of 62 tons was greatly increased.

The gates are not equipped with buoyancy chambers, which results in a considerable saving on weight and makes it possible to install valves in the gates for the purpose of establishing the level in the lock chamber. The disadvantage of omitting the buoyancy chamber, however, is that the pintles and trunnions become more heavily loaded. It is not abnormal for a pintle to carry a vertical load exceeding 62 tons, except the decrease due to uplifting water pressure and, at low water level, the eventual increase due to icing in the zone between high and low water. In the case of the miter gates of the Panama Canal, the pintles are subjected to a vertical load of ± 260 tons, in spite of the fact that buoyancy chambers are used. Moreover, in the case of the large miter gates of the recently constructed Stechovice lock (lift in excess of 20 m), which were not equipped with buoyancy chambers, the load amounted to 299 tons (Czechoslovakian Report, section I, question 2, at the Navigation Congress recently held in Lisbon). The pintles are designed for heavy loads.

The lift gate must be similar to those in the Wijk lock at Duurstede because this gate should fit there. Therefore, it should not be any heavier. Accordingly, preparation of the gate is postponed until all the ultimate profiles are obtained. Two lift gates will be constructed so that one gate would serve as a reserve gate for the three lift gates at Wijk near Duurstede and the single lift gate at Tiel.

The valves for all the gates are located on the outer, high water side of the gate; such an arrangement results in uncomplicated watertightness, facilitates ready replacement, and makes it possible to utilize the interior of the gate as a turbulence chamber and distributor for the water flowing into the lock chamber during filling; even within the gate the water can undergo vertical distribution (saving on length of lock chamber).

The pintle socket (K, Fig. 13) is attached to the gate and is provided with a manganese steel bearing. The shaft (P, Fig. 13) is inserted in a steel housing (H, Fig. 13) anchored in the lock floor. Also the shaft has a manganese steel bearing. Manganese steel was selected on account of its analogous use in dredge mills where excessive wearing is anticipated. Although the pintle socket is lubricated internally with the aid of a high pressure grease pump actuated by one of the valve operating mechanisms, the adequacy of the lubrication is doubtful because dirt is likely to penetrate there. The argument is that poor lubrication is better than no lubrication. The trunnion (Fig. 14) likewise is lubricated automatically.

The watertight seal at the rear clearance is achieved by means of a wooden molding which fits against the granite anchor block. The concentrated force is transmitted to the concrete by means of the gate and wall trunnions. The trunnions are missing only at the lower members; therefore, these members are not subjected to a concentrated force. Such an arrangement is regarded as an improvement, in comparison with the arrangement in which the lower member

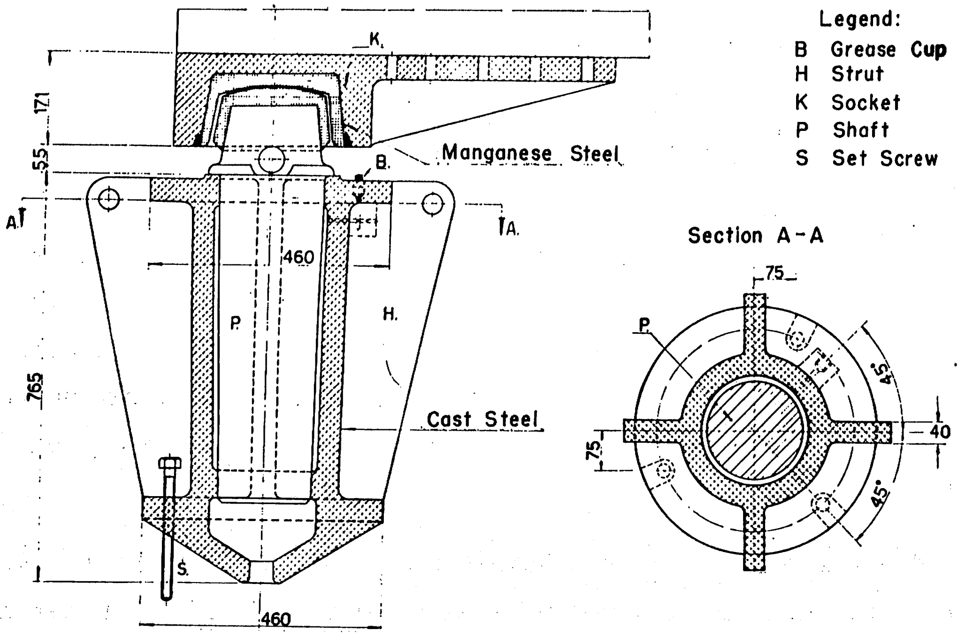


Fig.13 - Pintle and Socket

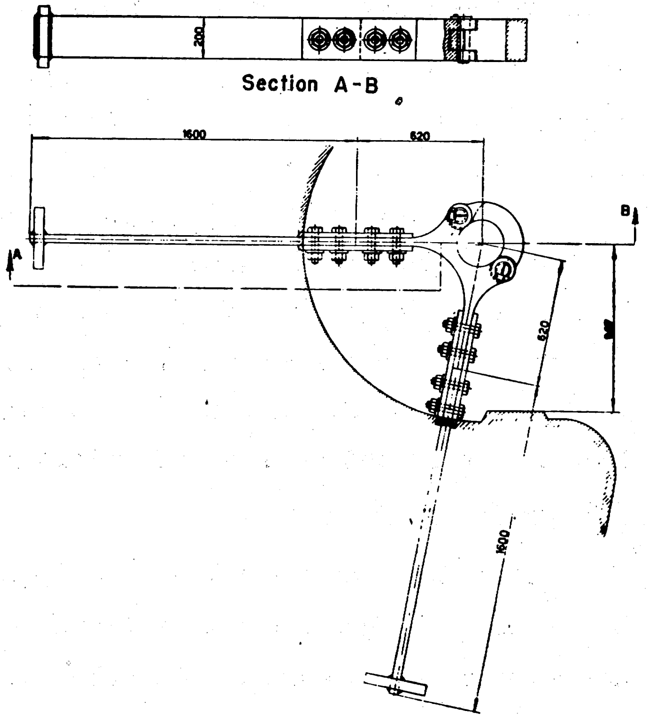


Fig.14 - Trunnion

is equipped with a trunnion (the Ravenswaay lock system). A gate trunnion at the lower member would be subject to wear during motion of the gate even after slight wearing of the side surface of the pintle or wearing of the socket bearing--the gate would repeatedly be offset by the trunnion--and, once it has become worn, it would definitely not function (Fig. 3b). The trunnions are provided with stainless steel cushions in order to reduce wearing (rusting and repeated scour of the rust always cause extensive wearing).

In designing the gates, the possibility was taken into consideration that, after completion of the Rhein canalization, the gates would occasionally have to operate in reverse. They would then have to be bolted successively. Provisions were made for subsequent installation of these bolts, while the pintle and trunnion were designed for reverse operation. In addition, the valves in the gates are designed to operate in both directions (see also the following section). Torsional bracing is already installed in the gate.

## E. The Valves

### 1. The Valves in the Gates

The valves in the gates (Fig. 15) are plane slide valves equipped with bronze strips which slide over stainless steel strips mounted on the gate. The vertical steel strips are lubricated at one-fourth and three-fourths of the valve height by means of the same high pressure grease pump which lubricates the pintle, the trunnion pin, and the connecting rod pivot in the gate. The horizontal strips are not lubricated because the grease will not be distributed at local application. In order to free the horizontal strips as much as possible--reduction of the required actuating power--they are mounted on flexible extensions from the valve skin plate (see vertical cross section). The horizontal gate strips are chamfered in order to prevent the corresponding valve strips from thrusting against them when the valves are actuated in a deflected position.

All of the strips which slide over one another are of a special, experimentally obtained composition; the bronze strips consist of cast bronze comprising 88 per cent copper, 8 per cent tin, and 4 per cent zinc, while the stainless steel strips have a strength exceeding 100 kg per sq mm. This combination results in a friction coefficient which remains smaller than 0.50 even when the lubrication does not function (at a different composition of the strips, the friction coefficient would increase in excess of unity and ultimately the motion would become quite jerky). In the case of lubricated bearing strips, the maximum friction coefficient should be 0.20 at the beginning of motion and 0.04 to 0.08 during the motion.

The displacement clearance of the valves in the grooves is 0.002 m in the lateral direction and 0.006 m normal to it.

If lockage should occur subsequently in the opposite direction, the steel strip S (Fig. 15) must be replaced by a stainless steel strip and a bronze strip $S_1$ must be installed in the **valve**. The strips are not lubricated during reverse lockage, but the lift is much lower then.

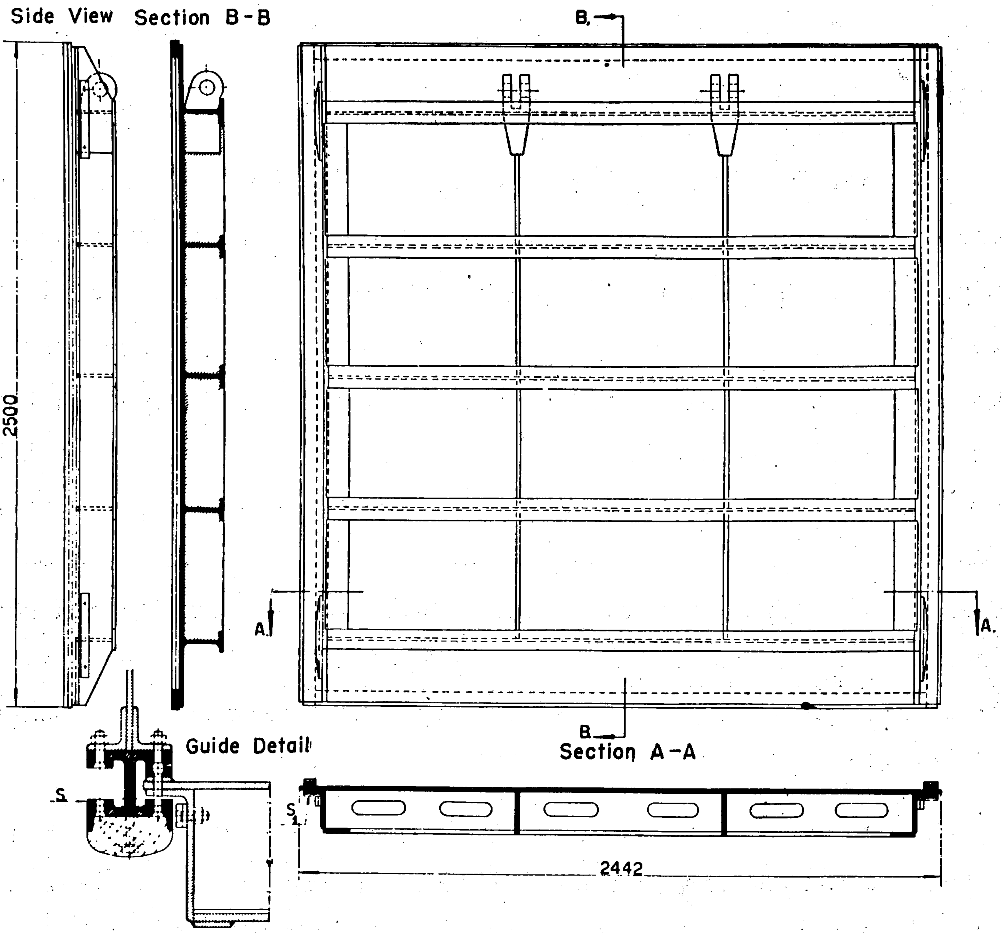


Fig.15 - Details of Slide Valve and Guides
S. Steel strip. $S_1$. Bronze strip.

## 2. The Culvert Valves

The culvert valves are unconstrained slide valves (Fig. 16). The system consists of a main valve and an auxiliary member. The main valve is a slide valve which is connected to the auxiliary member by means of hinged links; the auxiliary member is equipped with rollers. The traction force is applied to the auxiliary member. The latter advances a little past the main valve during raising operation. The rougher the surface of the slide strips, the greater is this advance. The force with which the main valve presses on the slide surfaces during motion is smaller than the horizontal water pressure; the auxiliary member relieves the load on the slide valve. The slide surfaces are not lubricated; their composition is given under E-1.

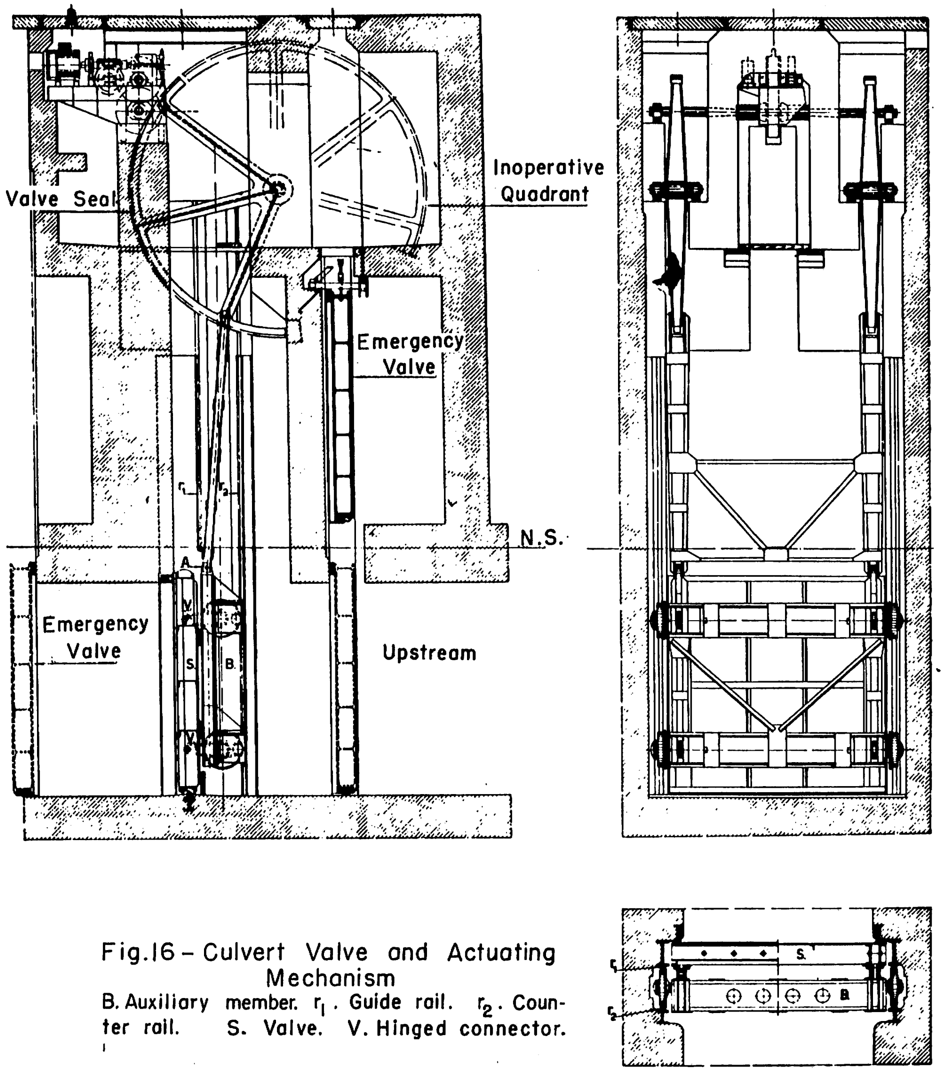


Fig.16 – Culvert Valve and Actuating Mechanism
B. Auxiliary member. $r_1$. Guide rail. $r_2$. Counter rail. S. Valve. V. Hinged connector.

During closing of the valve under high horizontal water pressure it is likely that the auxiliary member will pull the main valve along with it. When the valve is closed, however, the hinged links must remain horizontal in order to prevent the occurrence of a clearance between the main valve and the bearing surfaces and, consequently, incomplete seal. This occurs when the actuating mechanism continues to operate after the hinged links have reached their normal final position. In this way the auxiliary member will descend a little too low and then will rise the same distance, while the main valve remains at lowest position. The valves are entirely similar to those used in the culverts of the Wijk lock at Duurstede.

## F. The Actuating Mechanisms

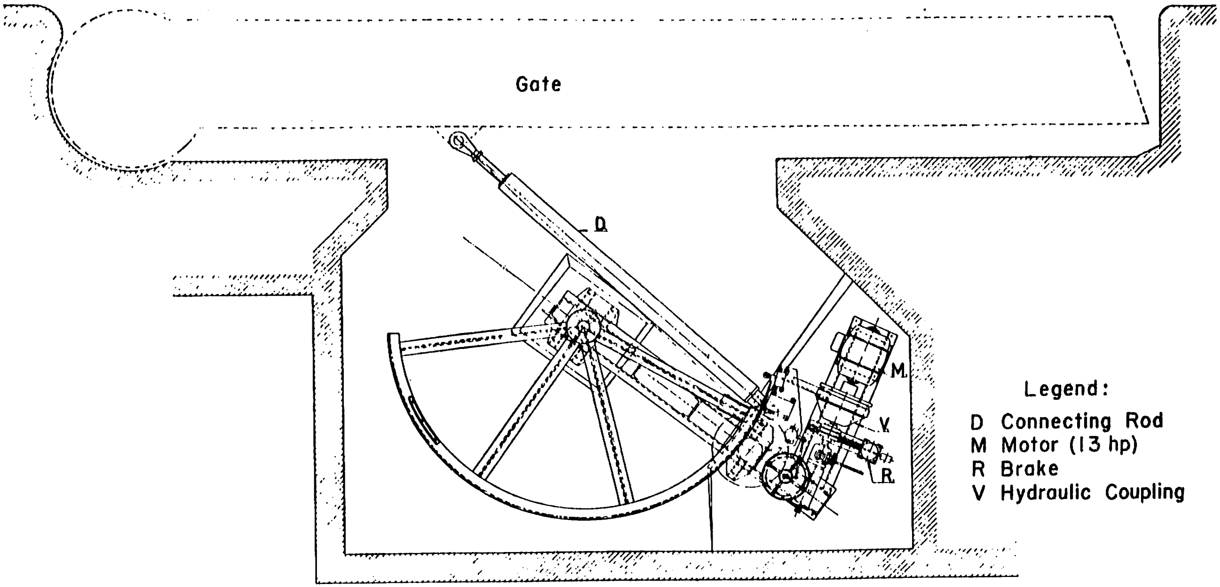
### 1. The Miter Gates

The actuating mechanism for the miter gates is similar to that at Ravenswaay, although the gates are higher because they must be able to move in deeper water and withstand greater pressure (Fig. 17). The only difference is that a hydraulic coupling between motor and gear system and a brake are used in the present case.

The hydraulic coupling makes it possible to obtain the above similarity even with regard to the motor capacity (13 hp). Should the required power at very high water levels exceed the available motor capacity, then the coupling will slip and the gate will move much slower; the resistance will adjust itself to the available motor capacity. That is, the principal resistances, which are proportional to the square of the gate speed, become smaller at slower gate motion. Moreover, if the gate encounters an abnormally high resistance during its motion, caused by a sudden wave, for example, then the gate may cease moving, while the motor continues to rotate. When the resistance has subsided, the gate will gradually resume its motion.

The gear system is based on an actuated half wheel (Panama wheel). The duration of the gate motion is 1 min.

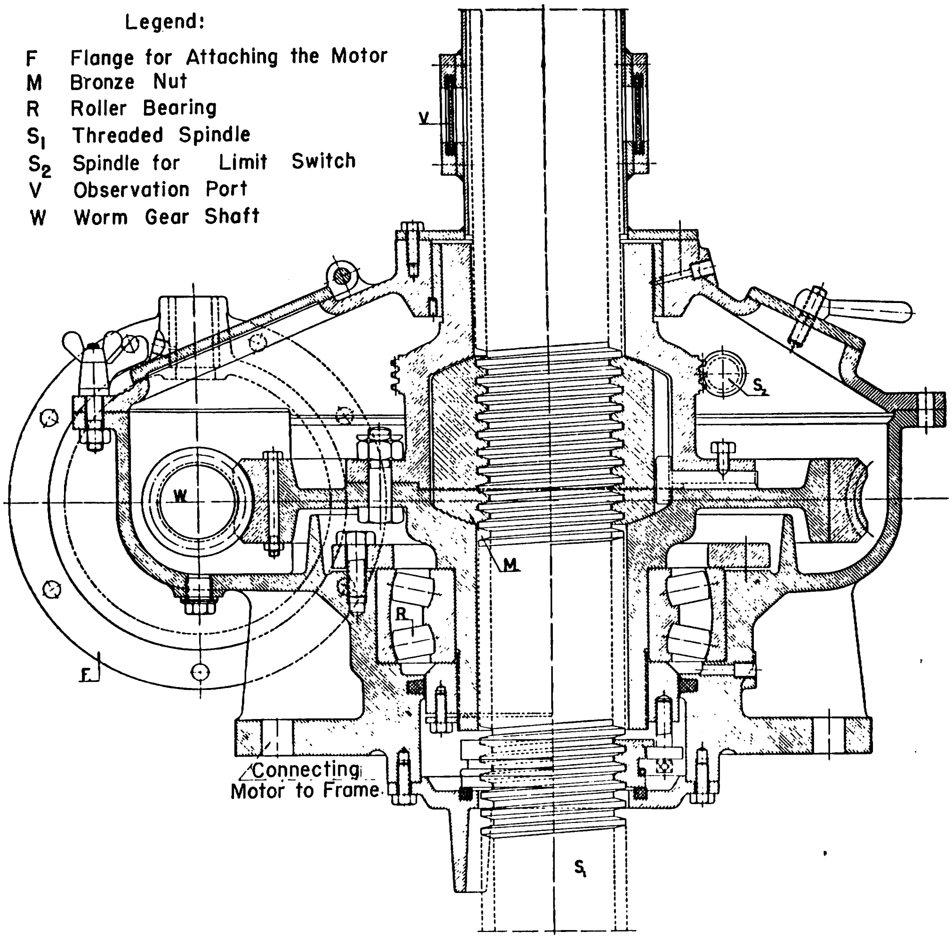
The brake causes the gate to stop during closing before the leading edges of the gate set come in contact with each other. The gap is closed by the head which occurs during establishment of the level in the lock chamber, whereby the springs in the connecting rod become tensed. The advantage of



Legend:

- D Connecting Rod
- M Motor (13 hp)
- R Brake
- V Hydraulic Coupling

Fig.17 - Actuating Mechanism of a Miter Gate



Legend:

- F Flange for Attaching the Motor
- M Bronze Nut
- R Roller Bearing
- $S_1$ Threaded Spindle
- $S_2$ Spindle for Limit Switch
- V Observation Port
- W Worm Gear Shaft

Fig.18 - Vertical Section Through the Gear System for a Slide Valve

the described system is that the gap will recur before the water attains the same level on opposite sides of the gate. As soon as the gap occurs, a warning signal is given to the service personnel that the gate may be opened. A push button, installed in the leading edge of one of the gates of the set, appears and is accompanied by a light signal.

A push button will likewise appear in the case of the Ravenswaay gates, but not before the lock chamber is completely filled. Moreover, this occurs only after excess water has entered the lock chamber due to the inertia of the inflow, so that the head becomes reversed and the gates are pressed open a little, referred to as gaping. In the case of the Tiel lock, which is considerably more busy as a navigation lock than the Ravenswaay lock--continuously so far--the time required for establishing the level in the lock chamber is thus reduced, as the vanishing of the last couple of centimeters of head requires the longest relative time. Thus, the gates may already be opened when the head is 0.10 m or 0.20 m, depending on whether the level in the lock chamber is high or low, respectively. A hydraulic coupling is effective also in this case; if the resistance due to water pressure is too high, the coupling will slip until the resistance has decreased sufficiently and the gate can begin to move.

Use of a brake was desirable because it was injudicious to rely on the self-braking action of the worm in the gear system; in the case of storm, the gates would tend to proceed too far in one direction and insufficiently far in the other direction. In addition, the gap would be closed by the water pressure, instead of causing tension in the springs.

It should be noted that the wind force, which is independent of the gate speed, is factually the criterion when a hydraulic coupling is used; the friction resistances of the pintle and trunnion are unimportant because the lever arm is short.

The slide bearings and the linkage between the connecting rod and the half Panama wheel are lubricated by an automatically operating high pressure grease pump.

### 2. The Lift Gate

The actuating mechanism for the lift gate will be similar to that of the gates of the Wijk lock at Duurstede. The gate speed is 0.20 m per sec in the water and 0.40 m per sec above the water. The speed transition occurs automatically, although the water depth is not constant.

In spite of the rapid rate of gate motion, the lift gate is opened slower than the miter gates because of the longer distance involved, although the lift gate is actuated by a 120-hp motor (the converter requires even more power), whereas a set of miter gates requires merely a 26-hp motor.

With regard to the actuating mechanism, reference is made to De Ingenieur, No. 14 of 1937 and No. 32 of 1935. Here it will merely be stated that the motor is a direct-current motor with Ward Leonard switching.

### 3. The Gate Slide Valves

The mechanism for the gate slide valves is shown in Fig. 18. It is essentially the same as that used in the other large locks of the Amsterdam-Rhein Canal. It consists of an actuated horizontal worm gear connected to a spherical, movable bronze nut. The nut, which is forced to rotate with the gear, moves a threaded spindle up and down. The vertical force is transmitted axially to roller bearings. The worm gear is equipped with a spindle for actuating a limit switch. A housing with covered top, into which the vertical spindle moves during raising of the valve, prevents rain water from penetrating into the worm gear housing. This spindle housing has observation ports which make possible periodic checking whether the valve is lowered to the proper lowest position, that is, whether the corresponding limit switch is functioning properly. When the limit switches do not function, the spindle passes out of the nut. If this occurs at the lowest valve position, the valve and spindle fall several centimeters downward onto the stops mounted on the gate. The spindle cannot roll down into the lock chamber because it is still held in the housing of the system.

The motor is a 5-hp direct-current motor with Ward Leonard switching. The gate speed ranges from 1 to 2.85 cm per sec.

### 4. The Culvert Valves

The actuating mechanism for the culvert valves is similar to that of the Wijk lock at Duurstede. It consists of two vertical quadrants actuated by a central gear system located above the highest water level (Fig. 16). The quadrants are connected to the auxiliary member at A by means of hinged links. The motor has a capacity of 10 hp, and the valve speed is 14 mm per sec.

The quadrants can be turned sufficiently far to clear the path along which the valve must proceed during exchanging of valves. The limit switch for downward motion is set in such a way that the auxiliary member first brings the main valve into lowest position and then the hinged links between the main valve and auxiliary member resume their horizontal position so that the main valve is no longer relieved by the auxiliary member.

The valves regulate the culvert discharge. The discharge of both culverts is separately indicated in the appropriate control room. It is proportional to the gradient in the culvert, which is indicated by two floats located more than 300 m apart in the right culvert section. Each of the two floats actuates a small generator which drives a small motor by means of an electrical shaft. These motors are located in the control room and each operates one pointer of a protractor. One of the pointers is rigidly attached to the protractor. The angle between the pointers indicates the drop between the two floats and, hence, the discharge. Of course, the protractor must be calibrated.

## G. The Lighting

The lighting consists of sodium vapor lights located 11 m above the lock plateau. The lights illuminate the lock area and the wall on the other side. Extra lights are located near the gates in order to illuminate them.

The lights for the guide walls and mooring stations should actually be located on the bank opposite the rows of mooring posts, so that the mooring bits would be illuminated, but the distance involved is too large. Therefore, the lights are located on the mooring posts, 66 m apart. Reflection of the light from the water adequately illuminates the mooring bits with diffused light.

## H. Operation of the Lock

Although one-way locks can be operated by one operator, two men will be employed normally, while the lock master is ambulent. The lock is too long for operation by one person; one man cannot supervise both waiting places for ships. Operation by one man is adequate at night and on Sundays or holidays.

A signal installation, located in the approaches, is used to warn the service personnel that a ship is approaching. If the lock is operated by two men, it is divided into two regions, each containing two successive lockheads. The two regions can communicate via telephone.

The lock gates are operated locally; the operator must ascertain that the gate passage is free, that nothing is moving over the gate (gates), and that no debris is involved. As soon as the gate (gates) is (are) closed, the attendants at the control board begin the filling or emptying of the lock chamber. If an 85-m chamber is involved or if only one man is attending to the lock, the attendant proceeds towards the closed gate (gates) of the other lockhead during establishment of the level in the lock chamber, in order to open this gate (gates). If the gates involved are opened by the other attendant, the former attendant remains in his own zone. The control boards are located in chambers. Experience with open air location was not entirely satisfactory.

Closing of the valves in the gates occurs automatically as soon as the limit switch for opening the gate is actuated. It has already been stated in part II-B that the switching operations for the opening schedule of the gate slide valves likewise proceed automatically. Finally, the transition from the low speed of the lift gate (in the water) to the higher speed (above the water)--the water level at the location of the lift gate varies with that of the Waal River--occurs automatically. Otherwise, everything automatic is avoided in order to minimize the sources of operation interruption.

The lock attendants regulate the discharge of the culverts as well. Of course, this does not require much time. Loudspeakers provide acoustic contact between the lock attendants and the vessels in the approaches.

The lockage signals are given by means of electric lights--one light each on opposite sides of the passage at the ends of the lock and only one light each on the starboard side of each intermediate lockhead. At the ends of the lock, the lights mark the approach (they are installed at 0.20 m outside the exposed surface of the lock and not any closer because of the danger of collision due to cargo protruding outside the vessels or listing of overloaded ships); such an arrangement is unnecessary in the case of the intermediate lockheads because the ships already are between the lock walls.

The signals are as follows:

| For the Terminal Lockheads | For the Intermediate Lockheads |
|---|---|
| Safe: green on both sides. | Safe: green at starboard. |
| Danger: red on both sides. | Danger: red at starboard. |
| Occupied: two red lights under each other at starboard and one red light on port side. | |
| Lock is being readied: red at starboard, green on port side. | |

I. The Highway Bridges (Fig. 2)

Only one of the three highway bridges is currently under construction, that is, one of the two bridges for State Highway 15 (Dordrecht-Nijmegen). The bridges consist of steel girders on eight piers. The fixed support is installed on the last wall along the extension of the lock under construction, hence as much as possible in the middle of the bridge. The spans are 26.80 m each. Since the moments in the terminal spans are maximal, the corresponding girder height is increased (1.80 m versus 1.30 m). The lateral beams are No. 85 and No. 65 I-beams, respectively, in the state highway bridges and the provincial road bridge. There are no longitudinal beams because the concrete deck assumes their function.

The bridges are delivered in sections and are erected on the site. Originally the bridges were designed as completely welded structures. However, shortly after the war, when it was necessary to order the material for the bridge under construction, it was impossible to obtain skirting of steel suitable for welding, so that riveting had to be used. The webs of the main beams are welded, as well as the transitions to the lateral beams. All goose plates are riveted.

Since the bridge under construction will not be open in the future to bicycle traffic, no bicycle paths are provided, although such traffic will be permitted until the provincial road is completed. It is possible that the second state highway bridge as well as the provincial bridge will be entirely of welded construction, except the goose plates.

The railroad bridge is designed by the Netherlands Railways.

# THE DEVELOPMENT OF LOCKS
# WITH VERY HIGH LIFTS

(De ontwikkeling naar schutsluizen met zeer grote vervallen)

by

J. P. Josephus Jitta

De Ingenieur, No. 15, April 14, 1950, pp. B37-41

# LIST OF ILLUSTRATIONS

# THE DEVELOPMENT OF LOCKS WITH VERY HIGH LIFTS

Currently the development of locks leads to utilization of very high lifts. This is evident from the reports on the 17th International Navigation Congress, held in Lisbon in 1949, which discussed the means for overcoming the difficulties involved in high lifts (section I, question 2). According to the corresponding French Report, a normal lock, designed to overcome a lift of 65 m, is under consideration in France (Lyon-Geneva navigation canal, Genissiat Falls).

Half a century ago a lift of 3 m was regarded as high. Such a lift was rarely exceeded, for instance, when the lock involved construction in rock, and bulkheads could be avoided by erecting masonry or concrete structures against the rock. When steel bulkheads and reinforced concrete were introduced, the aspect of limitation in lift was no longer a decisive factor from the point of view of construction. The magnitude of the lift, which has come to be regarded as feasible, has depended ever since on the manner of filling and emptying of the lock chamber and on the water reserve. In the subsequent discussions, it is assumed that the latter factor is absent.

The feasibility of rapidly filling or emptying the lock chamber in such a way that the ships in the chamber would not be subjected to stresses during lockage has been the subject of intensive investigation for a considerable time. With respect to this, filling of the lock chamber is less favorable than emptying because the energy of the flowing water must be dissipated in the lock chamber during filling and outside the chamber during emptying. Thereby it occurs that in the beginning of filling, when the head is maximal, the water depth in the lock chamber is minimal, while at the beginning of emptying the water depth is maximal (the magnitude of the longitudinal forces acting on the ships in the lock chamber, being of greatest importance in the case of not too wide locks, is inversely proportional to the water depth). These are the reasons why only the filling operation is discussed in the following.

It is well understood that filling of the lock chamber through an opening in the lock gate (gates) would have no effect whatever upon the tranquil position of the ships, but the filling period would be excessively long.

The larger the opening or openings through which the water flows into the lock chamber, the faster the filling and the greater the chance that the ships would be subjected to stresses due to the inflowing water. It is true that the principal forces acting on the ships, except in broad canal locks, are longitudinal forces which can be diminished by means of opening the inlets as slowly as possible at the beginning of filling, for instance, by raising most slowly the valves controlling the inlet (or inlets). In the case of an unsuitable filling system, however, the filling period would be excessively long (the effect of the valve opening period upon the duration of filling is an increase amounting approximately to half the opening time). Currently it is generally regarded as unsatisfactory if the filling time is longer than 8 min.

Originally filling of the lock chamber involved valves in the gates (at that time exclusively miter gates). No other method of filling the lock chamber has been sought for centuries. But as the lock chambers and the lift --consequently the quantity of water--became larger, the adjustable openings to be installed in the gates would have had to be so large that the gates (at that time exclusively wooden gates) would have been greatly weakened. It became necessary, therefore, to arrange discharge channels (designated as loop culverts) in the lockhead walls. These culverts ran straight through, parallel to the lock axis, and discharged into the lock chamber which was bounded by the ground profiles, or curved past the gates towards the lock chamber when the chamber design was such that the former type of culvert was not feasible. As long as control of the culverts consisted of manually operated plane valves, the system was satisfactory (valve speed very low); as the quantity of lockage water increased, however, the culverts became too large for manual operation of the valves. When electrical operation of the valves was introduced, the following difficulties arose: turbulent water in the lock chamber caused the ships to lurch to and fro and occasionally the hawsers broke. As a result, it became necessary to arrange the culverts along the entire length of the lock and to establish the inflow into the lock chamber by means of ports or laterals. The result achieved in this way was always quite satisfactory in the case of not excessively large quantities of lockage water. It was assumed that thereby the water entered uniformly into the lock chamber through all the laterals simultaneously and in equally divided amounts.

In the case of the Panama Canal locks, which were 33.50 m wide, 305 m long, and had a lift up to 10 m, the improvement process proceeded even further. There the laterals were installed in the lock floor normal to the lock axis, one lateral from each culvert successively; the laterals extended across ± 5/6 of the chamber width, and discharge into the chamber occurred through a series of openings in the upper wall of the laterals, uniformly distributed across the lock chamber. Originally it was intended to use only one culvert (the ideal may well be achieved at present, even though one culvert were used), but the result was lack of uniformity; the upstream laterals discharged the least water, while the downstream laterals discharged the most. Moreover, in each lateral the discharge from openings increased in the downstream direction. Consequently, the ships were subjected to forces which pushed them in the direction of the discharging culvert; this was rather troublesome because the ships were held along the lock axis by four tractors (see "Hydraulics of the Panama Canal," by R. H. Whitehead, presented at the International Engineering Congress held in San Francisco in 1915).

Utilizing the knowledge of these facts, it was established in 1920 that the filling phenomena of the third lock at Hansweert (maximum lift about 2 m) conflicted with that observed at the Panama Canal. Thereby it was found that at the beginning of filling, the laterals began to discharge water successively, judging from the eddies which formed on the upper surface of the lock chamber at some distance in front of the laterals; these eddies were caused by the water jets issuing from the laterals and piercing the water surface in the chamber. It was impossible to determine what occurred during the later stage of filling because of the large depth of water in the chamber and because the eddies spread over the entire upper surface of the chamber.

The inconsistency in the observations at the Panama Canal locks and the Hansweert lock motivated the direct need for conducting tests on the existing largest IJmuiden lock, currently known as the Middle Lock, which was 25 m wide and 225 m long, whereby the filling occurred through culverts with 11 laterals in each lock wall (see <u>Reports and Communications of the Waterways Department</u>, No. 23).

Pendulums were mounted along one side of the lock, one pendulum in front of each of the 11 laterals; each pendulum was watched by an observer. The deflection of each pendulum was observed and recorded every 2 sec; a sound signal was used (see also the article by J. A. Ringers in De Ingenieur, No. 39, 1924). The results were as follows: at first only the upstream lateral discharged a noticeable quantity of water, followed successively by the other laterals. Nearly 1 min elapsed before all the laterals discharged an observable quantity of water. As more laterals began to discharge, the discharge from the upstream laterals increasingly diminished, beginning with that of the first lateral, and yielded more water to the last laterals. Once this was established, it became possible to explain the seeming contradiction between the phenomena observed at the Panama locks and the Hansweert lock. In the former locks the observations did not refer to the beginning of filling, so that the opposite phenomenon was established.

It will be seen that the higher the head and the longer the laterals, the shorter the time interval during which the upstream laterals dominate, so that this time interval is not the most important in the case of the Panama Canal locks.

What is actually the case? Considering a culvert with very short laterals, thus practically constituting openings in a very thin culvert wall, the pressure of the high water outside the culvert is propagated immediately after the beginning of valve opening. In the first lateral the propagated pressure initially vanishes and begins to rise appreciably only when the water in the lateral has acquired some velocity $[h = \mu^2 (v^2/2g)]$. Because of the inertia of the water in the culvert section between this lateral and the next one, a certain time interval elapses during this process. If the pressure rise is considerable, then it is propagated to the next lateral, and so on. The higher the head and the greater the resistance in the lateral (the inertia of the water in the lateral is also regarded as resistance), the faster the pressure rise at the inlet of a lateral and the faster the transmission process.

As long as no water flows yet past the first lateral and the velocity of the water in the culvert is still negligible, the discharge direction is normal to the culvert axis. The greater the flow past the lateral and, therefore, the higher the flow velocity in the culvert past the lateral, the more oblique becomes the direction of the water jet issuing from the lateral and, therefore, the discharge correspondingly diminishes. For this reason the laterals located farther downstream will ultimately discharge more water.

No matter how a culvert with laterals is arranged, the ideal flow conditions anticipated can never be achieved. If the conditions are favorable at the beginning of the filling operation, as a result of careful shaping of the culvert as well as proper size and direction of the laterals, they will no longer be such at the end of filling. Accordingly, a culvert with laterals never can yield an ideal solution; this does not imply, however, that such a solution would not be satisfactory in the case of not excessively large quantities of lockage water.

Once it was realized that culverts with laterals do not constitute an ideal solution, this type of design, often costly because it necessitated wide and deep lock-chamber walls, was immediately discarded in the Netherlands. This decision was substantiated by the investigations, conducted at the German Hydraulic Laboratories, of the forces acting on the ships during filling of the lock chamber.

Therefore, loop culverts were used in the north lock at IJmuiden which was 50 m wide and 400 m long. This made it possible to base the lock-chamber walls at high elevation and resulted in a saving which amounted at that time to 1,500,000 gulden, that is, one-eighth of the total cost of the concrete and steel structure. Appropriate tests, conducted at the Berlin Hydraulic Laboratory--such a laboratory does not yet exist in the Netherlands--prove that transverse forces act on the ships, in addition to the longitudinal forces. The transverse forces are caused by the water jets from the culverts striking the ships even after recoiling from the opposite walls. Therefore, it was essential to arrange that the water jets should not strike the ships; this was achieved by bending the culverts toward the gates of the lockhead delivering the water, which is currently the standard arrangement. It was found essential that the inflow in the zone where the ships are located should be parallel and uniformly distributed over the wetted chamber profile. For this reason the ideal condition cannot be achieved by means of sidewise inflow (culverts). Obviously, it was contemplated again to discard the culvert system. At present, therefore, it is being investigated primarily whether filling of the lock chamber should occur through valves in the gates or by raising the gate proper (lift gates). The use of sector gates, which are opened for the purpose of filling the lock chamber (they became popular in France after the war), is comparable in principle with the use of loop culverts.

Recourse to culverts is the only solution if it seems not feasible to utilize the system of filling through and with the gates, for example, when the turbulent zone of the water in the lock chamber near the discharging lock-head, where the ships may not be moored, would be proportionally too large at an allowable filling period, or when the gate would necessitate a double skin plate (roller gate in the case of large sea locks). Under such conditions, culverts with laterals are used in inland locks, whereby filling the lock chamber at very high lifts actually requires an excessively long time, considering modern concepts. The ships are permitted then to rise not faster than approximately 1.5 m per min. Thus, filling of the Bonneville lock (Columbia River in North America)--which is 500 ft long, 70 ft wide, has a lift of nearly 20 m, and utilizes culverts with laterals--requires 11.5 min in the case of large vessels and 27 min in the case of small vessels, the latter vessels requiring a more calm chamber. In the case of the locks of the Rhein Canal near Kembs (the largest is 185 m by 25 m, has a maximum lift of 15.87 m, and utilizes culverts with laterals), the ships rise at a rate of 1.35 m per min. Filling of the Stechowitz lock in Czechoslovakia (118.4 m by 12 m, lift approximately 20 m) requires 12 min. (The preceding data are taken from the reports of section I, question 2 of the International Navigation Congress held in Lisbon in 1949.)

The question arises whether the mode of filling the lock chamber can be such that would permit maintaining a filling time of 8 min, independently of the lift and the size of the lock. This question can be answered affirmatively. It is definitely possible to apply a filling system in which this can be attained. For this purpose, the filling would occur not through a culvert with ports but by means of converting each port into a separate culvert, hence through many individual culverts,* designated as transverse culverts (or laterals), which receive water independently of one another and discharge in a uniformly distributed manner along the lock-chamber axis. In this way, the nonuniformity of culverts with ports is eliminated, and the inherent advantages are fully utilized. Improved vertical distribution of the water at the beginning of filling is achieved by deepening the lock chamber several additional meters (suggested by the engineer Henry in the valuable French Report presented in section I, C-1 of the Congress, which parallels the present article

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*<u>Locks and Other Hydraulic Structures in and Along Canals</u>, pp. 29 and 53, by this author, published by de Erven F. Bohn at Haarlem.

in many respects). At a later stage, as the ship has already risen several meters, the distribution becomes considerably more improved (distance of several meters between culvert outlet and ship). Of course, it is essential to open the culvert valves extremely slowly in the beginning.

Floating mooring bits should be installed in the walls because the steady pitching of the hawsers may possibly be detrimental and quite hazardous in any case. During the rising the ships will, as it were, roll with the rise when they lean against the floating mooring bits.

Of course, hydraulic laboratory tests are necessary in order to establish the details of the filling system, for example, whether it is necessary to install energy dissipators, such as a concrete slab with slots distributed over its entire surface (grids), parallel to and at some distance above the bottom of the lock (at the surface of the water cushion, as suggested by the engineer Caquot in the French report cited previously).

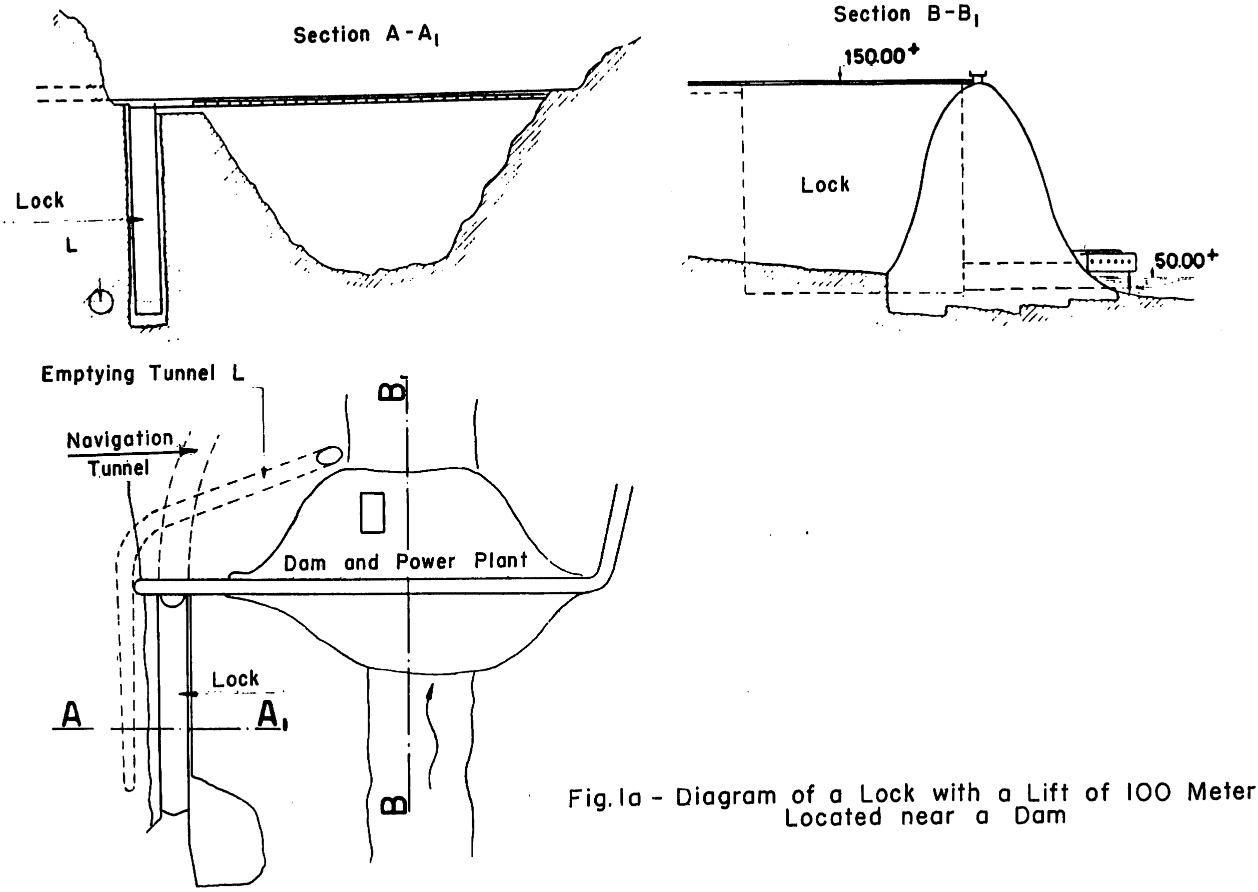

Fig. 1a - Diagram of a Lock with a Lift of 100 Meters, Located near a Dam

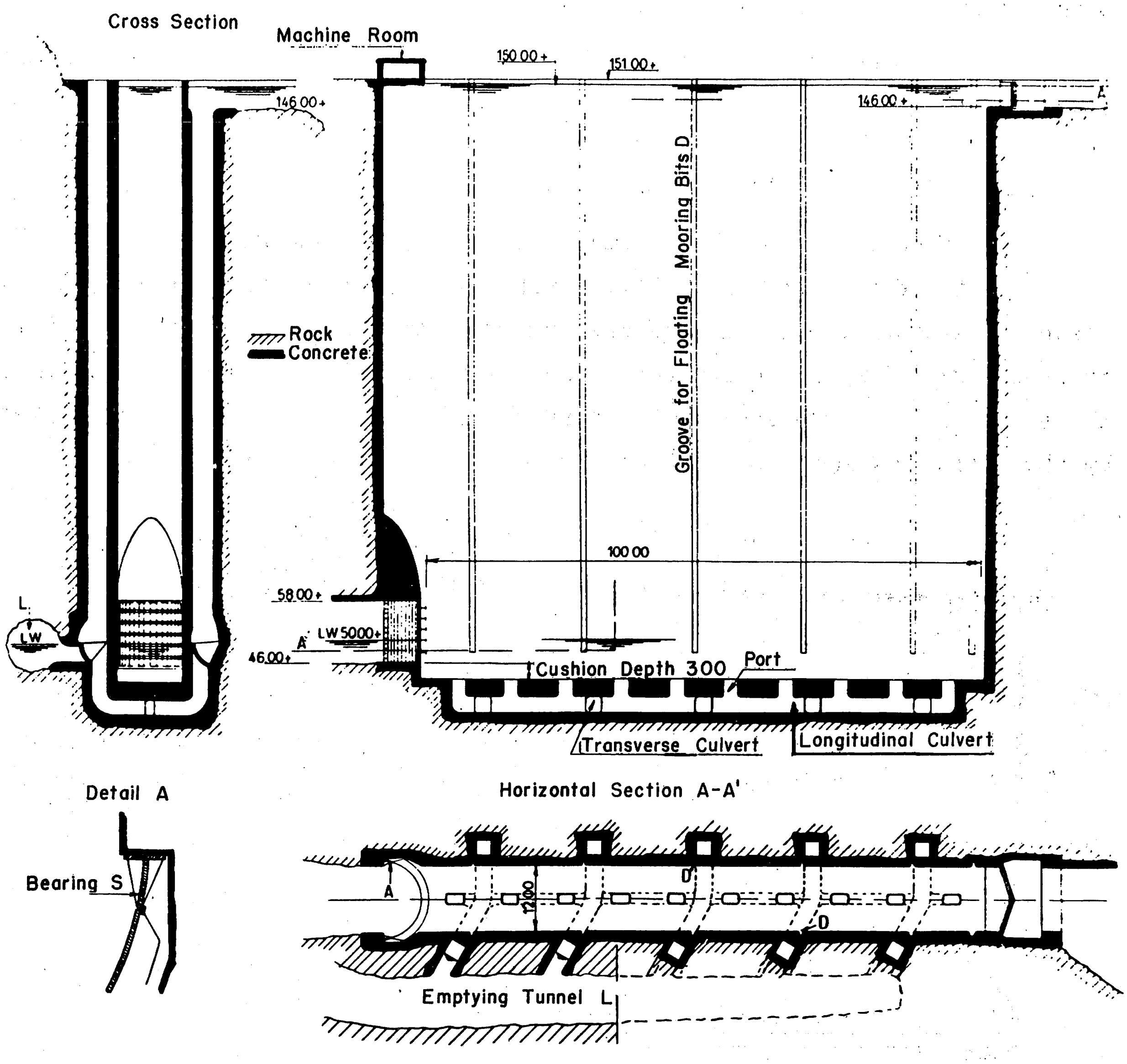

Fig. 1b – Design of a Lock with a Lift of 100 Meters
Emptying proceeds not quite uniformly because of the bending of the transverse culverts, but the ships are not disturbed. Perpendicular inflow results from adequate port length.

Figures 1a and 1b show a diagram of a lock located near a dam and having a lift of 100 m. Naturally, a good foundation is essential there. This would generally be stable, as large dams are constructed as much as possible in a region consisting of rock. The lock is hewn out in the rock, as it were. The walls and floor actually constitute nothing else but covers on the rock. Stable walls as such would have to be fairly impracticably heavy, even though they might be constructed vertically in an offset manner.

The transverse culverts end along the lock-chamber axis at a longitudinal culvert which receives water exclusively from the transverse culverts. Originally it was intended to connect the outlets of the transverse culverts to short longitudinal culverts, each having two perpendicular ports located symmetrically with respect to the transverse culvert; by interconnecting the short longitudinal culverts, the advantage was obtained that the filling would not be disturbed when one transverse culvert is shunted. Factually the resulting system is not a culvert with laterals, but it is laterals with a culvert.

The relatively large number of required culvert valves cannot be regarded as a disadvantage, since the number of valves at filling through the gates would often be still larger (as many as 24 valves in the case of the Beatrix double lock at Vreeswijk). The water flowing towards the lower pool during emptying of the lock chamber can be diverted through a large tunnel* towards a spot where the ships would not be disturbed--to immediately downstream of the dam, for example.

It is obvious that complications will arise during designing the details of a lock which has to accommodate such high lifts, so that the design would result in relatively unusual construction features.

The only suitable valves are segment valves, sector valves,** or shortened cylinder valves, whereby a proper watertight seal is possible. In the case of slide valves, the required tractive force at the given lock dimensions would be excessively large (at the beginning of valve opening, when it

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*This tunnel must be sufficiently spacious to preclude the character of a culvert.

**Discussed in the next article of this compilation - M. P.

is necessary to set the valve into motion, this force amounts to nearly 20 per cent of the horizontal water pressure acting on the valve). In the case of roller valves (for example, slide valves relieved by means of the auxiliary member*), the excessive roller pressure constitutes a disadvantage.

Miter gates or lift gates are suitable for adjustable closure of the upper lockhead. In the case of the lower lockhead, where the horizontal water pressure would be particularly large, the suitable closure is a lift gate that is semicircular in plan view (no concentrated force), such as is currently used and contempleted for future use in France upon recommendation by the engineer Caquot, with the explicit understanding that this gate becomes stressed in compression, for the purpose of a better seal at the transition from the upper bearing to the side bearings, so that it prevents utilizing the advantage of enlargement of the lock chamber due to the space enclosed by the gate. A concrete headwall is constructed above the gate which is not any higher than is strictly necessary, so that the lock becomes a so-called shaft lock. The connection to the lower pool may in this case be a tunnel that is entirely independent of the emptying tunnel.

Besides the construction of the described lock, the following designs require consideration:

1. A coupled lock.
2. A step lock.
3. A lock with spare basins.
4. A lift structure.

A coupled lock, whereby lockage must proceed in several stages and the ships must be shifted each time, will cause too much delay. Moreover, at a given time lockage is possible only in one direction. The latter complication is avoided in the case of a step lock, as the ships moving in opposite directions can bypass each other in the short pools between the locks. But lockage will proceed still slower than in the case of the coupled lock because the ships must proceed every time from one lock into the next; simple shifting of the ships is not involved.

A lock with spare basins functions too slowly; the ships do not proceed continuously during lifting. Moreover, this design is very expensive relative to the other because of the successive water chambers (accumulation of spare basins).

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*Discussed in the preceding article of this compilation - M. P.

A lift structure is generally regarded as vulnerable; it must be periodically inactivated for purposes of inspection and repair. Therefore, the entire unit is factually a machine. It is true that lifting of the ships proceeds very rapidly (a lift of 100 m can be overcome in 5 min at a moderate lift rate of 0.40 m per sec), but time is lost during passage to and from the lift cradle because it is essential that the cradle be as narrow and short as possible in order that the mass involved in the lifting would be as light as possible.

Although the design shown in Fig. 1 requires a considerable expenditure, it offers such great advantages that it deserves overall consideration among the given cases. A design involving filling through separate transverse culverts deserves consideration even in the case of a more normal high lift, if it is not feasible to fill the lock chamber through the gate (gates), as, for example, when it is necessary to construct a lock near a movable dam with high head (Fig. 2). The longitudinal culvert may be equipped with laterals (Fig. 3) in the case of wide locks, so that filling would proceed uniformly also in the transverse direction. Emptying of the lock chamber can occur through the gate (gates).

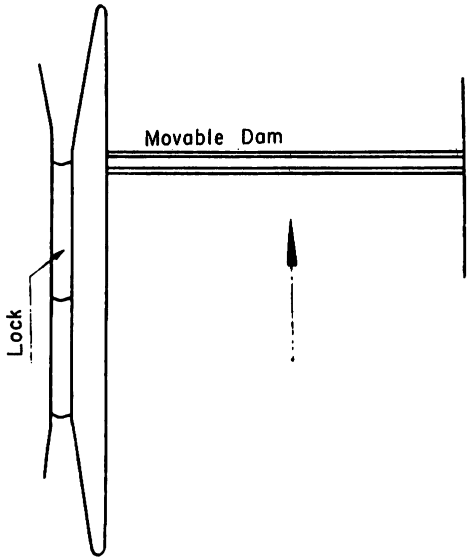

Fig.2 - Diagram of a Lock Located near a Movable Dam

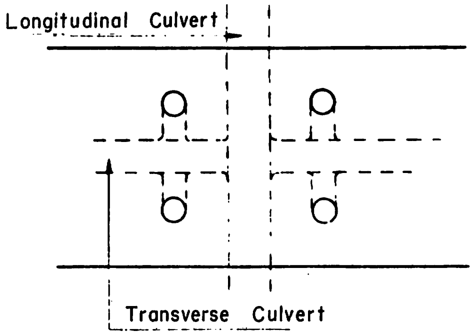

Fig.3 - Distribution of Filling Culverts for a Wide Lock with very High Lift

If a second lock is designed near the first lock, both locks can be filled by means of transverse culverts and all control valves of the culverts can be located in the same wall. The longitudinal culvert of the first lock would have to be interrupted intermittently in order to accommodate passage of the transverse culverts, if it is desired not to make the construction any more expensive.

Of course, installation of a complicated culvert system is judicious only in the case of a rock base. A normal floor, containing the system and subjected to high bending stresses and sliding, would require excessive expenditure.

# SEGMENT VALVES OR SECTOR VALVES FOR CONTROLLING HIGH HEADS AND SECTOR GATES FOR LOCKS

by

J. P. Josephus Jitta

(Segment - of sectorschuiven voor het keren van grote
vervallen en sectordeuren)

*De Ingenieur*, No. 15, 1950, pp. B42-44

# LIST OF ILLUSTRATIONS

# SEGMENT VALVES OR SECTOR VALVES FOR CONTROLLING HIGH HEADS AND SECTOR GATES FOR LOCKS

## A. Segment Valves or Sector Valves

When water is turned by a segment valve or sector valve, the resultant of the water pressure on the skin plate (S, Fig. 1) always passes through the center of rotation. During opening of the valve there occurs an additional uplift force caused by the water streaming under the valve (force on the arms A, Fig. 1, and on any horizontal stiffeners of the skin plate). For this reason the resultant of all the forces acting on the valve no longer passes through the center of rotation, so that the force required to raise the valve will be not as small as is usually assumed.

The difficulty involved in the case of sector valves is, apart from the large space occupied, the required watertight seal between the skin plate and the bearings of the concrete structure. At all times a clearance must be available in order to facilitate the motion, and this clearance is packed with rubber, leather, or elastic sheeting; yet this does not provide an ideal solution. Moreover, the rubber or other substances are subjected to wear due to the dragging under pressure over the bearings attached to the concrete structure.

If the front edge, shaped as a circular arc, of the bearing block has a center located above that of the skin plate, so that the blocks would have so-called free rotation, the resulting design still is unsatisfactory because a clearance will still occur at high water pressures when the valve arms are under compression, while these arms will stretch under tension and cause jamming of the valve. Inserting rubber into the bearing blocks naturally would limit the jamming force, yet wear would occur along the path which the valve must cover during the motion in order to eliminate the pressure upon the bearing of the concrete structure. Once worn, the water seal becomes inadequate. Moreover, during the lowering operation, the valve would tend to get stuck if an irregularity occurred between the bearing blocks and bearings.

Usually the valve is placed in such a way that the arms are stressed in tension (Fig. 1). If such is not the case, then the valve shaft would become evacuated during water flow under the valve, so that air would be entrained with the water flow (see the American Report of communication 2, section I, of the 17th International Navigation Congress held in Lisbon in 1949).

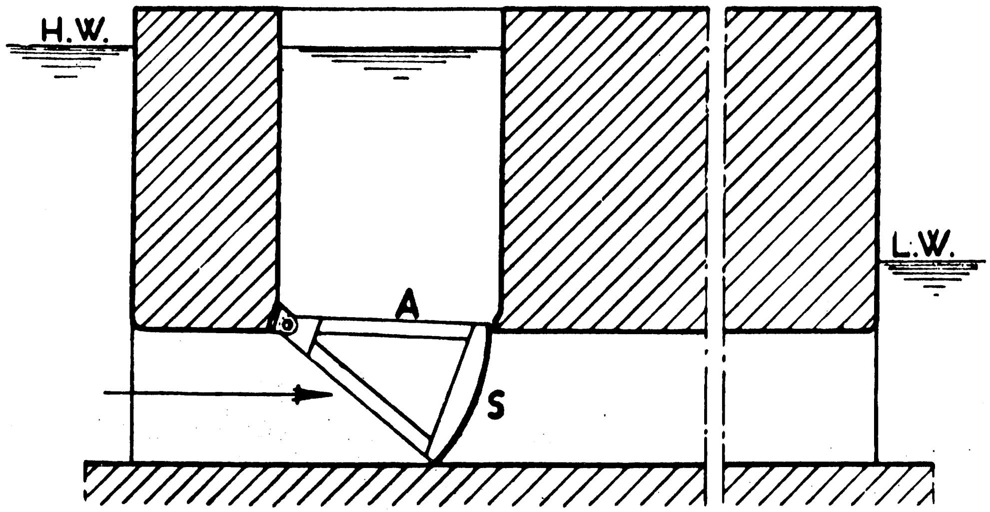

Fig.1 - Diagram of a Filling Culvert Controlled by a Sector Valve

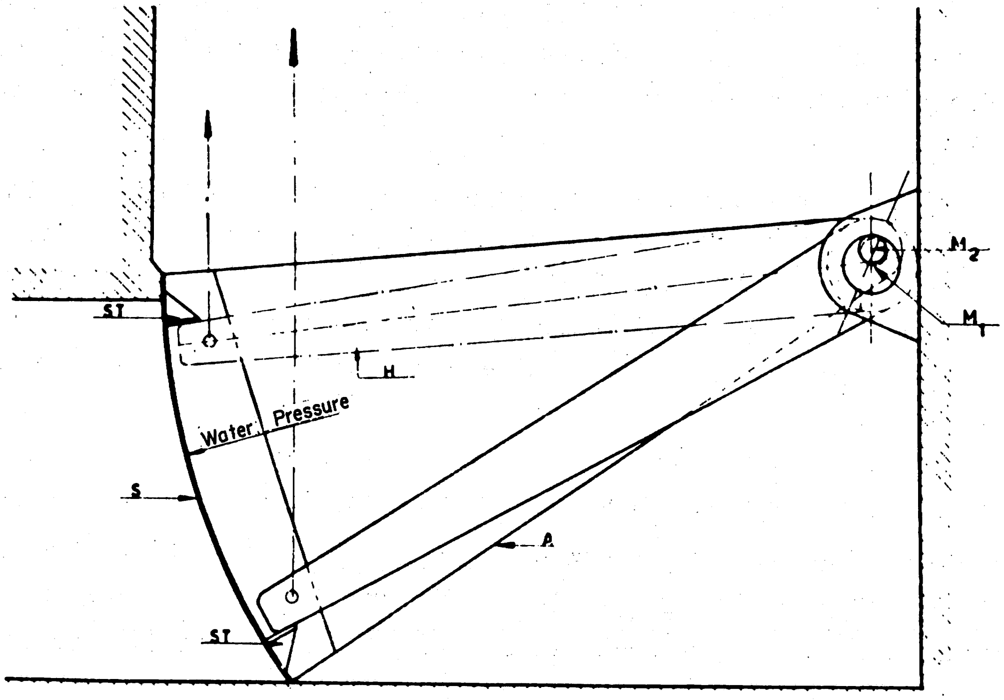

Fig.2 - Uplift Compensator for a Sector Valve, Equipped with an Eccentric Shaft

$M_1$ rotates in a cushion block attached to the concrete structure; it forms one unit with lever H. $M_2$ is eccentric with respect to $M_1$ and forms one unit with it.

In the following analysis, therefore, it is assumed that the arms of the skin plate are stressed in tension by the water pressure.

The only good solution for the seal of a segment valve is obtained by using an uplift compensator which pulls the valve slightly back before the valve is raised (0.01 m, for example). In order to perfect the seal, the bearing blocks can be provided with a partially inserted rubber strip which, unstressed, protrudes less than the thickness of the clearance formed. In this way the rubber is not subjected to wear and will not cause any resistance to motion.

The uplift compensator may consist of an eccentric shaft in the center of rotation, which is twisted by means of a lever before the rising of the valve (Fig. 2). When the valve is sufficiently drawn back, the lever begins to rise with it. The weight of the valve must be sufficiently large in order to prevent rising of the valve before it is drawn along with the lever. Of course, such is definitely the case under normal conditions. The actuating mechanism should be able to stop at the instant when the valve is fully closed. If it is found that leakage still occurs--this can be ascertained--then the stop should be shifted. If the stop is installed too low, the eccentric shaft will be stressed in torsion, which is undesirable.

If it is necessary to close the valve while it is turning water, the lever must be equipped with a ballast weight or the actuating mechanism would have to exert pressure on it. In order to pull the valve sufficiently back, the lever must cover a large distance, which may be regarded as a drawback because of the time loss involved during opening.

A better uplift compensator is obtained by means of the design shown in Fig. 3. When the free end V of the lever is raised, the valve is pushed back. Thereby a slight displacement occurs at the hinges $M_1$ and $M_2$. The center of the skin plate passes through $M_1$; the valve rotates about this point during the motion of rising or lowering. Since $M_2$ is located above $M_1$, the valve under uplift will never exhibit the tendency to move upward of its own accord under the influence of the eccentric support at $M_2$. On the contrary, because of the eccentricity, the valve will be pressed against the culvert floor, which will improve the lower seal in case this seal results from the valve touching the floor of the culvert.

If the ratio of the lever arms is 1:15, the end V of the lever must be raised 0.15 m, except for some existing free play or resulting later from wear, in order to uplift the valve a distance of 0.01 m. In that system the

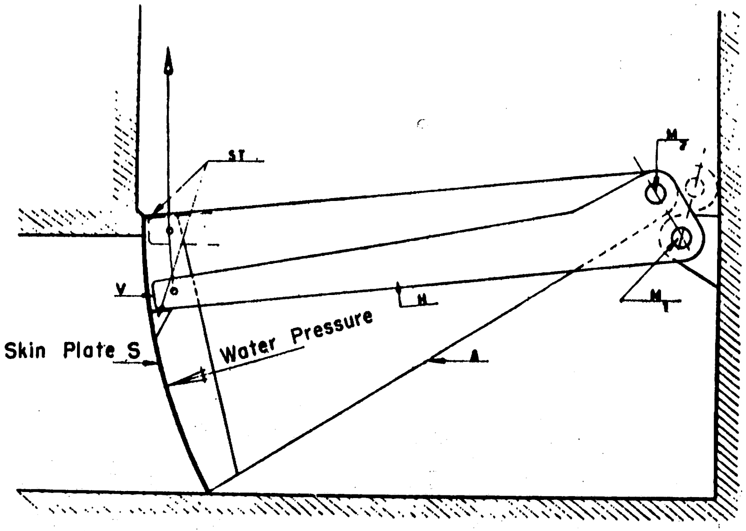

Fig.3 - Uplift Compensator for a Sector Valve, Equipped with a Lever

$M_1$. Center of skin plate; the shaft rotates in a cushion block attached to the concrete structure. $M_2$. Center of rotation of the valve about the lever H. St. Stop. A. Arm.

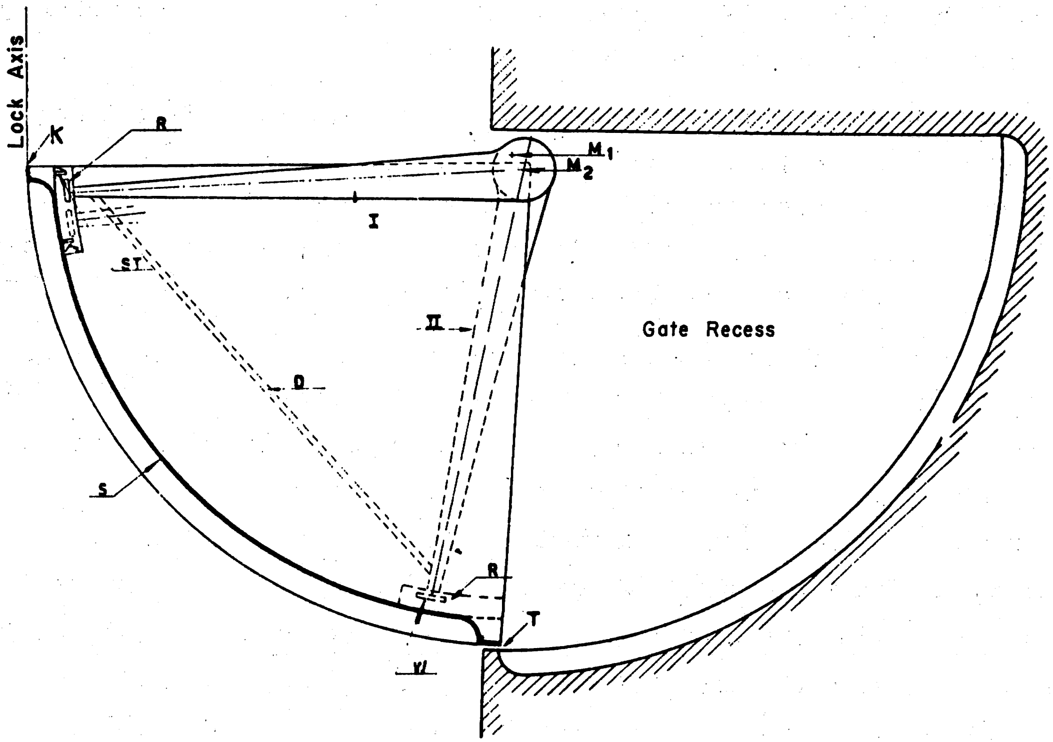

Fig. 4 - Diagram of a Sector Gate for a Lock

$M_1$. Center of skin plate S. $M_2$. Center of rotation of the gate about levers I and II which are connected by the rod D. W. Wheel. R. Roller path. The shafts rotate in cushion blocks attached to the concrete structure.

torsion on the lever is small and the wear at the pivots will be smaller than in the case of an eccentric shaft.

After the lever has traversed this distance of 0.15 m, the valve will begin to rise with the lever. Thereby the valve revolves about $M_1$. After the valve has reached the lowest position during closing, the point V must continue to descend at least 0.15 m more in order to make the closure of the valve watertight.

In this system both the water pressure and lever weight are always mutually effective in producing adequate contact between valve and bearing of the concrete structure. Therefore, weighting the lever is not necessary, nor is it necessary that the actuating mechanism exert pressure on the lever.

If the stop for V is installed too low, then the moment induced by the weight of the lever will be absorbed by bending stresses in the shafts of $M_1$ and $M_2$ and not, as in the case of application of an eccentric shaft, by torsion of a shaft.

## B. Sector Gates

Sector gates are currently in style in France. The advantages attributed to such gates mainly are: (1) a small actuating power, and (2) the feasibility of obtaining a good mode of filling the lock chamber by means of complete opening of the gates and the possibility of shortening the filling period by opening the gates before the head has completely subsided. [See the article "L'emploi des portes à secteur dans les ouvrages de navigation intérieure" (Use of Sector Gates in Inland Navigation Locks) by Fernand Dumas, published in La Technique des Travaux of July-August, 1949, and also communication 2, section I, French Report, of the 17th International Navigation Congress held in Lisbon in 1949.]

In the following discussions it will be assumed that the high water pressure occurs at the convex side of the skin plate. When the gates are opened there occurs a clearance near T (Fig. 4) through which the water streams into the lock chamber via the gate recess. By installing ingenious flaps (not shown in the drawing) rotating about a vertical axis at K, it is possible to prevent entrance of the water into the lock chamber in and along the lock axis as long as the head has not subsided sufficiently (see the article by Dumas).

The application of sector gates is readily considered even outside France, for example, at the huge tidal lock in the designed Sea-Level Canal near the existing Panama Canal (see De Ingenieur, No. 32 of 1949, for example).

The question whether use of sector gates in normal cases is actually preferable to that of the more current gate types is left unanswered here. Since sector gates seemingly tend to occupy an important position among the types of lock gates used, it will be determined herewith whether the current designs can be improved at a given point under given conditions. That point pertains to adequately watertight closing, which is often required. According to Dumas' article, rubber in combination with air pressure is commonly used in France for this purpose.

The least complicated and best watertight seal, however, can be obtained by making use of an uplift compensator. If the compensator consists of an eccentric shaft, the gate would have to be held fast in each case until it is uplifted, in order to prevent its premature motion with the lever which causes rotation of the shaft. In the case of sector gates gravity will not assist in protecting the gate from premature turning, as in the case of sector valves. A drawback of the current design would be the long path which the free end of the lever must traverse in order to uplift the gate over a short distance (time loss during opening).

If the uplift compensator is made in the manner shown in Fig. 3 (see Fig. 4), then the gate need not be held in place until it is completely uplifted if the water pressure acts in the direction of the center of rotation $M_2$. The reason is that the resultant of the water pressure on the skin plate passes through $M_1$, even during opening of the clearance, so that a couple about $M_2$ arises and retains the gates against the sill. If the water pressure acts in the opposite direction, then the gate would be readily held in place during uplift.

Thus, if the operation is to proceed in both directions, the recommendation to hold the gate firmly during the uplift is valid in the case of either ebb or flow and is less complicated in either case. If the lift is only in one direction, satisfactory location of $M_1$ with respect to $M_2$ will readily assure that during uplift the gate will not begin to turn prematurely during opening.

The lever I, which serves for uplifting at the upper pivot, is located near the upper edge of the gate, while the lever II, the function of which is the uplifting at the lower pivot, is located near the lower edge of the gate. The two levers are connected by the inclined rod D. When the lever I is actuated, the motion is repeated by the lever II along the foot. The vertical component of the force thus acting on D can be transmitted to the free ends of the levers, each being equipped with a roller which could roll between the skin plate stiffeners to be installed at the place, for which purpose the path involved is provided with rails or strips at R.

The uplift path (that is, the distance along which the gates are pulled back), usually not longer than 0.01 m, can be regulated by means of the stops St. The watertight seal can be prefected by inserting a rubber strip in the bearing blocks in such a way that it protrudes less than the width of the clearance formed by the uplifting.