UNITED STATES
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION

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DESIGN OF ROLLER GATES

by

C. P. VETTER

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Denver, Colorado
October 14, 1937

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MEMORANDUM TO CHIEF DESIGNING ENGINEER

SUBJECT: DESIGN OF ROLLER GATES

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By C. P. VETTER, ENGINEER

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Under Direction of

H. R. McBIRNEY, SENIOR ENGINEER, CANALS

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INTRODUCTION

It is the intention in this memorandum to give a short description of the so-called "roller gate" and an outline of the methods developed for the design of the 75-foot roller gates for the All-American canal headworks of the Imperial Dam, Boulder Canyon project, and the proposed 110-foot roller gate for the Roza Dam, Yakima project.

It appears that very little information is available in technical literature concerning the details of design of this type of gate. It has, therefore, been necessary to develop the methods given herein largely from basic principles of hydrodynamics and analytical mechanics.

In this work, valuable contributions have been made by the various members of the Diversion Dam group and other engineers of the Canal section.

A. DESCRIPTION OF GATE

The roller gate or rolling weir, although a European development,has been used extensively in this country over a period of more than 20 years.

One of the earliest American installations was for the diversion dam across the Colorado River near Grand Junction, Colorado, built by the Bureau of Reclamation. These gates have been in continuous operation since 1915 without difficulties of any kind. In later years, the roller gate has been used extensively by the War Department for dams on the Mississippi and Ohio Rivers and at the present time (1937) four gates are being installed by the Bureau of Reclamation for the All-American canal headworks on the lower Colorado River.

The roller gate consists of a horizontal hollow steel plate cylinder which extends into a recess in each end pier. An apron, extending along the length of the cylinder, effects a seal with the bottom of the waterway when the gate is at the lowest point of its travel. In case the gate is not designed for passing ice or trash over the top, it is generally provided with a flash weir, similar to the apron but extending upward when the gate is in the closed position. The purpose of the flash weir is to prevent overtopping of the gate by waves and to provide freeboard above the highest longitudinal element of the cylindrical shell.

Around each end of the cylinder is a rim consisting of a rack and a smooth track. The track rolls on a similar track placed in the recess in the pier and the teeth of the rack engage with the teeth of a similar rack also placed in the recess. A guide ring fastened to the gate and a counterguide supported on the pier in the recess opposite the track prevent the teeth of the racks from becoming disengaged in case trash should accumulate on the track or between the teeth. The gate is operated from one end only by means of a sprocket chain wound around the end of the cylinder and carried to a hoist placed on top of the pier.

One advantage of the roller gate is its extreme ruggedness and simplicity of construction and operation. Another advantage is the wide unobstructed opening available between piers for passage of ice or trees. Although installations with more than 150 feet clear opening are rare at the present time, it would doubtless be feasible to design gates of considerably greater length. It is interesting to note that for over 30 years hardly a single change has been made in the structural details or method of operation of the gate.

Watertightness along the sill, in the case of a non-submergible gate, is usually effected by means of an oak beam bolted to the apron and resting on an adjustable I-beam sill. The proportions of the gate should be such that the sill reaction is not less than 2,000 to 3,000 pounds per linear foot when the gate is closed. To obtain watertightness along the sides, the gate is provided with flexible shields attached to the upstream face of the gate and extending from the bottom seal on the apron to the top of the flash weir. To the upstream edge of each shield is bolted an oak or rubber sealing strip. The sealing strips travel on and bear against steel or machined cast-iron armature plates set in the piers. In some installations the armature plates are set at a slight angle so that the sealing strips bear against the plates only when the gate is near its closed position.

In the case of submergible gates, a well is provided in the crest of the dam. When the gate is submerged to allow ice and trash to pass, the apron extends into the well and a special rubber seal usually maintains contact between the apron and the upstream wall of the well. On submergible gates the lower parts of the tracks in the pier recesses are usually curved.

The rotation of the gate to effect raising is accomplished by means of a sprocket chain attached to a chain anchor at one end of the gate and actuated by a motor-driven sprocket-chain hoist. The hoist is usually located in a hoist house on top of one of the end piers. In the case of several gates in a group, two hoists are often placed together in one hoist house. Only alternate piers will thus have hoist houses. A locking link is usually provided which may be latched to the gate in its fully raised position, thus securely holding the gate and permitting the sprocket chain to be removed. Figures 1 to 5, inclusive, show typical details of roller gates.

B. GENERAL DESIGN

The loads on the gate are dead load and water pressure. The supporting reactions, when the gate is suspended, are: The chain pull (usually parallel with the track), the track reaction at the driven end (normal to the track), the track reaction at the nondriven end (normal to the track), the tooth reaction at the driven end (parallel with the track), and the tooth reaction at the nondriven end (parallel with the track). When the gate is resting on the sill the chain pull is zero and the sill reaction is usually assumed to have a direction along the tangent to the face plate of the apron or tangent to the cycloid describing the motion of the tip of the apron at the point where the cycloid intersects the sill. There are thus five reactions to be determined; but since there are also five equilibrium equations in a three-dimensional system (three projection equations and two moment equations) the system is statically determinate as far as reactions are concerned.

The dead weight of the gate may be estimated, with sufficient accuracy for preliminary designs, from figure 6.

The water load, when the gate is resting on the sill and there is no overpour, is the hydrostatic pressure on the apron, the upstream cylinder wall, and the flash weir. Since the faces of both the apron and the flash weir usually have the form of circular arcs, the determination of the hydrostatic pressure is particularly simple. In figure 7 is shown a cross section of the gate. Divide the water depth into a number of equal parts, for instance, one foot. Mark the point of application of the water pressure on each element of the wall; on the first element the water pressure acts at a depth of two-thirds of a foot, on all others the water pressure may be assumed to act at the center of the slice. The water pressure on each element has the direction of the radius to the point of application. Next, draw a force polygon to the water pressures 1, 2, 3, etc. In drawing the force polygon it should be remembered that the horizontal components of the water pressures equal the depth of the respective points of application below the water surface, multiplied by the height of the slice (one foot) and by 62.5 pounds. In the case of force 3, the magnitude of the horizontal component equals the depth below water surface multiplied by "a" and by 62.5 pounds. The resultant R, of the water pressure on the wall A-B is represented, in direction and magnitude, by a line from the beginning of 1 to the end of 3. In location it is represented by a line equal and parallel to R_1 and going through the center C_1.

The resultants R_2 and R_3 are found in similar manner and the total resultant is obtained in location, direction, and magnitude by geometrical addition of R_1, R_2, and R_3. To avoid the accumulation of errors due to the laying off of the individual forces 1, 2, 3, etc., draw a curve $x = \frac{1}{2}\ 62.5\ y^2$ where y is the depth of water (fig. 7,c). Extend the horizontal lines, which divide the water depth into equal parts, to intersect the curve EF and draw vertical lines through the points of intersection. It is directly evident that the individual forces of the force polygon must fall between two adjacent vertical lines.

When the gate is partly open the determination of the water pressure is more complicated. The net water pressure on the face of the gate is obviously the hydrostatic head less the velocity head of the water flowing adjacent to the gate.

There are two general approaches to the determination of the velocities upstream from the gate. One is by the mathematical theory of hydrodynamics, the other by the use of one of the "analogies", the electric analogy or the membrane analogy.

By the theory of hydrodynamics, the application of which is convenient only if the floor of the waterway is an approximately plane surface or has the shape of a circular cylinder upstream from the sill, the circular arc of the apron is assumed extending all the way to the water surface and the problem is to find the expression for flow between a circular arc and a straight line, or between two circular arcs, which intersect at the point B_1.(fig.8) The following investigation is confined to the case where one boundary is straight. In the coordinate system indicated on figure 8 the stream function for the flow may be expressed as follows:

$$F(Z) = a \log_e \frac{Z - \ell}{Z + \ell} = \varphi + i\psi \quad \ldots\ldots\ldots\ldots\ldots(1)$$

where a is a constant and ℓ is the distance from the origin of the coordinate system to the point of intersection between the circle and the straight line.

$Z = x + iy$, $i = \sqrt{-1}$ and φ and ψ are defined by the following relationships:

$$\frac{\partial \varphi}{\partial x} = \frac{\partial \psi}{\partial y} = u, \qquad \frac{\partial \varphi}{\partial y} = -\frac{\partial \psi}{\partial x} = v$$

u and v being the velocity components parallel with the x-axis and y-axis, respectively, or, in polar coordinates:

$$\frac{\partial \varphi}{\partial r} = \frac{1}{r}\frac{\partial \psi}{\partial \theta} = w_r, \qquad \frac{1}{r}\frac{\partial \varphi}{\partial \theta} = -\frac{\partial \psi}{\partial r} = w_\theta$$

w_r and w_θ being the velocity components in the radial and tangential direction, respectively.

φ and ψ are real functions of x and y and may be determined as follows:

$$Z - \ell = (x - \ell) + iy = r_1 (\cos \delta_1 + i \sin \delta_1) \ldots\ldots \quad (2)$$

It can now be shown that

$$\cos \delta_1 + i \sin \delta_1 = e^{i\delta_1} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (3)$$

By inserting (3) in (2):

$$Z - \ell = r_1 e^{i\delta_1} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (4)$$

By similar reasoning:

$$Z + \ell = (x + \ell) + iy = r_2 (\cos \delta_2 + i \sin \delta_2) =$$

$$r_2 e^{i\delta_2} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (5)$$

By inserting (4) and (5) in (1):

$$F(Z) = a \log_e \frac{Z - \ell}{Z + \ell} = a \left[\log_e \frac{r_1}{r_2} + i(\delta_1 - \delta_2) \right] =$$

$$\varphi + i\psi \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (6)$$

By separating real and imaginary parts:

$$\varphi = a \log_e \frac{r_1}{r_2} \quad \text{and} \quad \psi = a(\delta_1 - \delta_2) = a\gamma \quad \ldots\ldots\ldots (7)$$

From the fundamentals of hydrodynamics it is known that

$$\psi = C = \text{arbitrary constant} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (8)$$

represents the equation for a stream line.

The equation γ = constant, however, is the equation for a circle with its center on the y-axis. $\gamma = \alpha$ represents one boundary of the flow, namely, the face of the apron, and $\gamma = 0$ the other boundary, namely, the x-axis beyond the points B_1 and B_2. The stream function therefore satisfies the boundary conditions and hence correctly represents the flow between the boundaries.

It is further known that if the arbitrary constant C is assigned successive values: C_o, C_1, C_2, C_3, etc., where:

$$C_1 - C_o = C_2 - C_1 = C_3 - C_2 \;\ldots\; \text{etc.},$$

the amount of water flowing between two successive stream lines (corresponding to successive values of C) will be equal. If it is desired, for instance, to divide the flow in six parts, each part carrying the same amount of water, the difference between the values of C corresponding to each boundary is divided in six equal parts and circles drawn corresponding to each value of C. The difference between the values of C in the case considered here is

$$a\alpha - 0 = a\alpha$$

so circles should be drawn corresponding to

$$a\gamma = a\frac{\alpha}{6},\ a\frac{2\alpha}{6},\ a\frac{3\alpha}{6},\ a\frac{4\alpha}{6},\ \text{and}\ a\frac{5\alpha}{6}$$

$$\text{or}\ \gamma = \frac{\alpha}{6},\ \frac{2\alpha}{6},\ \frac{3\alpha}{6},\ \frac{4\alpha}{6},\ \text{and}\ \frac{5\alpha}{6}$$

As mentioned, the centers of these circles lie on the x-axis and all circles go through the points B_1 and B_2. The radii of the respective circles are determined by:

$$\frac{\ell}{r} = \sin\gamma$$

$$r = \frac{\ell}{\sin\frac{\alpha}{6}},\ \frac{\ell}{\sin\frac{2\alpha}{6}},\ \ldots\ldots\ldots,\ \text{etc.}\ \ldots\ldots\ldots\ldots (9)$$

If the total discharge of the gate per linear foot is known or can be estimated, the amount flowing in the stream tube adjacent to the gate is one-sixth of the total, and the velocity along the surface of the gate may be computed by dividing one-sixth of the total flow by the distances from the face of the gate to the nearest stream line at the various points.

There is, however, a more direct method of finding the velocity along the face of the gate.

From the fundamentals of hydrodynamics it is known that

$$\frac{d\ F\ (Z)}{d\ (Z)} = u - iv \ \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (10)$$

The quantity $u - iv$ is called the "conjugate" complex velocity as compared with

$$w = u + iv$$

which is the "real" complex velocity. The conjugate velocity represents the image obtained by reflection from the real axis (the x-axis), of the real velocity. Since the absolute length of a vector is the same as the absolute length of its reflected image, the actual velocity may be found as the actual value of the reflected image.

From (1)

$$\frac{d\,F(Z)}{d\,Z} = \frac{d\left(a \log_e \frac{Z-\ell}{Z+\ell}\right)}{d\,Z} = a\,\frac{d\left[\log_e (Z-\ell) - \log_e (Z+\ell)\right]}{d\,Z}$$

$$\frac{d\,F(Z)}{d\,Z} = \frac{a}{Z-\ell} - \frac{a}{Z+\ell} \qquad \text{........................(11)}$$

By insertion from (4) and (5)

$$\frac{d\,F(Z)}{d\,Z} = \frac{a}{r_1\,e^{i\delta_1}} - \frac{a}{r_2\,e^{i\delta_2}} = \frac{a}{r_1}e^{-i\delta_1} - \frac{a}{r_2}\,e^{-i\delta_2} \qquad ..(12)$$

Bearing in mind that the complex quantity $x + iy$ may also be written $re^{i\delta}$ where r is the radius vector to the point and δ is the angle of the radius vector with the x-axis, see also (2), (3), and (4), the expression (12) is seen to represent the difference between two complex quantities.

$\frac{a}{r_1}\,e^{-i\delta_1}$ and $\frac{a}{r_2}\,e^{-i\delta_2}$, OE and OD in figure 8.

The actual value of this differernce, which is the actual value of the velocity, W, may be found by applying ordinary trigonometric formulas to triangle ODE

$$W_1^{\,2} = \overline{DE}^2 = \overline{OD}^2 + \overline{OE}^2 - 2\,\overline{OD}\;\overline{OE}\;\cos\gamma$$

$$W_1^{\,2} = \left(\frac{a}{r_2}\right)^2 + \left(\frac{a}{r_1}\right)^2 - \frac{2a^2}{r_1 r_2}\cos\gamma = a^2\,\frac{r_1^{\,2} + r_2^{\,2} - 2\,r_1 r_2 \cos\gamma}{r_1^{\,2} r_2^{\,2}}$$

$$W_1 = W = \frac{2\,a\,\ell}{r_1 r_2} \qquad \text{................................. (13)}$$

If the discharge under the gate, q per linear foot, is known from hydraulic model tests or can be estimated with sufficient accuracy, the value of W can be computed directly. It can be shown that the constant a is determined by

$a = -\frac{q}{\alpha}$ where α is measured in radians

hence $W = -\frac{2\,q\,\ell}{\alpha\, r_1 r_2}$ ....(14)

and the velocity head $h_W = \frac{W^2}{2g} = \frac{2\,q^2\ell^2}{\alpha^2 r_1^2 r_2^2 g}$ ....(15)

If the discharge q is not known, the velocity may be determined as follows: At the lower end of the apron all available head has been changed into velocity head since there is a free surface immediately beyond the edge, hence

$$\frac{(W')^2}{2g} = h' = \frac{4a^2\ell^2}{(r_1'r_2')^2\,2g}$$

where W' is the velocity at the edge of the apron, h' the depth of the edge below upstream water surface and r_1' and r_2' the distances from the points B_1 and B_2, respectively, to the edge. At an arbitrary point of the apron the velocity head:

$$h_W = \frac{W^2}{2g} = \frac{4a^2\ell^2}{(r_1r_2)^2\,2g}$$

Eliminating $4a^2\ell^2$

$$h_W = \frac{(r_1'r_2')^2}{(r_1r_2)^2}h' \qquad \text{(16)}$$

By subtracting h_W as determined from (15) or (16) from the static head at the arbitrary point, the net hydrodynamic pressure is found.

It should be noted that the value of h_W obtained from (16) is usually too great. The reason is that the water flowing adjacent to the apron does not continue along the same circle after it leaves the edge of the apron, as has been assumed here. Comparisons with hydraulic model tests have indicated that r_1' and r_2' should not be measured to the edge of the apron (point A in figure 8) but to a point A' located on the same circle a distance below A:

$$AA' = 0.10\ (AB_1)\ \text{to}\ 0.25\ (AB_1)$$

It is apparent that the above method for determining the velocities along the apron does not hold near the water surface, neither does it apply to gate openings which are large compared with the total depth of water. In these cases the actual stream lines do not even approximately approach the stream lines determined by (8).

If a better picture of the stream lines is desired, it may be obtained by means of the electric analogy apparatus. A sketch of this apparatus in its simplest form is shown in figure 9. The water surface upstream from the gate, the face of the gate, and the water surface of the jet emerging below the gate form one extreme stream line and the bottom of the waterway forms the other extreme stream line. Intermediate stream lines may be determined by forming the extreme stream lines of copper and sending an electric current from one of these electrodes through a suitable solution to the other and determining the points between the electrodes where the potential has a predetermined constant value. Let the potential of one electrode be P_1 and the other P_2, and let the two electrodes be connected by a resistance wire of length, ℓ. If it is intended to obtain five intermediate stream lines, connect a steel or brass needle through a galvanometer to a point of the resistance wire having a potential

$$P = P_1 + \frac{P_1 - P_2}{6}$$

and determine, by moving the needle from point to point in the solution, those points where no current flows through the galvanometer. A line through these points represents a stream line. By moving the needle connection successively to points on the resistance wire having potentials:

$$P_1 + \frac{2}{6}(P_1 - P_2),\quad P_1 + \frac{3}{6}(P_1 - P_2)\ \dots\ \text{etc.}$$

other stream lines are obtained.

Since one-sixth of the total amount of water flow between each two consecutive stream lines, the velocity at any point of the fluid may be determined if the total flow is known. In general, if the discharge per linear foot is q , the velocity is determined by

$$W = \frac{q}{nb} \qquad \text{.. (17)}$$

where n is the number of stream tubes. As stated above, all available head is transformed into velocity head at the lower edge of the apron. Hence, if the distance between this point and the nearest stream line is a, the velocity at some other point of the flow where the distance between adjacent stream lines is b is expressed by:

$$W = \frac{a}{b} \sqrt{2\ gh'} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(17a)}$$

where h', as before, is the head of water to the edge of the apron. In this manner the actual velocities along the gate may be found with close approximation. Instead of the electric analogy apparatus, the so-called membrane analogy apparatus may be used for experimental determination of the stream lines. For description and method of operation of this apparatus, see J.H.A. Brahtz: "Pressures Due to Percolating Water and their Influence upon Stresses in Hydraulic Structures", Communication no. 1, Second Congress on Large Dams. For comparative stream lines see figure 10.

If the roller gate is used as crest gate on an overflow weir or if the bottom of the waterway for other reasons has an irregular shape, a knowledge of the actual stream lines is essential for even approximate determination of the pressures, in that formulas (15) and (16) obviously are not applicable. If an electrical analogy apparatus or a membrane analogy apparatus is not available, the stream lines may be determined with sufficient accuracy by free-hand sketching. In the case of irregular boundaries the stream function F (Z) is not known and, as a rule, cannot be determined. Nevertheless the following relationship holds:

$$F\ (Z) = F\ (x + iy) = \varphi + i\psi$$

where φ and ψ are real functions of x and y. The family of curves represented by

$$\psi = C = \text{arbitrary constant}$$

has been shown to represent stream lines of the flow and it can further be shown that,

$$\varphi = C' = \text{arbitrary constant}$$

represents another family of curves which all intersect the stream lines at right angles. These curces are called the equipotential lines. If the arbitrary constants C and C' are so chosen that the constant difference between two successive values of the C constants equal the difference between successive values of the C' constants, the two families of curves will form a net of curve linear squares. Furthermore, if the curve linear diagonals are drawn, these will also form a net of curve linear squares. By means of this information, and a little practice, the two nets of squares can readily be sketched as shown on figure 11. When the stream lines have been drawn in this manner the further procedure is as given by formulas (17) or (17a).

If the gate is submergible so that water may pour over the crest possibly to a depth of several feet, knowledge of the pressure due to the overpouring water is desirable. Absolutely reliable values for these pressures are best obtained from a hydraulic model or from one of the analogy models mentioned above. However, since the magnitude of the pressure is small as compared with the other pressures on the gate, approximate values, close enough for both preliminary designs and most final designs, may be obtained as follows:

Assume a stream function:

$$F(Z) = F(x + iy) = iC \log_e Z = \varphi + i\psi$$

where C is real.

$$iC \log_e Z = iC \log_e (re^{i\theta}) = iC \log_e r - C\theta$$

Hence:

$$\varphi = -C\theta \quad \text{and} \quad \psi = C \log_e r$$

The stream lines:

$$\psi = C \log_e r = \text{const.}$$

are obviously circles, so that one boundary of the flow, namely, the surface of the drum, is correct. The other boundary, the free surface, is not correct, but the effect thereof on the pressures along the correct boundary is not very great.

Since the stream lines are circles, the velocity may be obtained by partial differentiation of φ with respect to θ:

$$W = W_\theta = \frac{\partial \varphi}{r\,\partial \theta} = -\frac{C}{r}$$

To determine the constant C, integrate between the limits r_1 and r_2 where r_1 is the radius of the drum and r_2 is the radius to some arbitrary point of the free surface.

$$q = \int_{r_1}^{r_2} W dr = \int_{r_1}^{r_2} - \frac{C}{r} dr$$

$$q = -C \log_e \frac{r_2}{r_1}$$

$$C = - \frac{q}{\log_e \frac{r_2}{r_1}}$$

and $$W = \frac{q}{r \log_e \frac{r_2}{r_1}}$$

The velocity at the surface of the gate is, therefore:

$$W_{r_1} = \frac{q}{r_1 \log_e \frac{r_2}{r_1}} \qquad \text{.....................................(18)}$$

and at the free surface

$$W_{r_2} = \frac{q}{r_2 \log_e \frac{r_2}{r_1}} \qquad \text{.....................................(19)}$$

It remains to determine r_2. At the free surface all available energy has been transformed into velocity, hence if the total available head at some point on the water surface is h:

$$\frac{W_{r_2}^{\ 2}}{2g} = \frac{q^2}{2g\ r_2^{\ 2} \left(\log_e \frac{r_2}{r_1}\right)^2} = h \qquad \text{.........................(20)}$$

From this equation r_2 may be determined if q is known. The quickest method is to draw circles with different radii r_2 and determine the point of the periphery which has the value of h determined from above equation (see fig. 12). When the surface curve has been drawn, the velocities W_{r_1} and the pressures on the gate may be determined in the usual manner.

In order to get consistent results, q, the discharge per linear foot, should be determined by a method analogous to the one used for determining the velocities. For this purpose the highest point of the gate (having horizontal tangent) is assumed to act as control. This assumption is not correct but the approximation is close enough for the purpose. A control section may be defined as a section which carries the maximum possible amount of water for a given amount of energy. Mathematically the depth at the control is obtained by differentiating the discharge with respect to the depth and equalling the differential to zero. This leads to the following equation for the depth:

$$\log_e \left(\frac{r_1 + d - h'}{r_1}\right) = \frac{2h'}{r_1 + d - 3h'}$$

From this equation h' may be determined for any values of r_1 and d. It may be readily verified that for $r_1 = \infty$, h' becomes 1/3d. When h' has been determined q is found from equation (20) in that $r_2 = r_1 + d - h'$:

$$q = (r_1 + d - h')\log_e \left(\frac{r_1 + d - h'}{r_1}\right) \sqrt{2gh'} \quad \ldots\ldots\ldots\ldots (21)$$

$$q = Cd^{\frac{3}{2}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (22)$$

where

$$C = (r_1 + d - h')\sqrt{\frac{2gh'}{d^3}} \log_e \left(\frac{r_1 + d - h'}{r_1}\right)$$

the values of C may be taken from the diagram shown on figure 13. It should be noted that the value for the discharge obtained in this manner is meant to be used primarily in connection with formulas (18), (19), and (20). If it is desired to obtain the actual discharge over the gate with close approximation a hydraulic model test will give better values. However, equation (21) has been found to give values very close to those obtained experimentally.

When the velocities and water pressures on the gate have been determined for various positions of the gate, the resultant water pressure is found by a method similar to that used for hydrostatic pressure and this resultant is combined with the resultant of dead weight into the resultant of all loads on the gate. In the case of a submergible gate the weight of a tree or of an ice floe resting on top of the gate should be added to the outside loads. It remains to determine the five gate reactions. In figure 14 is shown a schematic picture of a gate. C is the chain pull (assumed not parallel with the track) with components C_n (normal to the track) and C_t (parallel with track), N_d is the track reaction (normal to the track) at the driven end, N_n the track reaction at the nondriven end, T_d is the tooth reaction (parallel with the track) at the driven end, T_n the tooth reaction at the nondriven end. R is the total load on the gate (water pressure plus dead load) with components R_n (normal to the track) and R_t (parallel with the track). S, the sill reaction, is in this case zero. Considering figure 14, by taking moments about A-A:

$$N_d + C_n = N_n$$

and by projection on B-B:

$$N_d + C_n + N_n = R_n$$

hence:

$$N_n = N_d + C_n = \frac{R_n}{2} \quad \text{.................................... (23)}$$

By taking moments about B-B:

$$T_d - C_t = T_n$$

and by projection on A-A:

$$T_d - C_t + T_n = R_t$$

hence:

$$T_n = T_d - C_t = \frac{R_t}{2} \quad \text{.................................... (24)}$$

Finally, by taking moments around C-C, it is seen that the moment of R with respect to this axis must equal the moment of C, hence the resultant of these two forces must go through C-C. The graphical determination of the reactions is shown on figure 15, which is self-explanatory.

If the gate is resting on the sill (C, the chain pull, is zero), by taking moments about A-A:

$$N_d = N_n$$

and by projection on B-B:

$$N_d + N_n + S_n = R_n$$

hence:

$$N_n = N_d = \frac{R_n - S_n}{2} \qquad \text{..................................(25)}$$

By taking moments about B-B:

$$T_n = T_d$$

and by projection on A-A:

$$T_n + T_d - S_t = R_t$$

Hence:

$$T_n = T_d = \frac{R_t + S_t}{2} \qquad \text{..................................(26)}$$

Furthermore, the resultant of R and S must pass through C-C. The graphical determination of the reactions in the case of the gate resting on the sill is shown in figure 16.

The reactions should be determined for several positions of the gate and for several upstream water levels. It will often be found that the maximum values of chain pull and track reactions do not coincide with the maximum water pressure on the gate. A graph showing the variations of the reactions for the 75-foot roller gates for the All-American canal headworks is shown in figure 17.

C. DETAIL DESIGN OF GATE

The Circular Cylinder

The stresses in the cylinder shell are: 1. The beam stresses whereby the water load and dead load are transmitted to the supporting piers; and 2. The local stresses in the plate due to transfer of load from the plate to the interior framework of the gate. The beam stresses consist of normal and shearing stresses due to bending and shearing stresses due to torsion. If the total resultant of water load plus dead load is p per linear foot and ℓ is the span between piers, the maximum bending moment, assuming that the water load covers the whole distance between supports, is:

$$M = \frac{1}{8} p\ell^2$$

The section modulus, since the shell is very thin compared with the radius of the cylinder, is:

$$S = \pi r^2 t$$

where r is the radius of the shell and t the thickness of the plate at the center of the span.

The normal stresses in the center section due to bending, tension being positive, are thus:

$$\sigma_b = + \frac{\frac{1}{8} p\ell^2}{\pi r^2 t} \cos u \qquad (27)$$

The circumferential normal stresses (hoop stresses) due to bending are small and are determined by:

$$\sigma_h = + \frac{P}{2\pi t} \cos u$$

The shearing stresses due to bending are also small. They are determined by the following formula:

$$\tau_b = \frac{-R}{\pi r \ell t} x \sin u \qquad (28)$$

where x is the distance from the center of the gate measured along the axis to the cross section in which the shearing stresses are desired and u is the angle from a line parallel with R through the center of the cylinder to the radius to a particular point of the shell positive in the clockwise direction. The shear is positive in the clockwise direction if the section is viewed in the positive direction of the x-axis. Maximum shear occurs where u = 90° or 270°. At the points of maximum normal stress

$$\tau_b = 0 \; (u = 0 \text{ or } 180^\circ)$$

The torsional moment of the shearing stresses varies rectilinearly from end to end. At the nondriven end it is:

$$M'_n = T_n r \qquad (29)$$

and at the driven end:

$$M'_d = -(C + T_d)r \text{ ....} (30)$$

C is always positive and if T is considered positive if it acts downward on the gate, M' is positive in the clockwise direction if the section is viewed in the positive direction of the x-axis. The positive direction of the x-axis is toward the driven end. The shear stress is:

$$\tau_t = \frac{M'}{2\pi r^2 t} \text{ ....} (31)$$

The total shear stress at any point is obtained by adding (28) and (31).

The above formulas are based on the assumption that the hollow cylindrical shell acts as an ordinary beam from pier to pier. It is known that it will act in this manner if the load on the shell consists of parallel forces uniformly distributed per square foot of surface.* Since the load is not so distributed

* See paper by Herman Schorer, Trans. American Society of Civil Engineers, vol. 98, 1933, p. 101.

the cylindrical drum is provided with stiffening diaphragms spaced 9 to 12 feet, and the load is transferred from the plate to the diaphragms through horizontal beams 3 to 4 feet on centers along the periphery of the diaphragms. It is customary to assume that the total water load on the plate is transferred to the longitudinal beams and from the beams again to the diaphragms. For the purpose of designing the plates for direct water load the plates are usually assumed to be flat and are designed by the ordinary formulas for bending. It should be noted that in the case of a longitudinal seam over one of the beams the plate should be assumed to be restrained at the support only in case two rows of rivets are used. The rivet holes in one row should be deducted to obtain the net section at the support. If the connection between beams and diaphragms is such that the plate panels are supported along all four sides the formulas given by Westergaard and Slater*

* Proceedings of the American Concrete Institute, vol. 17, 1921, available in reprint and circular series of the National Research Council No. 32.

should be used. Bach's formulas for the design of slabs supported along four sides, although still given in many handbooks, should be used with caution. Support along four sides of a plate on the main cylinder will cause normal stresses in sections perpendicular to the axis of the cylinder, and those stresses should be added to the normal stresses given by (27). Therefore, this method of support is usually not employed for the main cylinder. However, it is generally used for the plates on the apron and the flash weir which do not carry beam stresses. Assuming that the plates of the main cylinder are supported on the beams only, the normal stresses on a section through the axis will be: σ_c, due to local bending of the plate and hoop stresses σ_h, due to bending of the cylinder as a whole. The normal stresses on a section perpendicular to the axis will be σ_b due to bending of the cylinder as a whole. In addition thereto, there will be shearing stresses due to both bending and torsion. Elastic members having stresses of this nature are usually designed by computing St. Venant's so-called "ideal" stress:

$$\sigma_i = \frac{m-1}{2m} (\sigma'_c + \sigma_b) \pm \frac{m+1}{2m} \sqrt{(\sigma'_c - \sigma_b)^2 + 4(\tau_t + \tau_b)^2} \quad ..(32)$$

where $\sigma'_c = \sigma_c + \sigma_h$

The sign of the square root should be so chosen that both quantities making up σ_i have the same sign, $m = \frac{1}{\nu}$ = the inversed value of Poisson's ratio. Usually m is taken at 4.0,

$$\frac{m-1}{2m} = \frac{3}{8} \text{ and } \frac{m+1}{2m} = \frac{5}{8}$$

Stresses computed by (32) should be kept within reasonable limits, say less than 14,000 pounds per square inch. Joints in the plates should be designed for the normal stress and shear which have to be transmitted. Normal load and shear per rivet should be added geometrically to give the resultant load on the rivet. The design of the longitudinal beams causes no difficulties.

In designing the diaphragms it may be assumed that all exterior loads, that is, all water loads on cylinder, apron, and flash weir, and all dead loads, are transferred to the diaphragm through the longitudinal beams and through the framing for apron and flash weir. The diaphragms are in turn supported by the cylindrical shell, through the longitudinal beams, the reactions being parallel and uniformly distributed per linear foot of periphery. Figures 1 and 3 show typical framing for the roller gates for the All-American canal.

The end diaphragm, also called the load disk, transfers all load, that is, water load, dead load, and chain pull, to the pier. Water load and dead load are transferred to the disk by means of shear stresses which may be computed from (28) by inserting $x = \frac{\ell}{2}$. The torsional stresses determined by (31) are also transferred to the disk by means of shearing stresses. The chain is usually attached to the drum outside the load disk in order not to interfere with the track segment and the guide ring. Special framing is therefore required to transfer the load from the chain anchor and the direct compression of the chain on the cylinder plate from their respective points of application to the load disk. Due to the heavy shear stresses between cylinder plate and load disk, the plate should be riveted directly to the load disk, special connections being provided on one side of the disk for the longitudinal beams. The reaction from the pier is transferred to the disk through the track and rack segment. It is obvious that any rational design of the load disk under this complicated loading is very difficult. It may be feasible to make an analysis by means of the photoelastic apparatus and this should doubtless be done in the case of very large gates. Usually the load disk is made of a solid plate, possibly with a small manhole in the center, but heavily braced with stiffener angles and also braced back to the main framing of the gate. Figure 4 shows the load disk for the roller gates for the All-American canal.

The track segments on the gate and the tracks on the piers are designed for the pressure N_d & N_n for the different positions of the gate. Since the pressures are usually greater at the lower positions of the gate, the lower parts of the tracks are often heavier than the upper parts. The best practice is to design the track in accordance with the results of tests by the University of Illinois* which were made mainly for the purpose

* University of Illinois Experiment Station, Bulletin No. 162. See also Bulletins Nos. 191 and 212.

of developing safe designing practice for tracks of bascule bridges. In case the gates are designed for a rarely occurring maximum water level it will be safe to base the width of the track on the load which will just produce permanent deformation. If the maximum load occurs with greater frequency a suitable factor of safety should be employed. The teeth of the track are designed by the usual methods.

Although the outline given here describes the successive steps which must be followed in the design of a roller gate, the prospective designer will do well in studying first the details of existing gates, especially such gates which are known to have given satisfactory service for a number of years.

\- - -

EXAMPLE I

Determine the water pressure on a partly closed roller gate.

Figure 10 shows a schematic cross section of a roller gate of the approximate dimensions of the All-American canal headgates.

Water surface: El. 191.0; Sill: El. 171.0; two-foot gate opening.

The static pressure head is indicated on the drawing.

Making use of formula (14), the discharge q, per linear foot, is estimated at 58.7 second-feet; the angle, α, is 39° or 0.68 radian; ℓ = 7.6 feet, hence:

$$W = \frac{2\,q\,\ell}{\alpha\, r_1 r_2} = \frac{2 \times 58.7 \times 7.6}{0.68\, r_1 r_2} = \frac{1312}{r_1 r_2}$$

The results for various points are shown in table I and the net pressures are plotted in figure 10.

Making use of formula (16) and taking AA' = 0.2 AB,

$$r'_1 = 2.22;\ r'_2 = 16.85;\quad h' = 18.4 \text{ ft.}$$

$$W = \frac{r'_1 r'_2}{r_1 r_2}\sqrt{2gh'} = \frac{1288}{r_1 r_2}$$

where r_1 and r_2 are the distances from B_1 and B_2, respectively.

The results for various points are shown in table I and the net pressures are plotted in figure 10.

Making use of formula (17a)

h' = 18.0 ft.

$W' = \sqrt{2gh'}$ = 34 ft./sec.

The distance between stream lines at A is a = 0.32 foot, hence, the velocity at any point is:

$$W = \frac{0.32 \times 34}{b} = \frac{10.88}{b}$$

where b is the distance between stream lines at the point where the velocity W is desired.

Using formula (17), the discharge per linear foot q, is estimated at 58.7 second-feet, hence:

$$W = \frac{q}{nb} = \frac{58.7}{6b} = \frac{9.80}{b}$$

The results for various points are shown in table I and the net pressures are plotted in figure 10.

TABLE I

Dist. to W.S.	Formula (14) = 58.7 c.f.s. W	h_W	Net Pressure	Formula (16) AA' = 0.2 AB_1 W	h_W	Net Pressure	Stream Lines by Electric Analogy Method: Width of Stream Tube	Formula (17) q = 58.7 c.f.s. W	h_W	Net Pressure	Formula (17a) W	h_W	Net Pressure
8.50	4.76	0.35	8.15	4.68	0.34	8.16	3.60	2.72	0.11	8.39	3.02	0.14	8.36
9.40	5.18	0.42	8.98	5.09	0.40	9.00	3.00	3.27	0.17	9.23	3.63	0.20	9.20
10.40	5.72	0.51	9.89	5.62	0.49	9.91	2.50	3.92	0.24	10.16	4.35	0.30	10.10
11.40	6.37	0.63	10.77	6.25	0.61	10.79	2.00	4.90	0.37	11.03	5.44	0.46	10.94
12.40	7.17	0.78	11.62	7.04	0.77	11.63	1.70	5.76	0.51	11.89	6.40	0.64	11.76
13.35	8.20	1.05	12.30	8.05	1.01	12.34	1.40	7.00	0.76	12.59	7.77	0.94	12.41
14.30	9.67	1.45	12.85	9.49	1.40	12.90	1.15	8.52	1.13	13.17	9.46	1.39	12.91
15.10	11.50	2.05	13.05	11.30	1.98	13.12	1.00	9.80	1.49	13.61	10.38	1.84	13.26
16.10	14.30	3.18	12.92	14.02	3.05	13.05	0.78	12.56	2.45	13.65	13.95	3.02	13.08
16.95	18.40	5.27	11.68	18.06	5.07	11.88	0.60	16.34	4.15	12.80	18.14	5.11	11.84
17.60	22.61	7.94	9.66	22.20	7.66	9.94	0.45	21.30	7.39	10.21	24.20	9.10	8.50
18.00	26.60	11.00	7.00	26.10	10.60	7.40	0.32	30.62	14.55	3.45	14.00	18.00	0.00

Formula (14) = $W = \dfrac{2\,q\,\ell}{\alpha\, r_1 r_2}$ Formula (17) = $W = \dfrac{q}{nb}$

Formula (16) = $W = \dfrac{r'_1 r'_2}{r_1 r_2}\sqrt{2gh'}$ Formula (17a) = $W = \dfrac{a}{b}\sqrt{2gh'}$

EXAMPLE II

Determine stresses in the skin plate of the main cylinder of 75-foot roller gate for the point where $u = 180^\circ$.

Actual span of gate: 73.5 feet = 942 inches.

Resultant of all loads p = 11,980 pounds per linear foot.

C = 82,000 pounds.

T_n = 233,000 pounds.

T_d = 315,000 pounds.

$N_d = N_n$ = 412,000 pounds.

Radius of gate drum: 7.0 feet = 84 inches.

9/16-inch skin plate.

13/16-inch rivet holes.

2-7/8-inch rivet spacing in circumferential seam.

Effective plate thickness for bending of the drum as a whole:

$$t = 0.5625 - \frac{12 \times 0.8125 \times 0.5625}{2.875 \times 12} = 0.5625 - 0.1590$$

$$= 0.4035 \text{ in.}$$

hence, by formula (27):

$$_b = - \frac{\frac{1}{8}\ 11,980 \times \frac{1}{12} \times \overline{942}^2}{\pi\ \overline{84}^2 \times 0.4035} = -\ 12,380 \text{ pounds per square inch.}$$

By formula (29)

$$M'_n = 233,000 \times 7.0 = 1,630,000 \text{ foot-pounds.}$$

And by formula (30)

$$M'_d = -\ (82,000 + 315,000)\ 7.0 = -\ 2,780,000 \text{ foot-pounds.}$$

Hence in the center of the gate:

$$M' = \frac{1{,}630{,}000 - 2{,}780{,}000}{2} = -575{,}000 \text{ foot-pounds.}$$

and by formula (31)

$$\tau_t = -\frac{575{,}000 \times 12}{2\ \ 84^2 \times 0.5625} = -276 \text{ pounds per square inch.}$$

It should be noted that in computing torsional shear the rivet holes need not be deducted. In computing the bending stresses, σ_c, due to direct water load, the average head of water is assumed to be six feet and the spacing between longitudinal channels 2.34 feet. The rivet holes are 13/16 inch spaced 5-3/4 inches. The plate is continuous over the channels.

Efficiency of joint:

$$e = 1 - \frac{0.8125}{5.75} = 1 - 0.141 = 0.859$$

$$\sigma_c = \pm \frac{\frac{1}{12} \times 6 \times 62.5 \times \overline{2.84}^2 \times 12}{\frac{1}{6} \times 12.0 \times 0.859 \times \overline{0.5625}^2} = \pm 5{,}560 \text{ pounds per square inch.}$$

$$\sigma_h = -\frac{11{,}930}{12 \times 2\pi \times 0.75 \times 0.859} = -247 \text{ lbs. per sq. inch}$$

Hence $\sigma_c' = \sigma_c + \sigma_h = -5{,}807$ or $+5{,}313$ lbs. per sq. inch

Finally, from formula (32), choosing the most unfavorable combination:

$$\sigma_i = \frac{3}{8}(+5{,}313 - 12{,}380) \pm \frac{5}{8}\sqrt{(+5{,}313 + 12{,}380)^2 + (2 \times 276)^2}$$

$$\sigma_i = -2{,}650 - 11{,}060 = -13{,}710 \text{ pounds per square inch.}$$

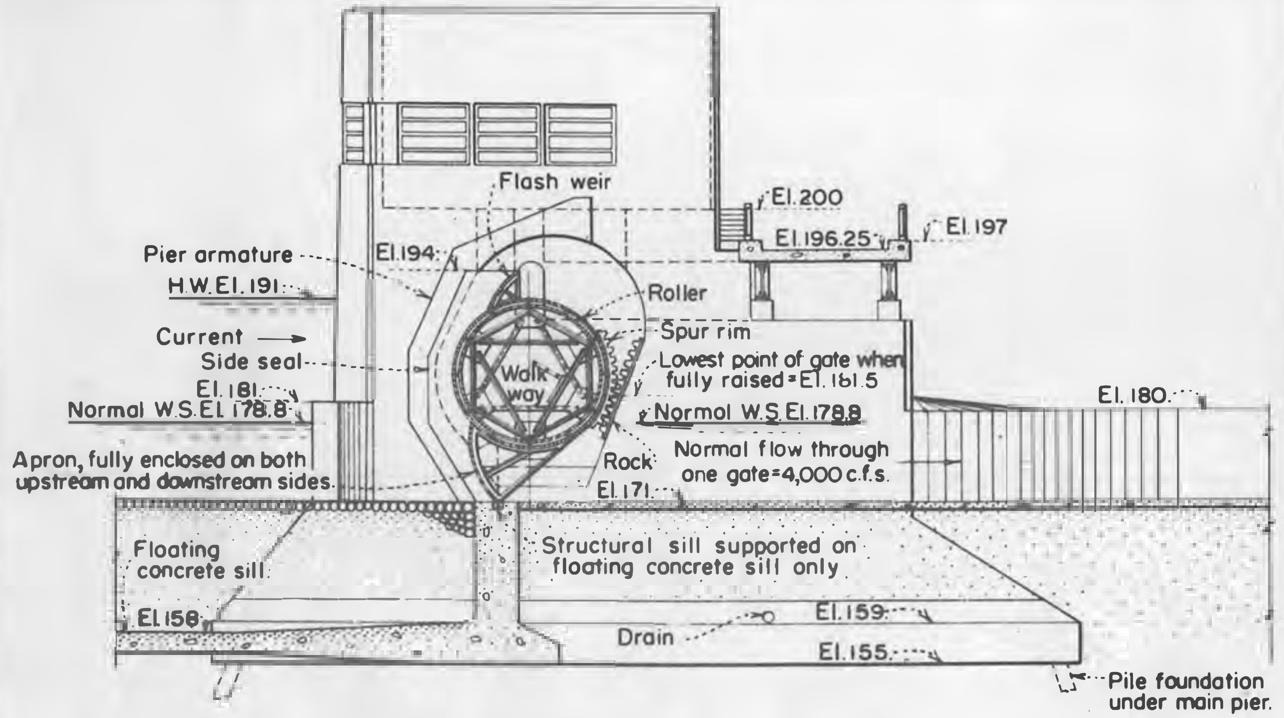


Fig. 1

CROSS SECTION OF THE ALL-AMERICAN CANAL HEADWORKS

212-D-3366

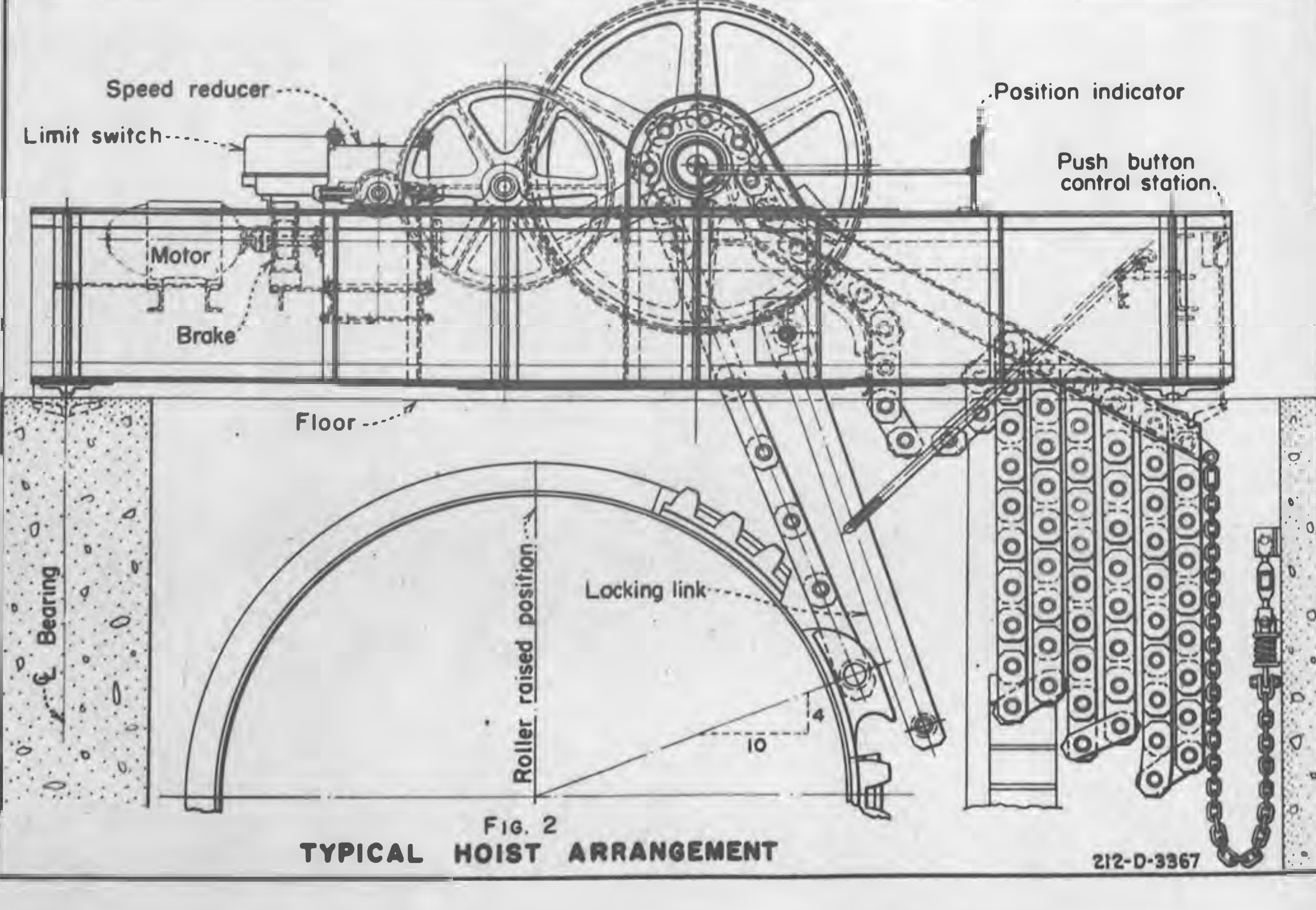


Fig. 2

TYPICAL HOIST ARRANGEMENT

212-D-3367

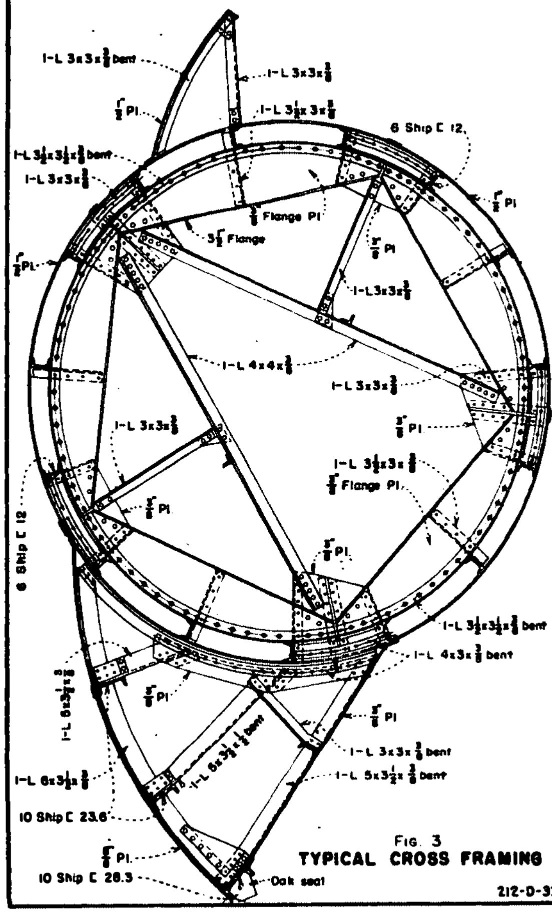


Fig. 3
TYPICAL CROSS FRAMING

212-D-3368

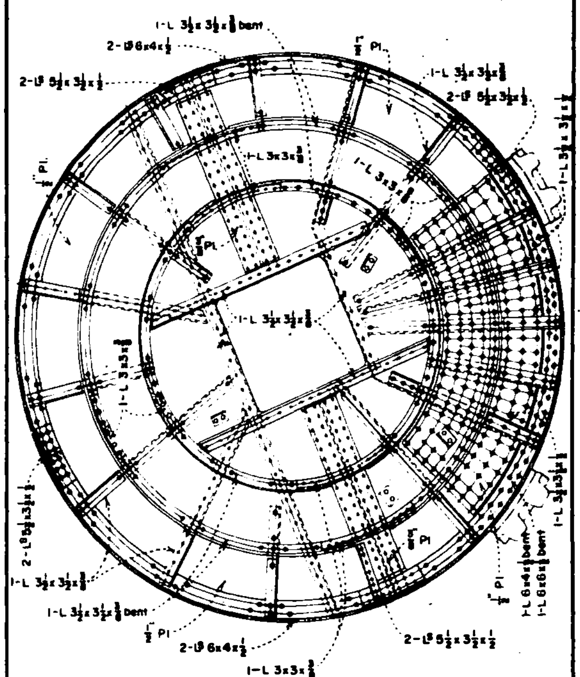


Fig. 4
TYPICAL FRAMING OF LOAD DISK

212-D-3369

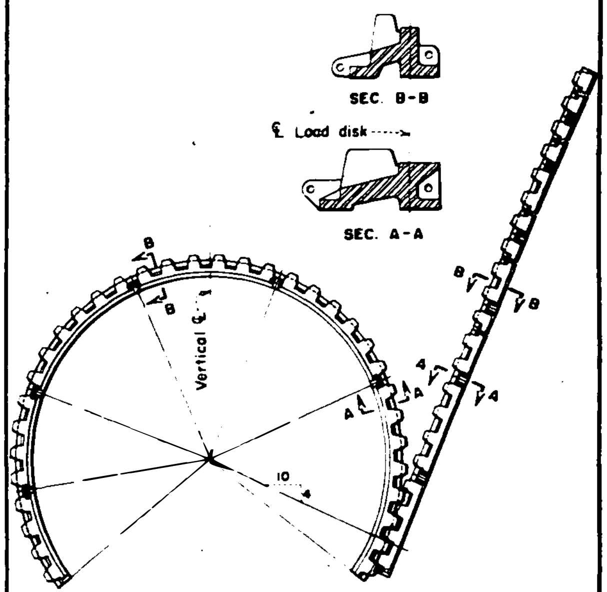


Fig. 5
DETAILS OF RIM AND RACK

212-D-3370

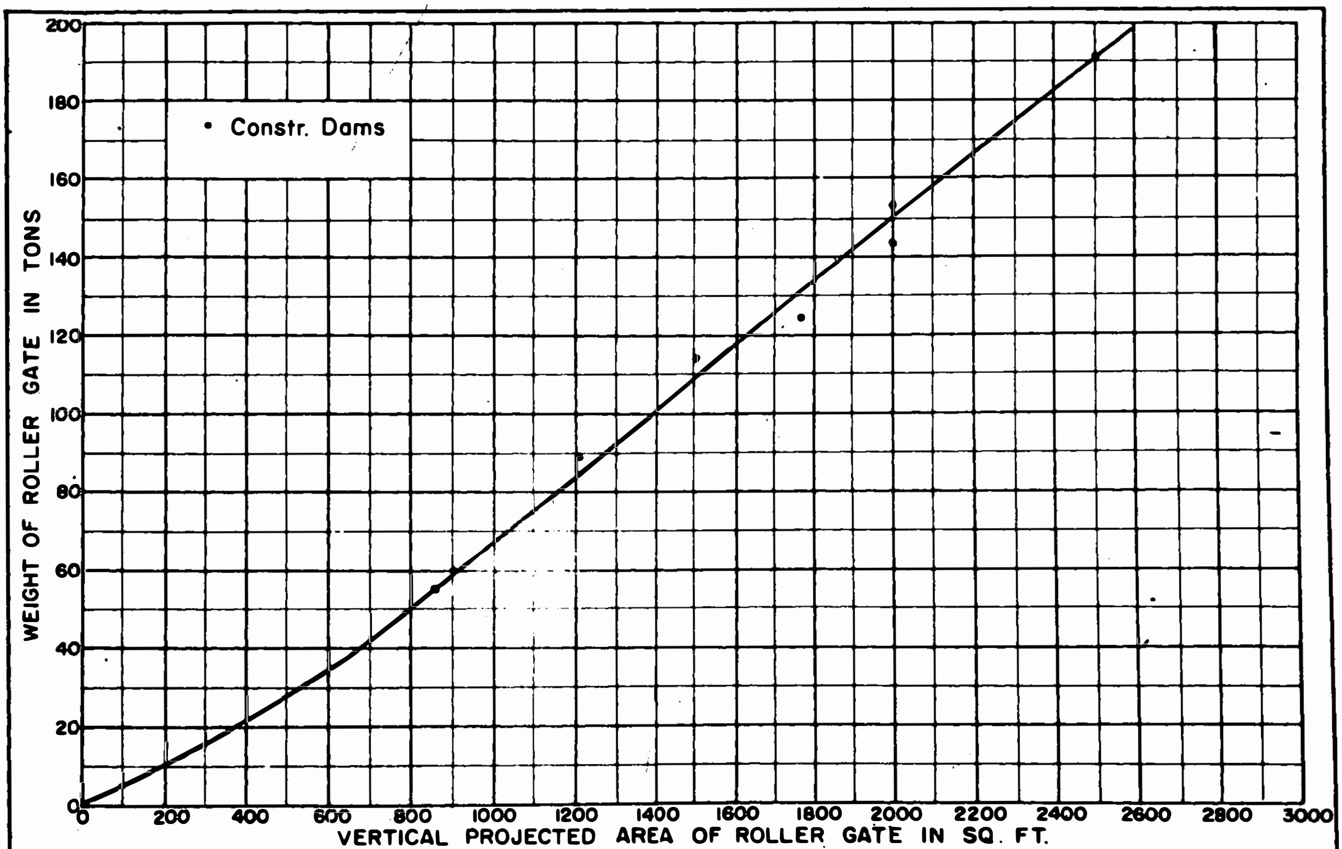


FIG. 6

212-D-3371

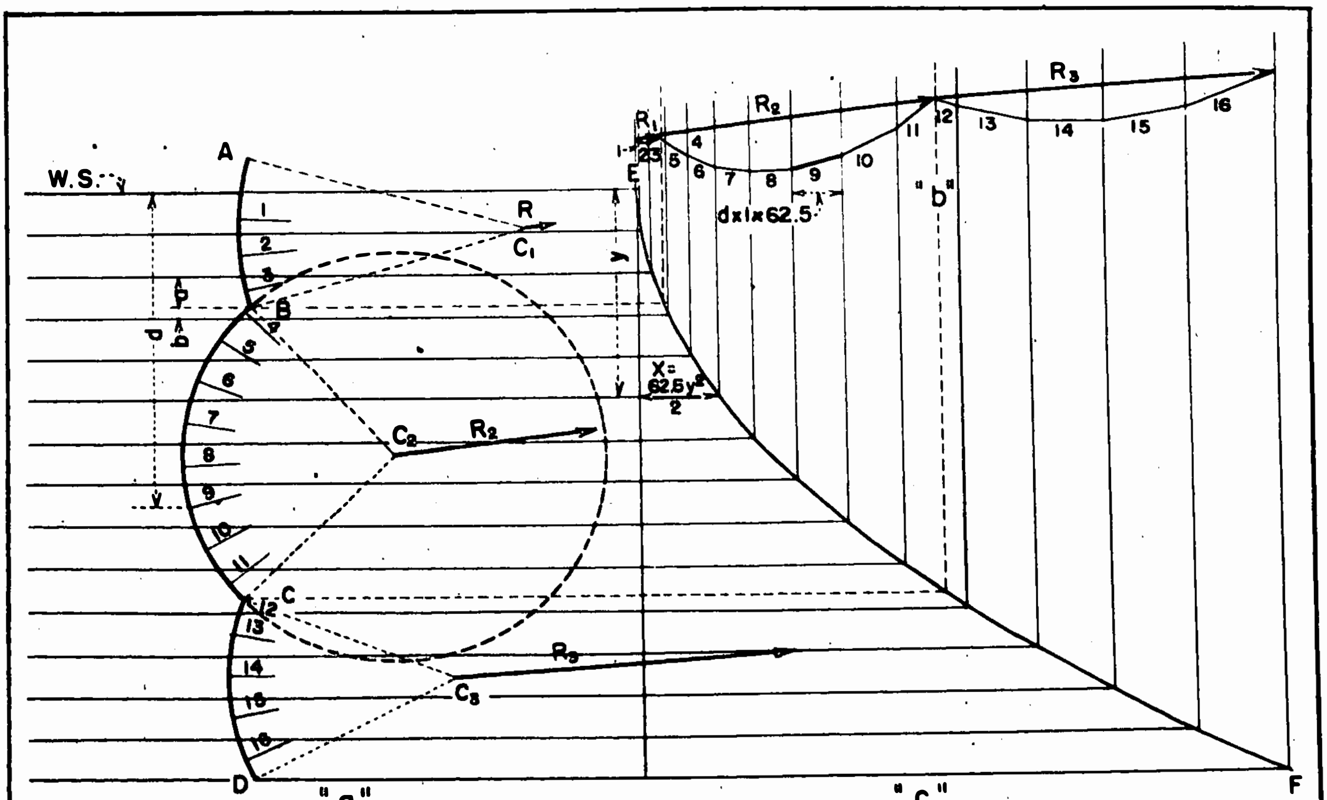


FIG. 7

212-D-3372

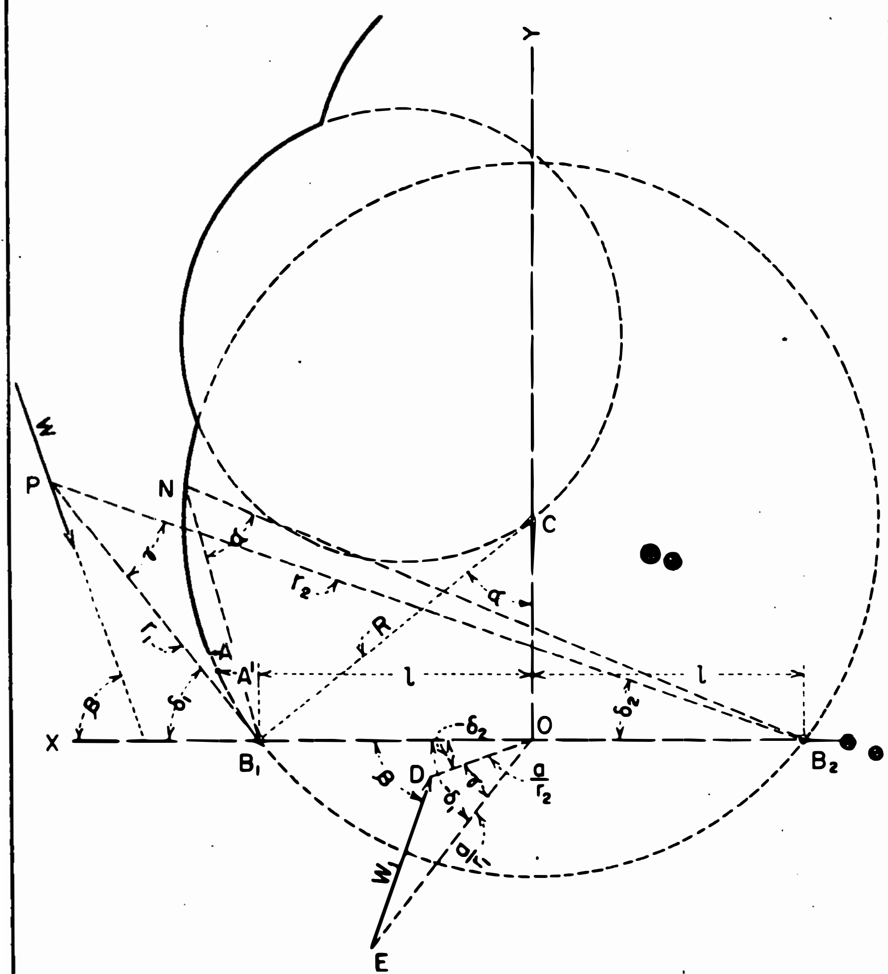


FIG. 8

212-D-3373

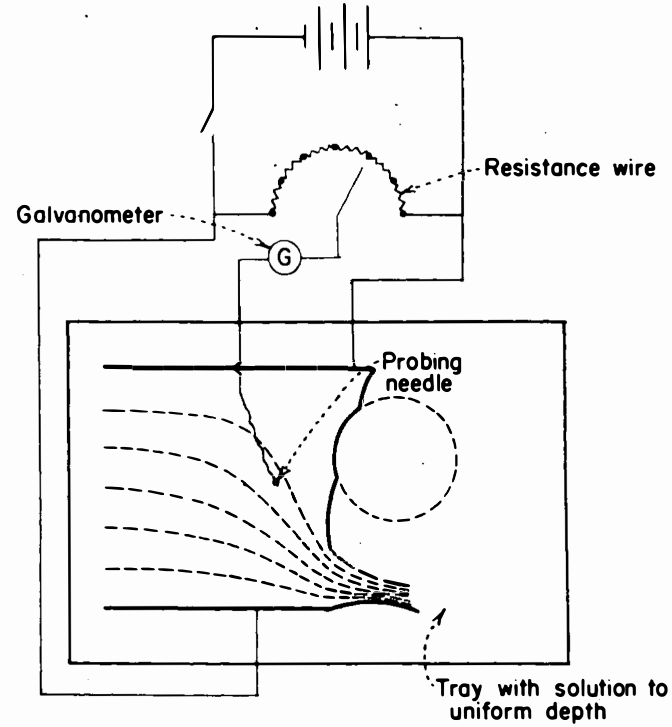


FIG. 9

212-D-3374

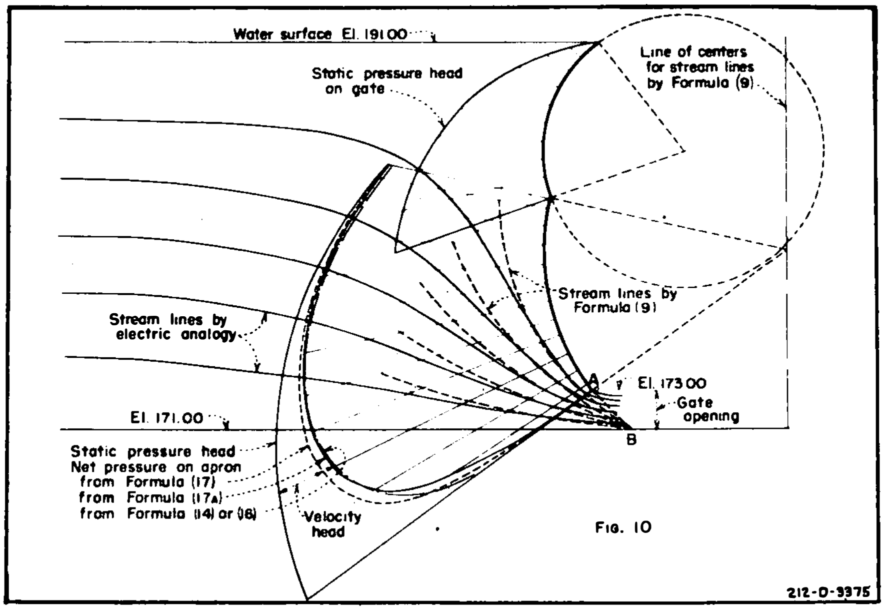


Fig. 10

212-D-3375

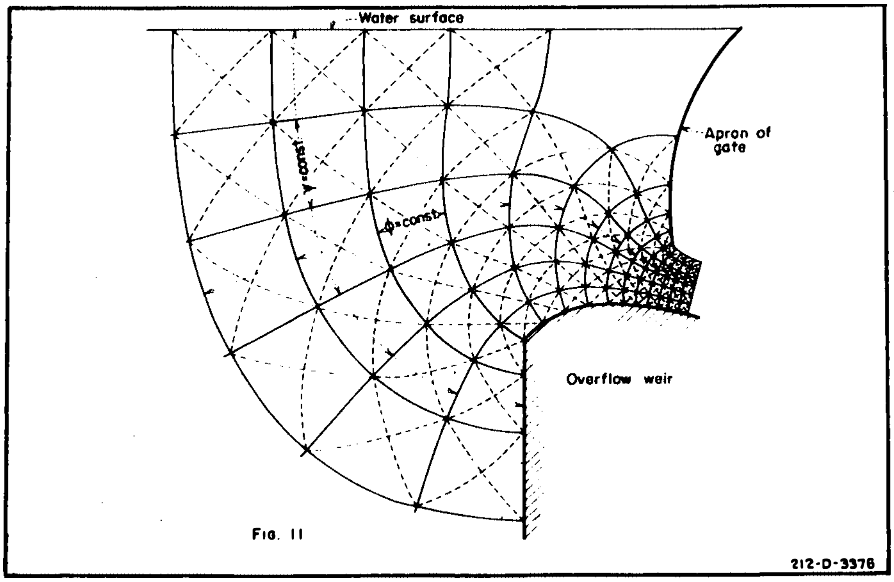


Fig. 11

212-D-3376

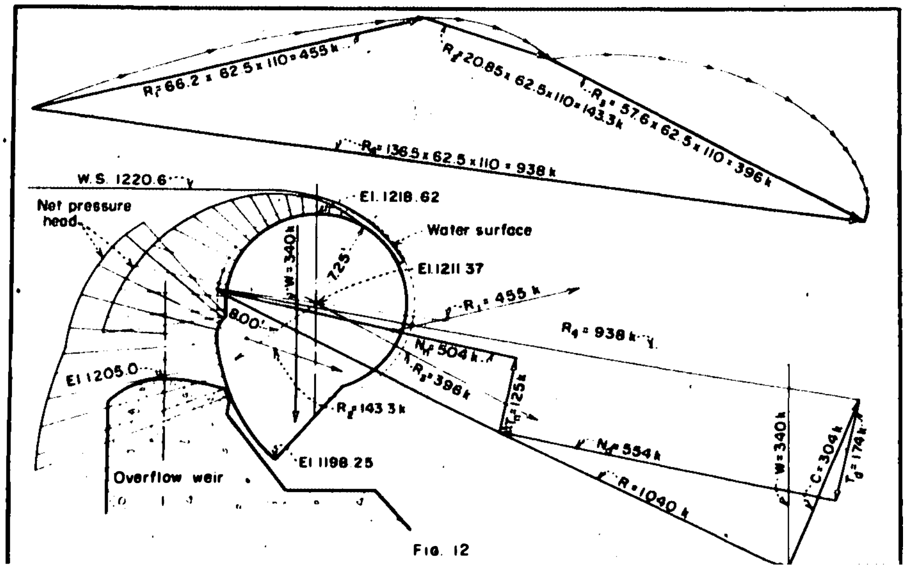
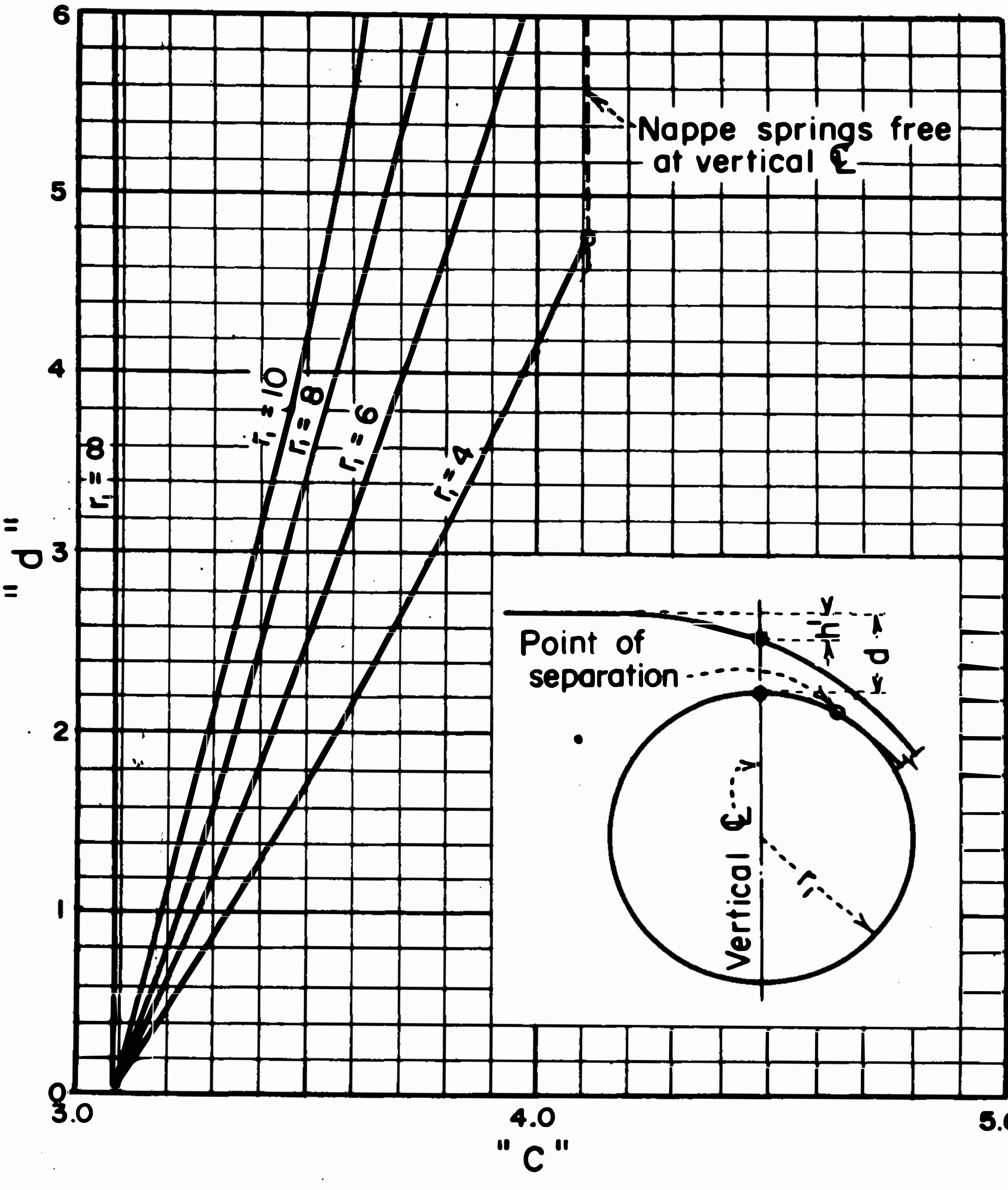


Fig. 12



$$Q = Cd^{\frac{3}{2}} \text{ where } C = (r_1 + d - h')\sqrt{\frac{2gh'}{d^3}} \log_e\left(\frac{r_1 + d - h'}{r_1}\right)$$

FIG. 13

212-D-3378

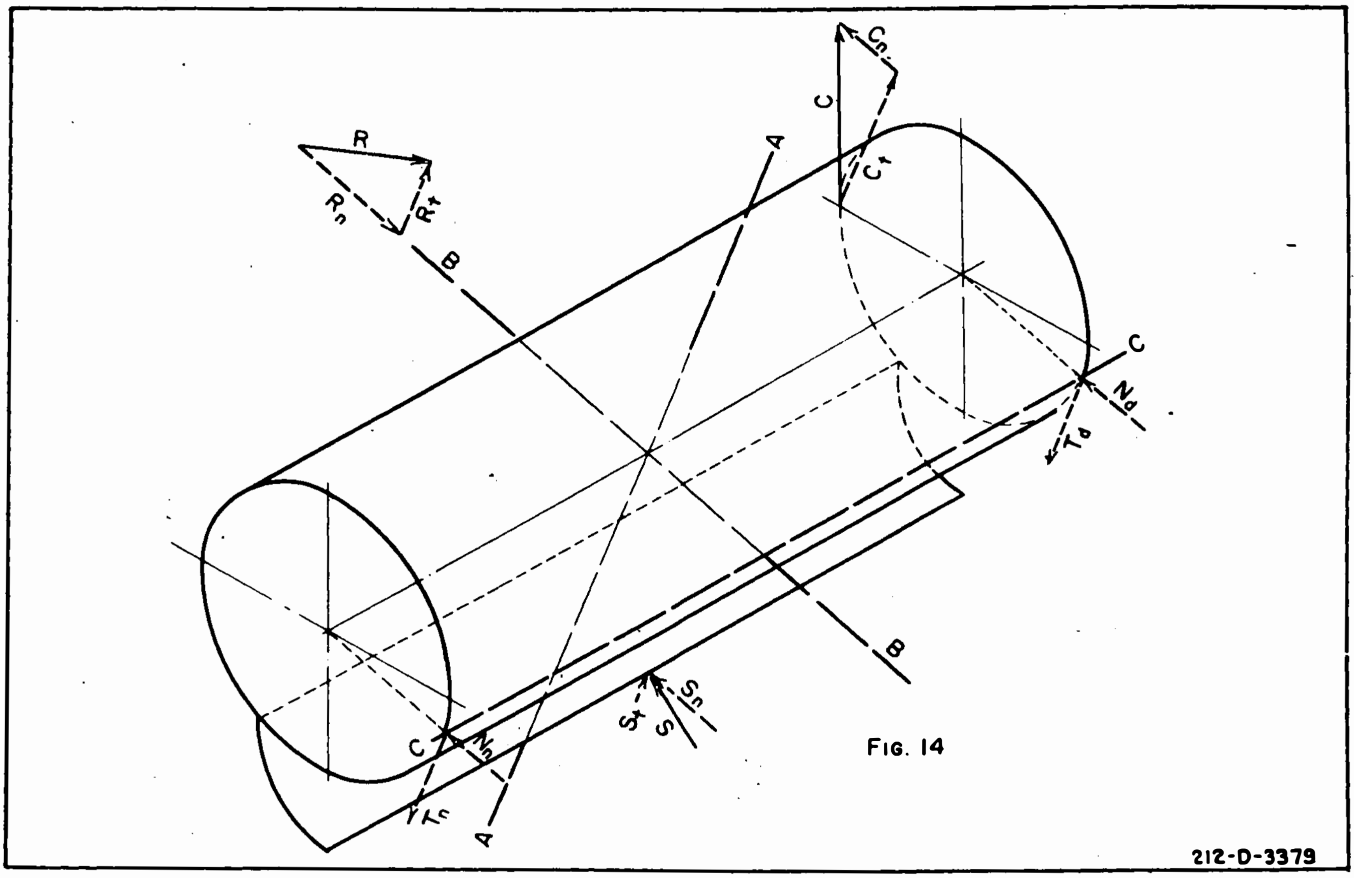


FIG. 14

212-D-3379

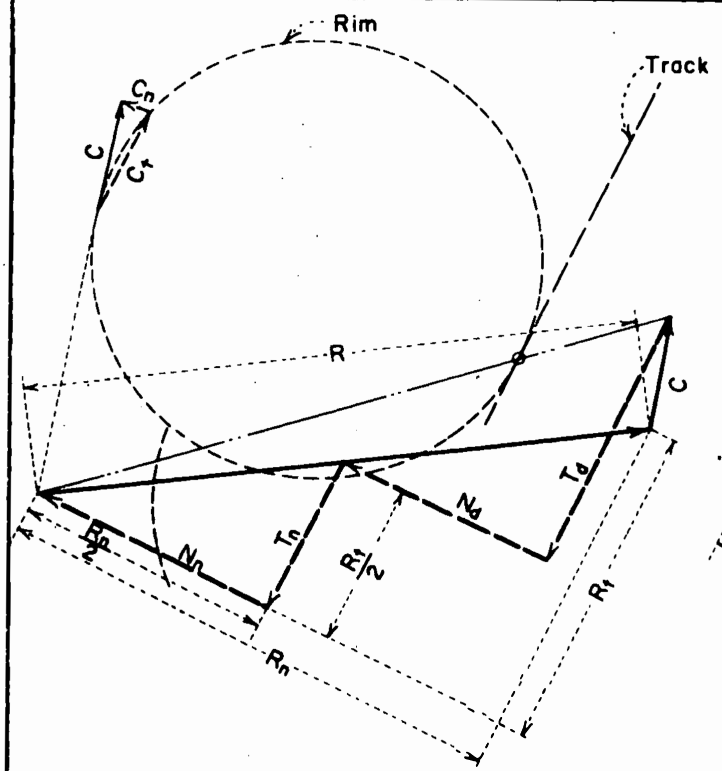


FIG. 15

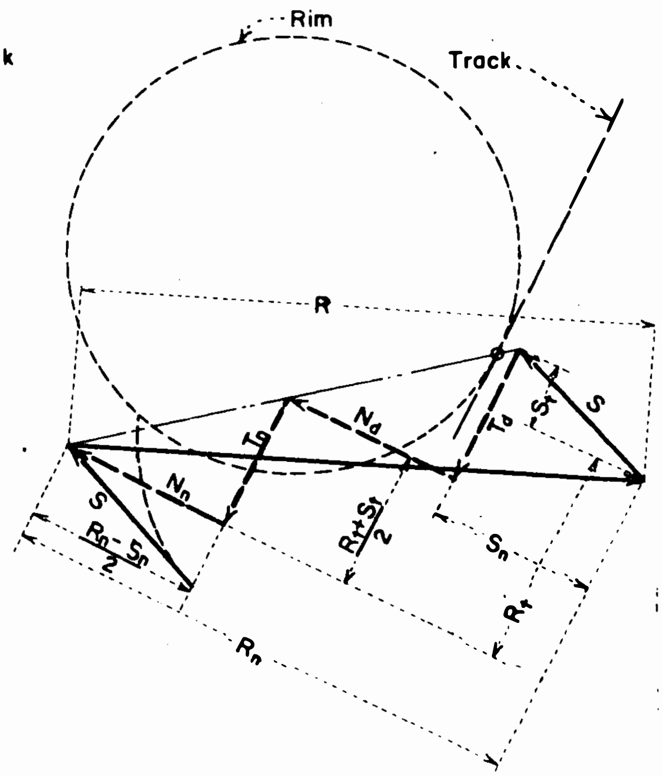


FIG. 16

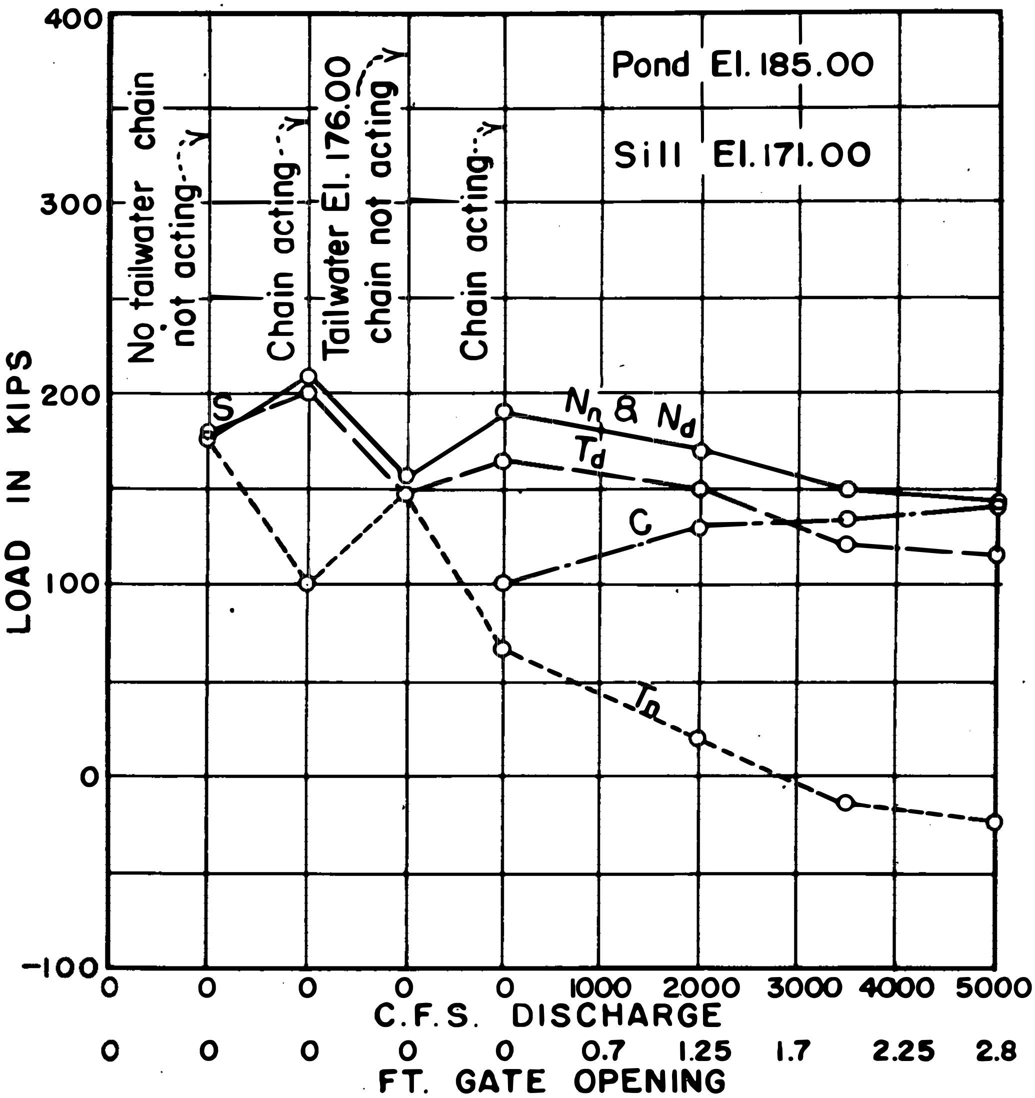


FIG. 17

212-D-3381