ABSTRACT OF THESIS

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A SYSTEMATIC APPROACH TO THE
HYDRAULIC AND STRUCTURAL PRINCIPLES INVOLVED
IN THE DESIGN OF LOW-HEAD RADIAL GATE

Submitted by
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In partial fulfillment of the requirements
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Colorado A & M College
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I. INTRODUCTION

The purpose of this thesis is to separate the individual factors involved in the analysis and design of radial gate, to examine each of these factors in light of known physical laws, to develop mathematical equations expressing these laws and their relation to the problem, and to correlate all of these factors in a rational and systematic process of analysis leading to an efficient and economical design.

II. HYDRAULIC PRINCIPLES INVOLVED IN THE ANALYSIS AND DESIGN OF RADIAL GATE

A. General Layout.

Two factors control the general layout or shape of a radial gate: the radius of gate, and the height of pin.

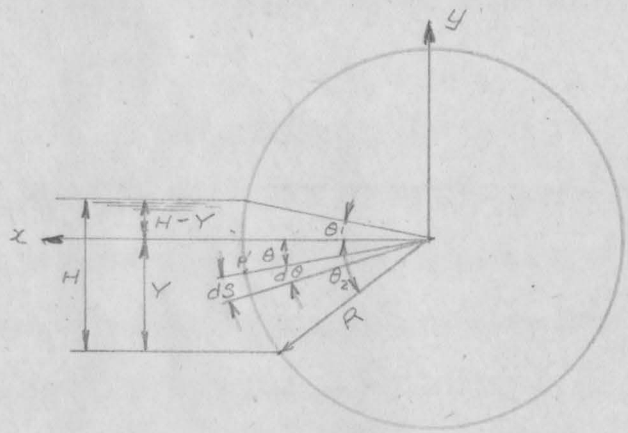
I. Radius of Gate. The radius of curvature, not only affects the direction of the upward water pressure, but also has an important bearing on the relative dead load reaction at the trunnion and upon the length and height of the pier and the weight of the struts. The longer the radius, the higher the elevation required for the runway and the larger the pier will be. On the other hand, too short a radius, or too great an inclination of the chord from the vertical will require a heavier gate and develop complicated problems in the trunnion anchorage caused by the excessive uplift. From an analysis of existing gates, the radius of gate varies from 1 to 5/4 times the height of gate. The statistical data upon which this statement is based are plotted as shown in Figure 1-a.

2. Height of Pin. The pin should be located above the ordinary

high water level, and should be high enough to permit the gate to be raised above floating material carried by the extreme flood. If the pin is placed too high in relation to the radius and position of the gate, an undesirable uplift pressure in the trunnion anchorage will be resulted. If it is too low, it will decrease the efficiency of the operation of gates. The values of height of pin for the existing structures are plotted in Figure 1-b. An average value of height of pin equal to 3/4 the height of gate may be used for preliminary layout.

B. Load Analysis.

The critical position for a non-submersible radial gate is ordinarily the normal closed position with the upstream face of the gate subjected to pressure caused by a full upper pool and an assumed unwatered downstream side. The magnitude of the total water pressure may be found by the method of integration.



Let ds = any infinitesimal segment of arc along the face of gate

θ = angle measured from the X-axis to any point p′ along the arc

p = unit water pressure at any point p′

then, $dP = p\, ds = p\, R\, d\theta$

$$= w\, R(\sin\theta_1 - \sin\theta)R\, d\theta = w\, R^2(\sin\theta_1 - \sin\theta)\, d\theta$$

$$P = w\, R^2 \int_{-\theta_2}^{\theta_1} (\sin\theta_1 - \sin\theta)\, d\theta$$

$$= w\, R^2 \left[\sin\theta_1(\theta_1 + \theta_2) + \cos\theta_1 - \cos\theta_2\right]$$

If $R = 1.25\, H$, $Y = 0.75\, H$,

$$\sin\theta_1 = \frac{H - Y}{R} = \frac{1}{5}, \quad \theta_1 = \sin^{-1} 0.2 = 11^\circ\, 32'$$

$$\sin\theta_2 = \frac{Y}{R} = \frac{3}{5}, \quad \theta_2 = \sin^{-1} 0.6 = 36^\circ\, 52'$$

$$P = w\, (1.25\, H)^2 \left[0.2\, \frac{(48^\circ\, 24')\pi}{180^\circ} + \frac{\sqrt{24}}{5} - \frac{4}{5}\right]$$

$$= 0.545\, w\, H^2 = 34\, H^2 \text{ lbs per foot width of gate}$$

......................(1)

When the gate is in partial opening position, flow passes through it at high velocities. Due to bending of stream lines, the distribution of pressure along the gate face no longer follows the hydrostatic law. It, however, can be computed through the aid of flow nets.

III. STRUCTURAL PRINCIPLES INVOLVED IN THE ANALYSIS AND DESIGN OF RADIAL GATE - HORIZONTALLY FRAMED

The horizontally framed radial gate is so termed because its skin plate is supported by a series of unequally spaced horizontal ribs. Two vertical side beams, supporting these horizontal ribs, are in turn supported at each end by side frames, by means of which the water load is transferred into the piers through the trunnion castings.

A. Skin Plate.

The skin plate is essentially a semi-continuous beam running vertically with the horizontal ribs acting as supports. The maximum bending moment used for design is :

$$M = \frac{1}{10} W L'$$

where, W = total water load on a one-inch strip of plate

L = the distance between the flanges of the horizontal ribs in inches

By equating it with the resisting moment of a plate of thickness "t", the following relation may be found :

$$L = \frac{263\ t}{\sqrt{H}} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots(2)$$

From Equation (2), a system of curves is plotted with "H" as ordinates, "L" as abscissas and "t" as a varible, as shown in Fig.7. For any plate thickness thus chosen, the allowable spacings of horizontal ribs could be easily determined for different values of water head "H". The rib spacing increases progressively towards the top of gate as the water load decreases, so as to make the skin plate stresses as uniform in intensity as possible.

B. Horizontal Ribs.

The horizontal ribs are designed as uniformly loaded simply supported beams. The maximum bending moment is :

$$M = \frac{1}{8} W' L^2 \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots(3)$$

where, W' = water load per foot width of ribs

L = distance between the center line of side beams

The section modulus required may be found from the charts in Fig. 9, for different values of "L" and the average water head "h".

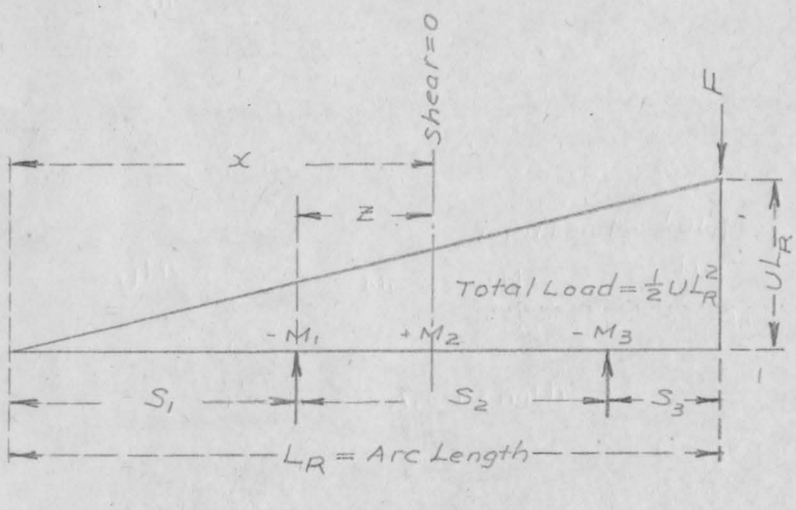
C. Side Beams.

The side beams, for ease of construction and assembly with the arms, are of welded steel plates which vary in depth of cross-sections. The theoretical location of the center line of arm connections on the inside of the skin plate is so placed that the negative bending moment of both cantilever sections is equal in magnitude to the maximum positive moment at the central span. The criterion may be derived as follows :

Let U = uniformly increasing load due to depth of water distributed on arc length "L_R" = 60 lbs per cu. ft. approximately.

z = distance along arc from the center line of upper arm to the section at interior span where vertical shear is equal to zero, or the section of maximum positive moment.

For simplicity, the arc of the face of gate is developed into a straight line and a unit width of gate is taken.



Then,
$$M_1 = -U S_1 \times \frac{S_1}{2} \times \frac{S_1}{3} = -\frac{1}{6} U S_1^3$$

$$M_2 = R_1 z - \frac{1}{6} U x^3$$

$$M_3 = R_1 S_2 - \frac{U(S_1 + S_2)^3}{6}$$

From criterion : $-M_1 = +M_2 = -M_3$

By equating $(-M_1) = (M_2)$;

$$\frac{1}{6} U S_1^3 = R_1 Z - \frac{1}{6} U X^3$$

$$R_1 Z = \frac{U}{6}(S_1^3 + X^3) \quad \text{..........(a)}$$

$(-M_1) = (-M_3)$;

$$-\frac{1}{6} U S_1^3 = R_1 S_2 - \frac{U}{6}(S_1 + S_2)^3$$

$$R_1 S_2 = \frac{U}{6}\left[(S_1 + S_2)^3 - S_1^3\right] \quad \text{...(b)}$$

By the equations for equilibrium :

$$\Sigma V = 0 \; ; \qquad R_1 + R_2 = \frac{1}{2} U L_R^2 + F \quad \text{...........(c)}$$

$$\Sigma M = 0 \; ; \qquad R_1 S_2 - \frac{U(S_1 + S_2)^3}{6} = -F S_3 - \frac{U S_3^2}{6}[2L_R + S_1 + S_2] \quad \text{...........(d)}$$

Since shear is zero at section at "Z" distance from the center line of upper arm, it may be written as :

$$R_1 = \frac{U}{2}(S_1 + Z)^2 \quad \text{.......(e)}$$

and;

$$L_R = S_1 + S_2 + S_3 \quad \text{.......(f)}$$

After solving these six equations, the following results will be found :

$S_1 = 0.3858\ L_R$; $R_1 = 0.4188\ P$

$S_2 = 0.4912\ L_R$; $R_2 = 0.6188\ P$

$S_3 = 0.1230\ L_R$; $-F = -0.0376\ P$

$1.0000\ L_R$ $1.0000\ P$

where P = pin load for half width of gate.

$$Z = \sqrt{\frac{2R_1}{U}} - S_1 = 0.2613\ L_R$$

Therefore, $M_1 = \frac{U S_1^3}{6}\,\frac{B}{2} = \frac{U S_1^3\, B}{12}$ (ft. lbs)

$$M_1 = U\, S_1^3\, B \quad (\text{in.} - \text{lbs})$$

$$= 3.45\, L_R^3\, B \quad (\text{in.} - \text{lbs})$$

$$\text{Section modulus required} = \frac{M_1}{f_s} = 0.0001914\, L_R^3 B \quad (\text{in.}^3) \qquad \ldots\ldots\ldots\ldots\ldots(4)$$

which is plotted graphically as shown in Fig. 10.

D. Arms.

The arms are fastened to the side beams with rivet bolts to facilitate erection in the field. The arms are designed as columns with L/r ratio not to exceed 120, where r = least radius of gyration. The lower arm carries 0.6188 P, and the upper arm, 0.4188 P. The pin load "P" may be computed from Equation (1) and is plotted as shown in Fig. 12, for different sizes of gates.

E. Pin Bearings.

The size of pin required depends upon the size of arms and the pin load. The pin should be designed both for bearing and bending, and the larger pin size required is selected. For bearing, the diameter of pin required to carry the pin load is :

$$D = \frac{P}{3500\, C} \qquad \ldots\ldots\ldots\ldots\ldots\ldots(5)$$

and for bending, the diameter of pin required is :

$$D = \sqrt[3]{\frac{4P\,(C + 3)}{\pi\, f_s}} \qquad \ldots\ldots\ldots\ldots\ldots\ldots(6)$$

where, P = pin load in pounds

C = width of bracket in inches

f_s = allowable stress of bending

= 23,750 lb. per sq. in.

The allowable pin loads for different sizes of pins and different widths of bracket are plotted as shown in Fig. 13.

IV. STRUCTURAL PRINCIPLES INVOLVED IN THE ANALYSIS AND DESIGN OF RADIAL GATE - VERTICALLY FRAMED

A vertically framed radial gate consists of curved vertical ribs to support the skin plate, horizontal cross-girders, and side frames transferring the thrust through the trunnion castings to the pier.

A. Vertical Ribs.

The vertical ribs are usually channels or light beams determined in spacing by the desirable skin plate thickness and the load to which the plate is subjected. The assumption of design is that the curved vertical ribs act as beams simply supported by the horizontal cross-girders. The same principle as used in the design of side beams for horizontally framed gate will also be applied here by placing the horizontal girders at such places that the negative moments at two supports will be equal in magnitude to the positive moment at the interior span.

Let b = spacing between vertical ribs in inches

then, $M_{max.} = 0.575\, b\, L_R^3$ ....(7)

which is plotted as shown in Fig. 15.

B. Horizontal Cross-girders.

The horizontal cross-girders may be of standard I-beams, built-up girders, or trusses depending upon the amount of water pressure to which it is subjected and the span of the gate. They are analyzed as beams simply supported by the side frames, with the load as obtained by the criterion in Section III.

For the upper girder :

$$W_U = 0.4188\ (\tfrac{1}{2}UL_R^{\,2}) = 12.6\ L_R^{\,2} \quad \text{(lbs per ft.)}$$

$$M_U = \frac{1}{8}\,W_U B^2 \times 12 = \frac{1}{8}\,12.6\ L_R^{\,2} B^2 \times 12$$

$$= 18.9\ L_R^{\,2} B^2 \quad \text{(in.-lbs)}$$

$$S_U = \frac{M_U}{f_s} = 0.00105\ L_R^{\,2}\ B^2 \quad (\text{in.}^3) \quad \text{......(8)}$$

For the lower girder :

$$W_L = 0.6188\ (\tfrac{1}{2}\,UL_R^{\,2}) = 19.6\ L_R^{\,2} \quad \text{(lbs per ft.)}$$

$$M_L = \frac{1}{8} \times 19.6\ L_R^{\,2}\ B^2 \times 12 = 29.4\ L_R^{\,2}\ B^2 \quad \text{(in.-lb)}$$

$$S_L = 0.00165\ L_R^{\,2}\ B^2 \quad (\text{in.}^3) \quad \text{..........(9)}$$

Equations (8) and (9) are plotted graphically as shown in Fig. 16 and 17. The plane of the arms may be swung inward from the pin to intersect the gate face approximately at the outer fifth-points. This arrangement effects considerable reduction in the weight of the horizontal members by converting them into one fixed and two cantilever beams of equal moments and at the same time removes the arms from ice danger. In this case, however, the anchorage must be designed for the lateral thrust thus generated due to the sloping side frames.

V. CONCLUSIONS

The individual factors which must be considered in the design of radial gate are: (1) the proper radius of gate; (2) the height of pin with respect to the total height of gate; (3) the hydrostatic pressure involved; (4) the hydrodynamic pressure involved; (5) the general type of framing to be used; and (6) the principles of design of the structural elements involved including the skin plate, the structural support for the skin plate, the side frames which permit rotation of the gate, and the trunnion pins and anchorage which supports the entire gate structure.

Determination of the proper radius of gate and the height of pin are functions of the total height of the gate. Local circumstances peculiar to each gate installation play an important part in determining the proper values of these two quantities. A critical study of existing installations which have been proven most satisfactory show a very definite relationship between the height of gate and each of these factors. These relations are shown graphically in Fig. 1-a and 1-b. The necessary size and strength of the individual structural elements comprising the gate are dependent upon the hydrostatic pressures, the hydrodynamic pressures and the general type of framing to be used. They are also closely interrelated so that no one element can be designed without consideration of the other factors. The thickness of the skin plate is a function of the hydrostatic and hydrodynamic pressures and the spacing of the primary members. The relationship of these factors is presented in Fig. 7. Size and strength of the primary members is a function of the hydraulic pressures, the type of framing to be used, the width of gate and the spacing between these members. The relationship between these factors is presented graphically in Fig. 9, 10, 15, 16 and 17. The size of the side frames and trunnion pins is a function of the hydraulic pressures and the height and width of the gate. The relationship of these factors is presented in Fig. 12 and 13.

The graphically representations presented in the figures mentioned above make it possible to determine the effect of each of these factors involved in the problem upon all of the other factors. With these data, it is possible for the designer to approach each individual problem systematically, to make a preliminary design for each of the two types of framing discussed in the thesis, to compare them and select the one best suited to his needs quickly and easily, and with due consideration for all the pertinent factors.

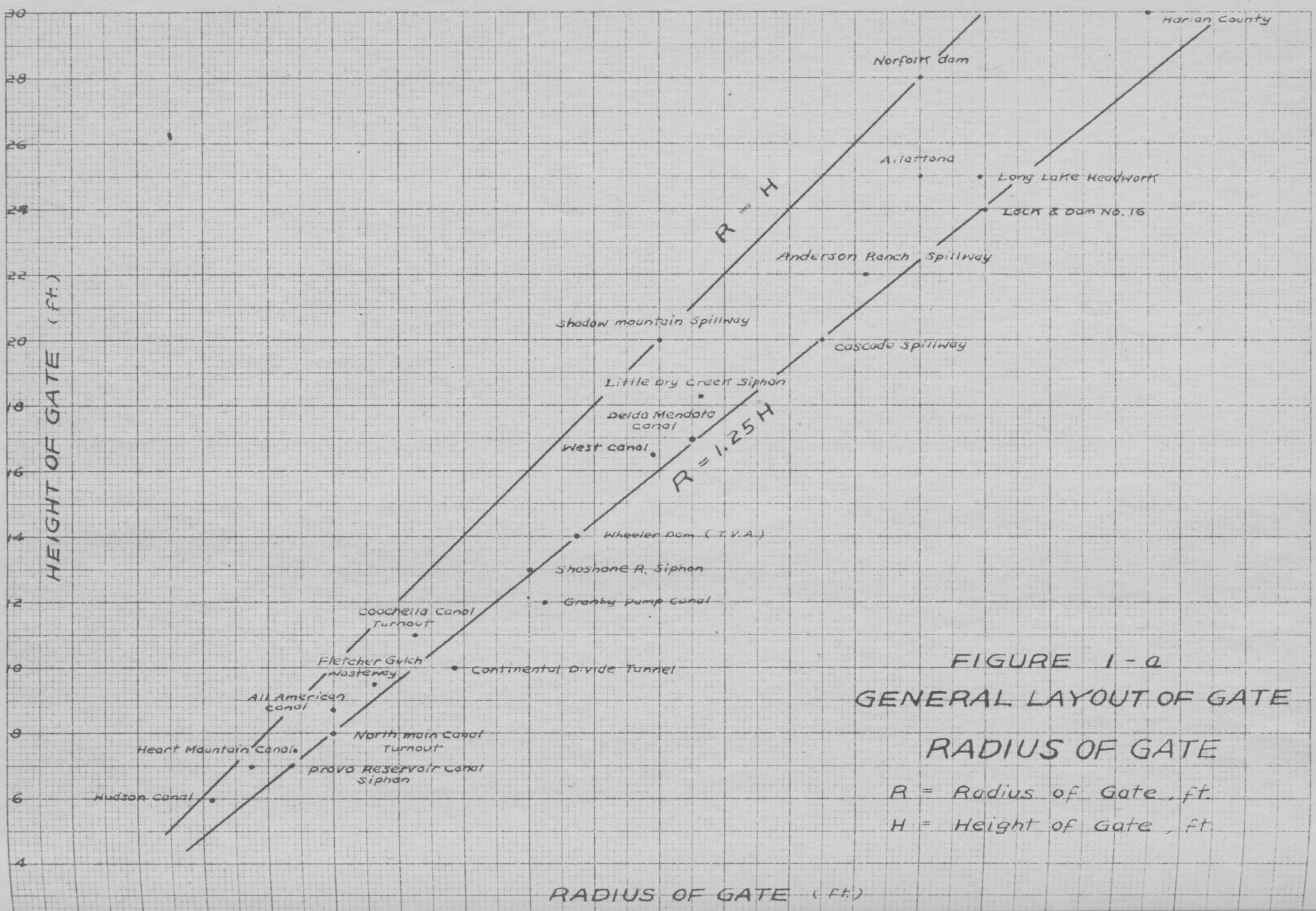


FIGURE 1 - a
GENERAL LAYOUT OF GATE
RADIUS OF GATE

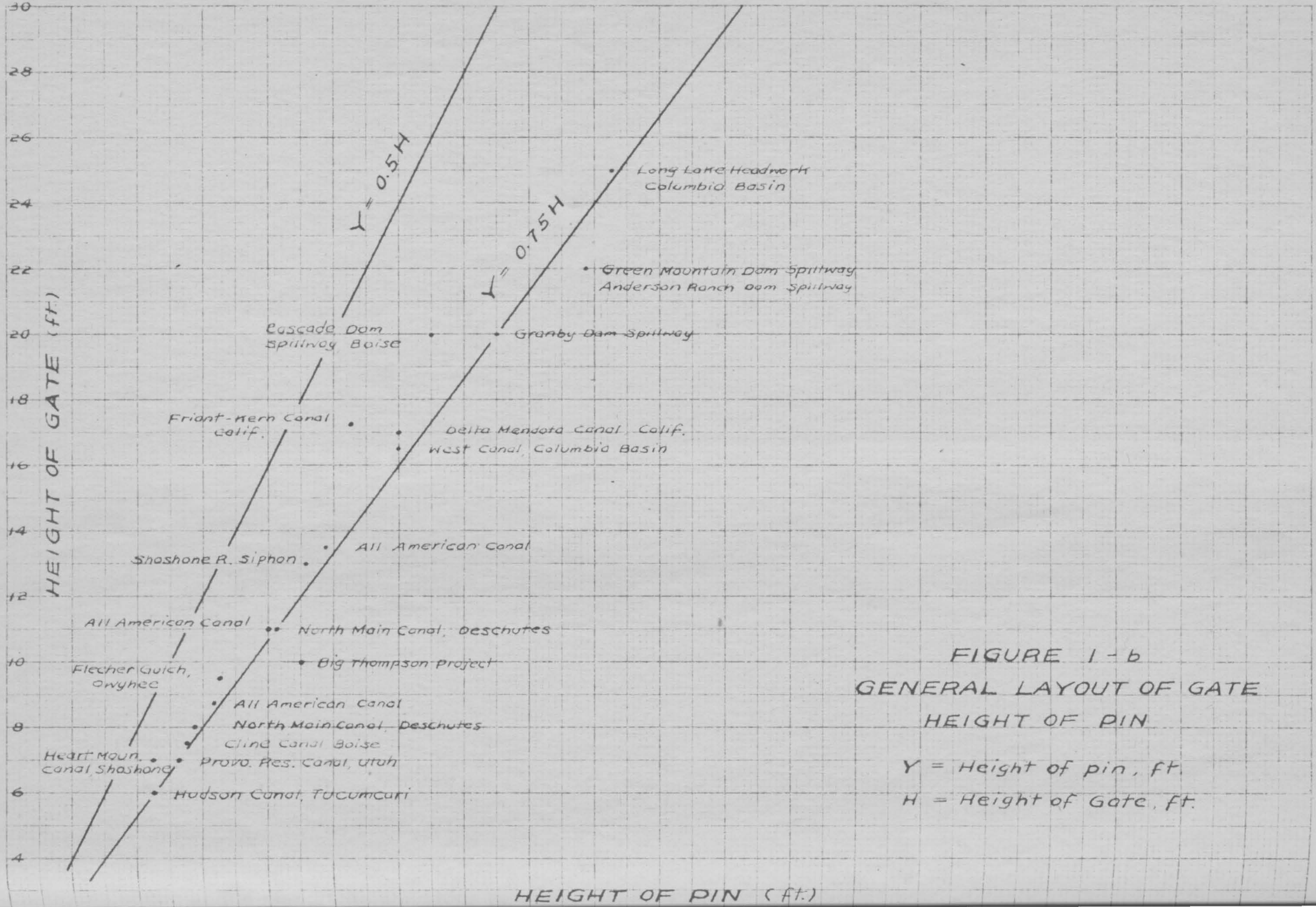


FIGURE 1-b
GENERAL LAYOUT OF GATE
HEIGHT OF PIN

Y = Height of pin, ft.
H = Height of Gate, ft.

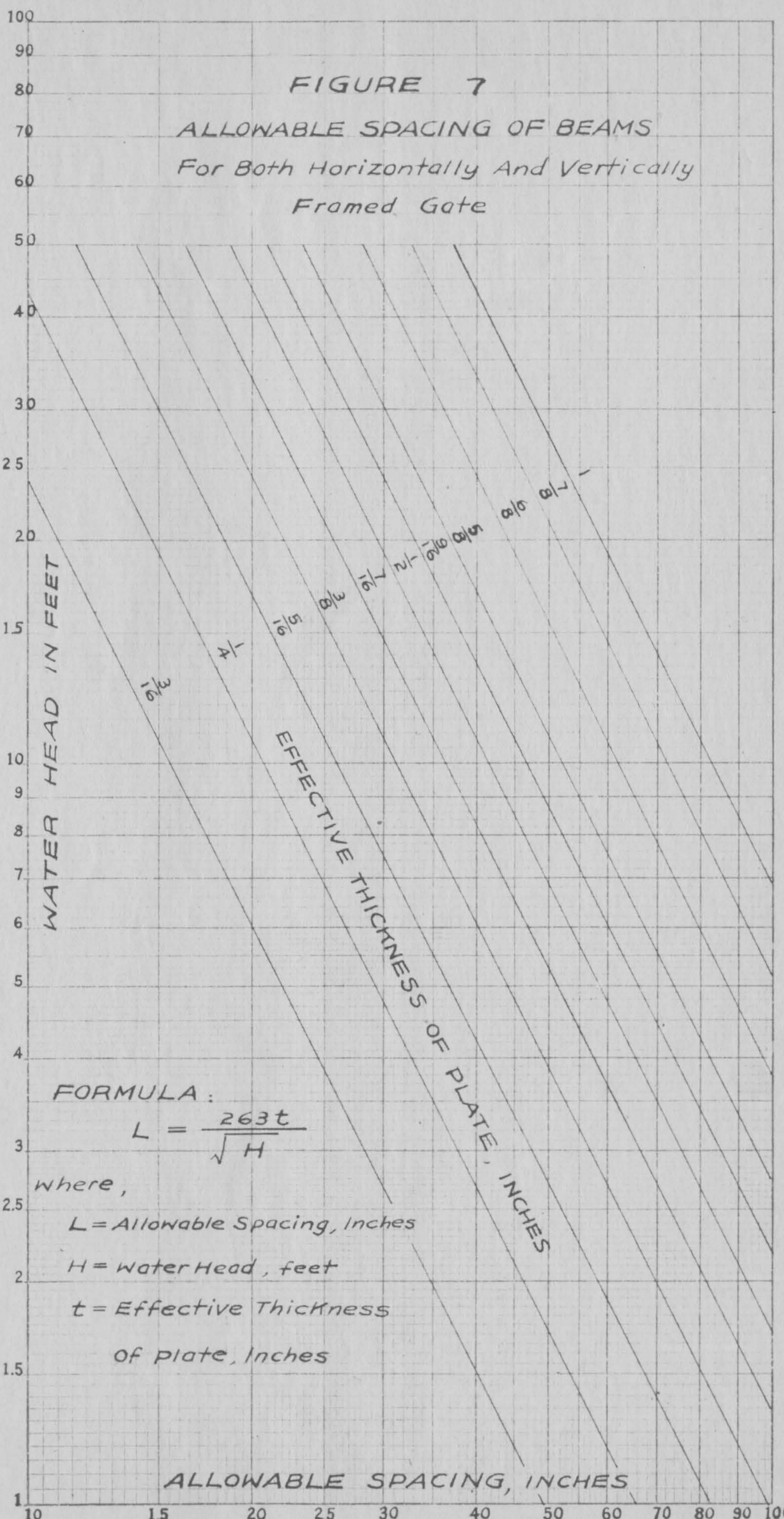


FIGURE 7

ALLOWABLE SPACING OF BEAMS

For Both Horizontally And Vertically Framed Gate

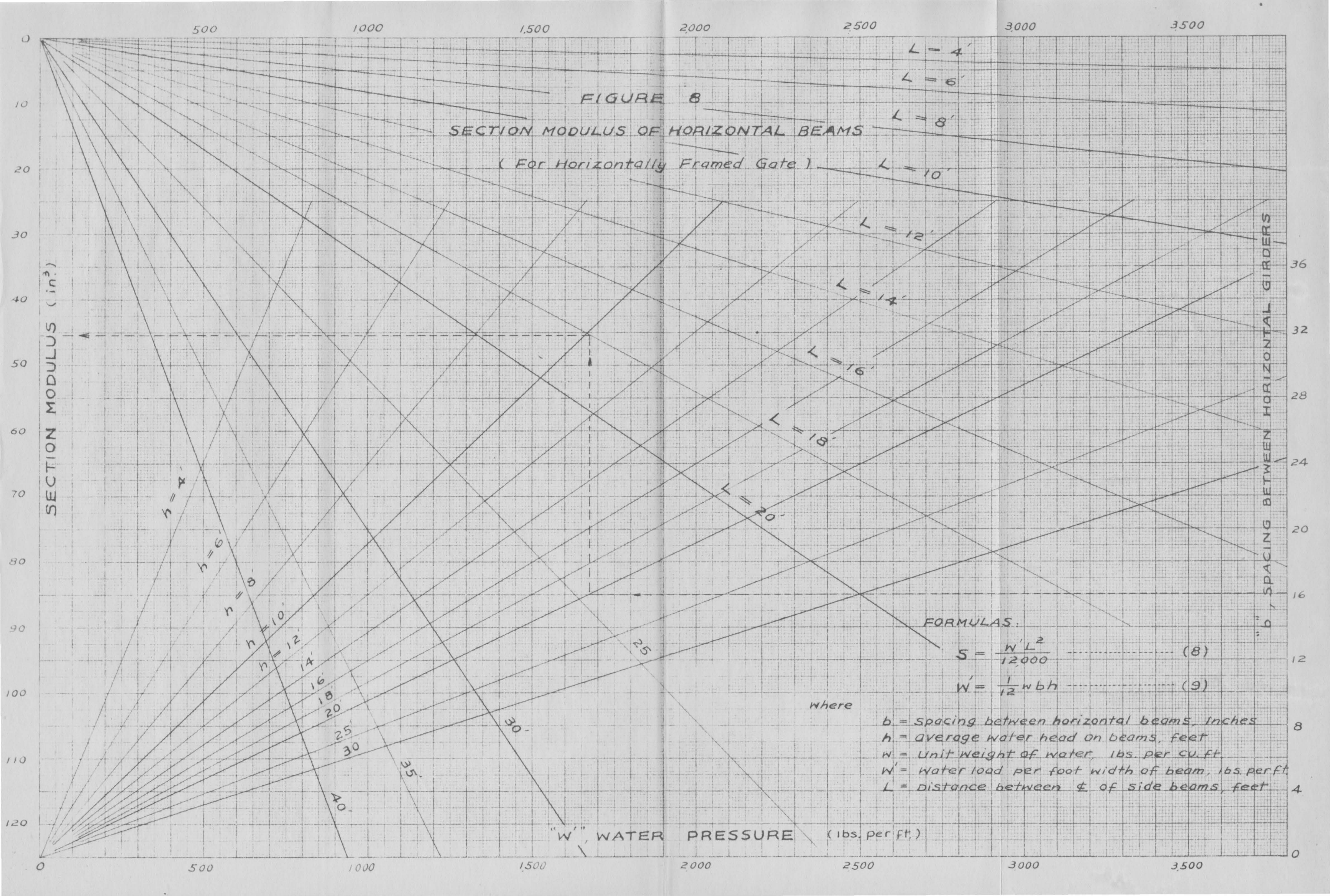


FIGURE 8

SECTION MODULUS OF HORIZONTAL BEAMS

(For Horizontally Framed Gate)

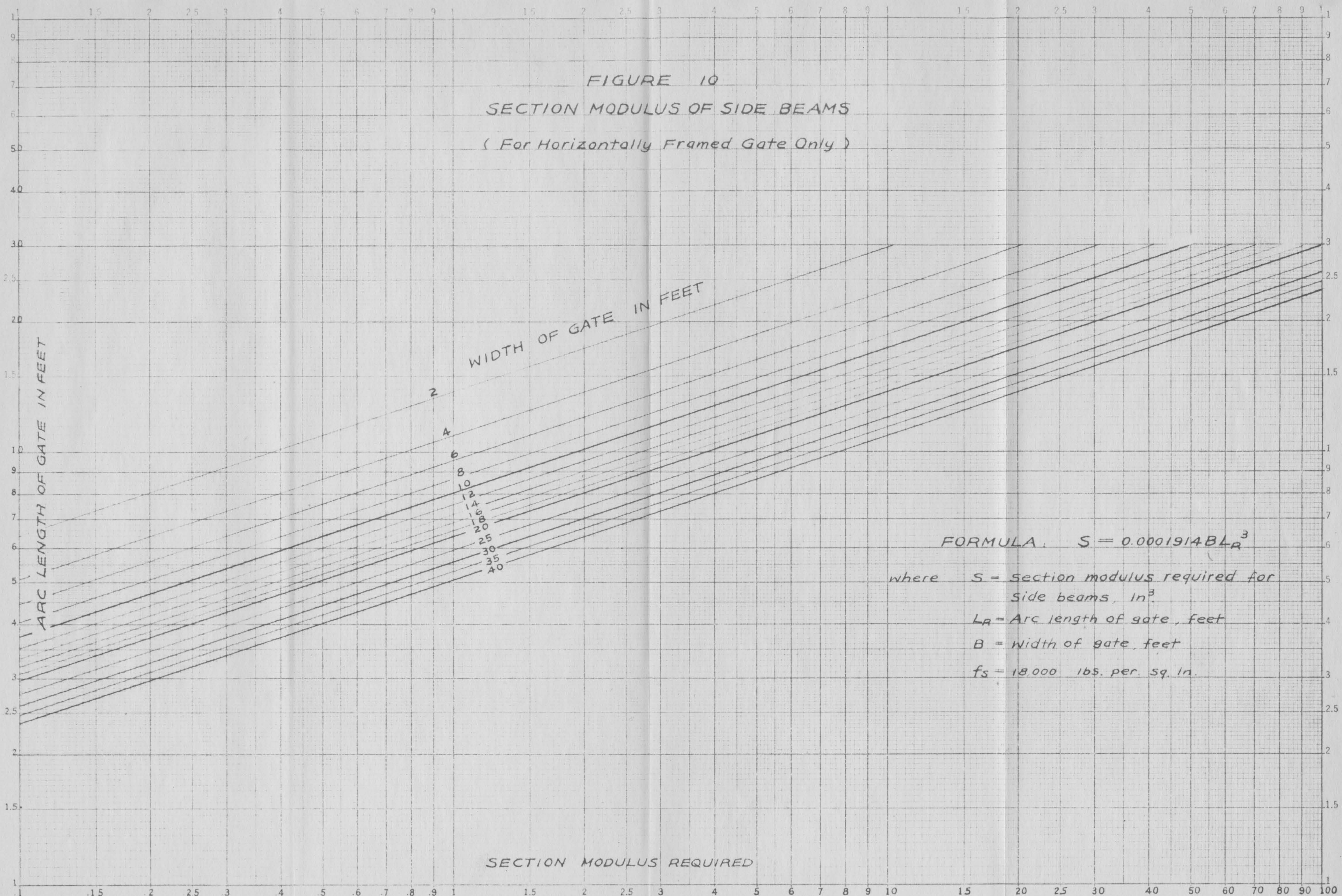


FIGURE 10
SECTION MODULUS OF SIDE BEAMS
(For Horizontally Framed Gate Only)
WIDTH OF GATE IN FEET
2
4
6
8
10
12
14
16
18
20
25
30
35
40
ARC LENGTH OF GATE IN FEET
FORMULA. $S = 0.0001914BL_R^3$
where S = section modulus required for side beams, In^3.
L_R = Arc length of gate, feet
B = width of gate, feet
f_s = 18,000 lbs. per. sq. in.
SECTION MODULUS REQUIRED

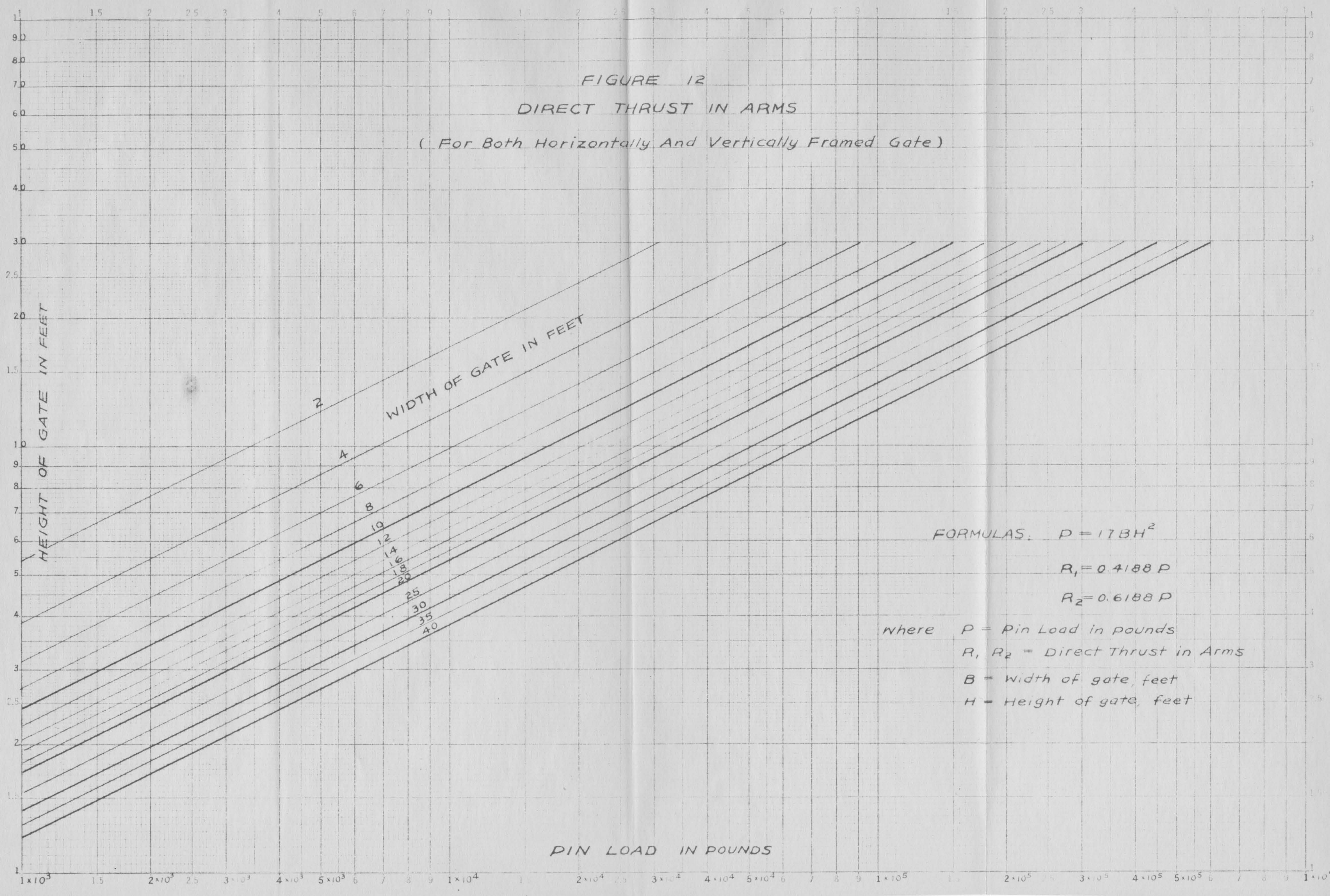


FIGURE 12

DIRECT THRUST IN ARMS

(For Both Horizontally And Vertically Framed Gate)

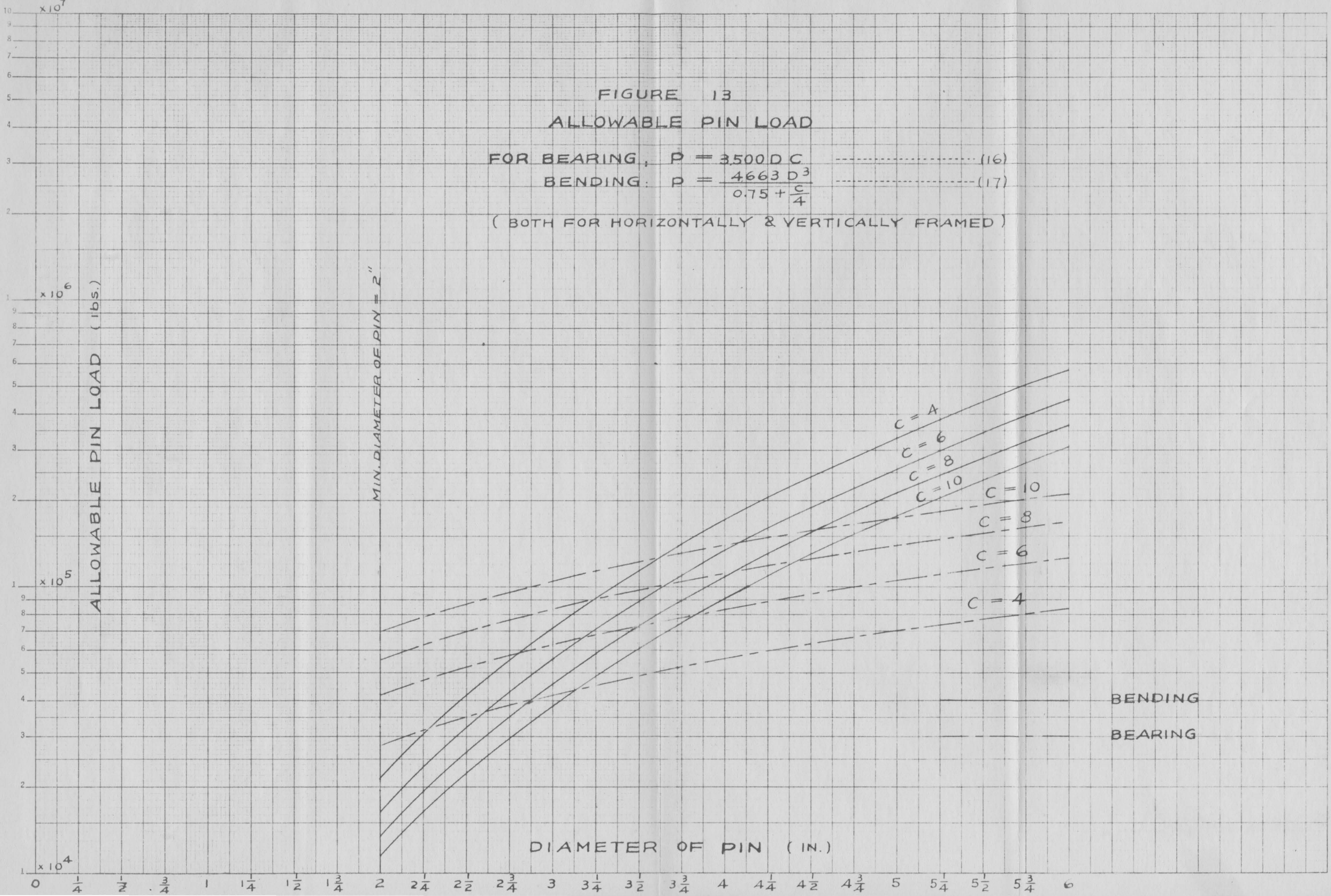
FIGURE 13

ALLOWABLE PIN LOAD

FOR BEARING, $P = 3500\,D\,C$ .... (16)

BENDING: $P = \dfrac{4663\,D^3}{0.75 + \frac{C}{4}}$ .... (17)

(BOTH FOR HORIZONTALLY & VERTICALLY FRAMED)



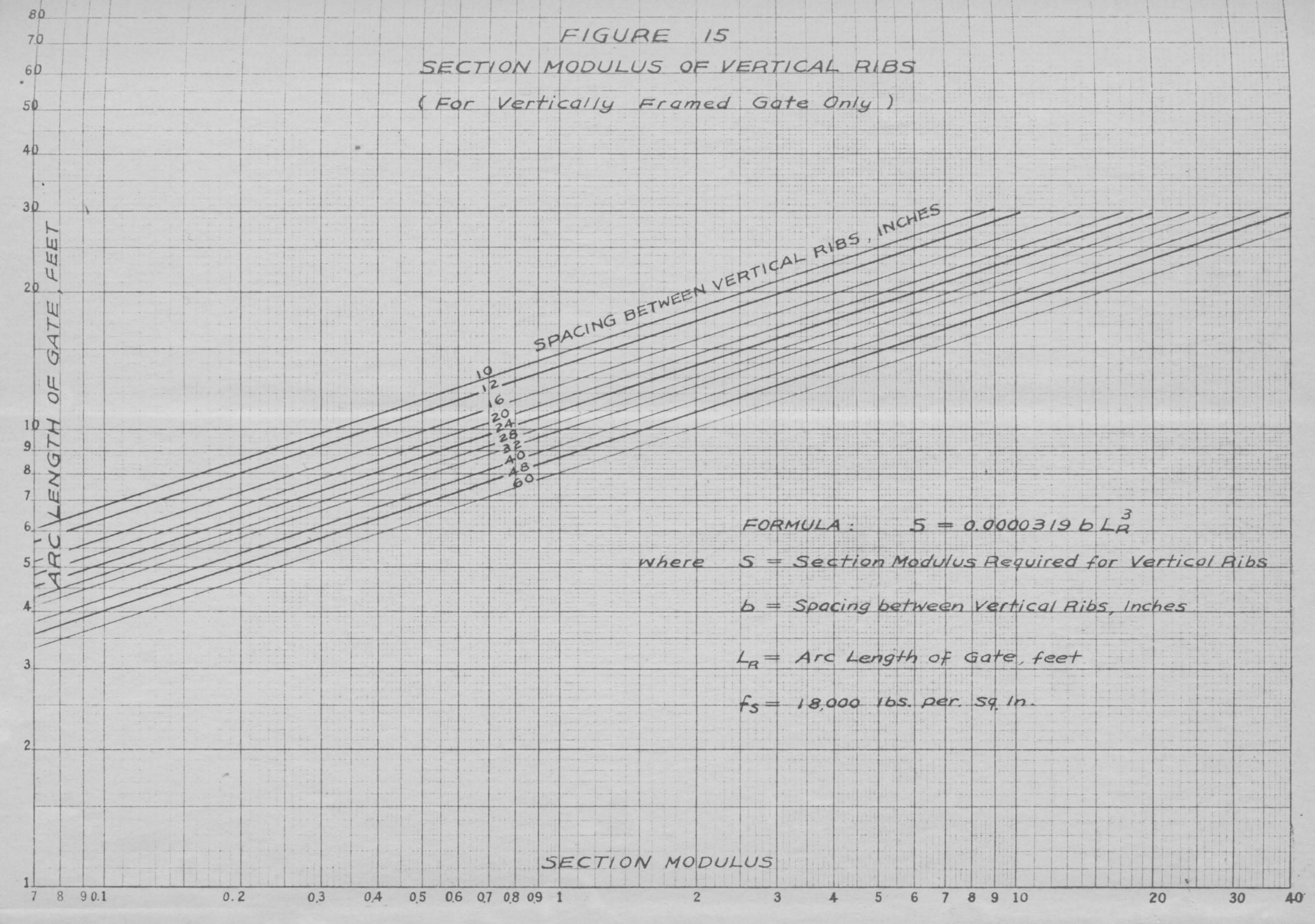


FIGURE 15

SECTION MODULUS OF VERTICAL RIBS

(For Vertically Framed Gate Only)

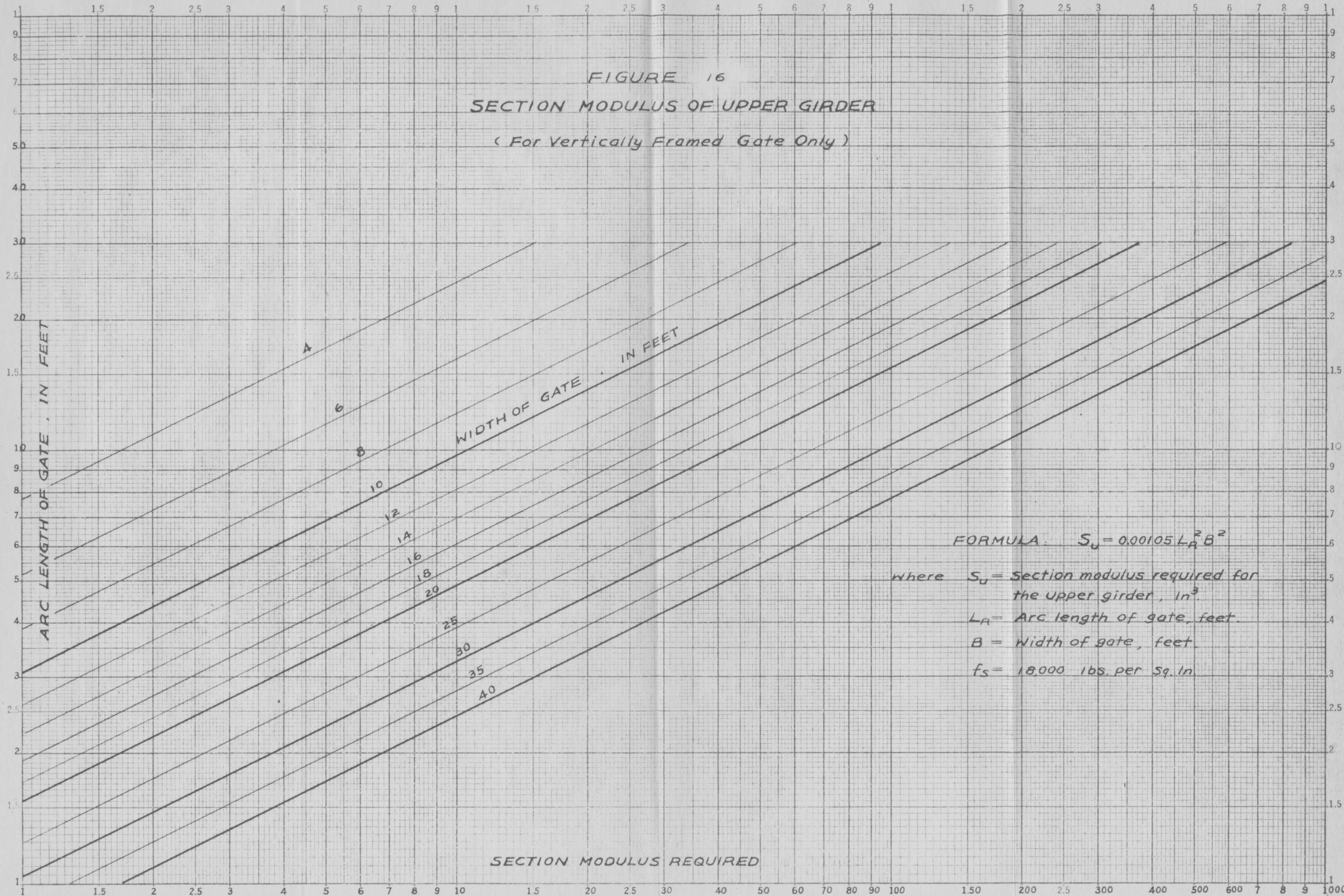


FIGURE 16
SECTION MODULUS OF UPPER GIRDER
(For Vertically Framed Gate Only)
ARC LENGTH OF GATE , IN FEET
SECTION MODULUS REQUIRED
WIDTH OF GATE , IN FEET
4
6
8
10
12
14
16
18
20
25
30
35
40
FORMULA: $S_u = 0.00105\, L_A^2 B^2$
where S_u = Section modulus required for the upper girder, In^3
L_A = Arc length of gate, feet.
B = Width of gate, feet.
f_s = 18,000 lbs. per Sq. In.

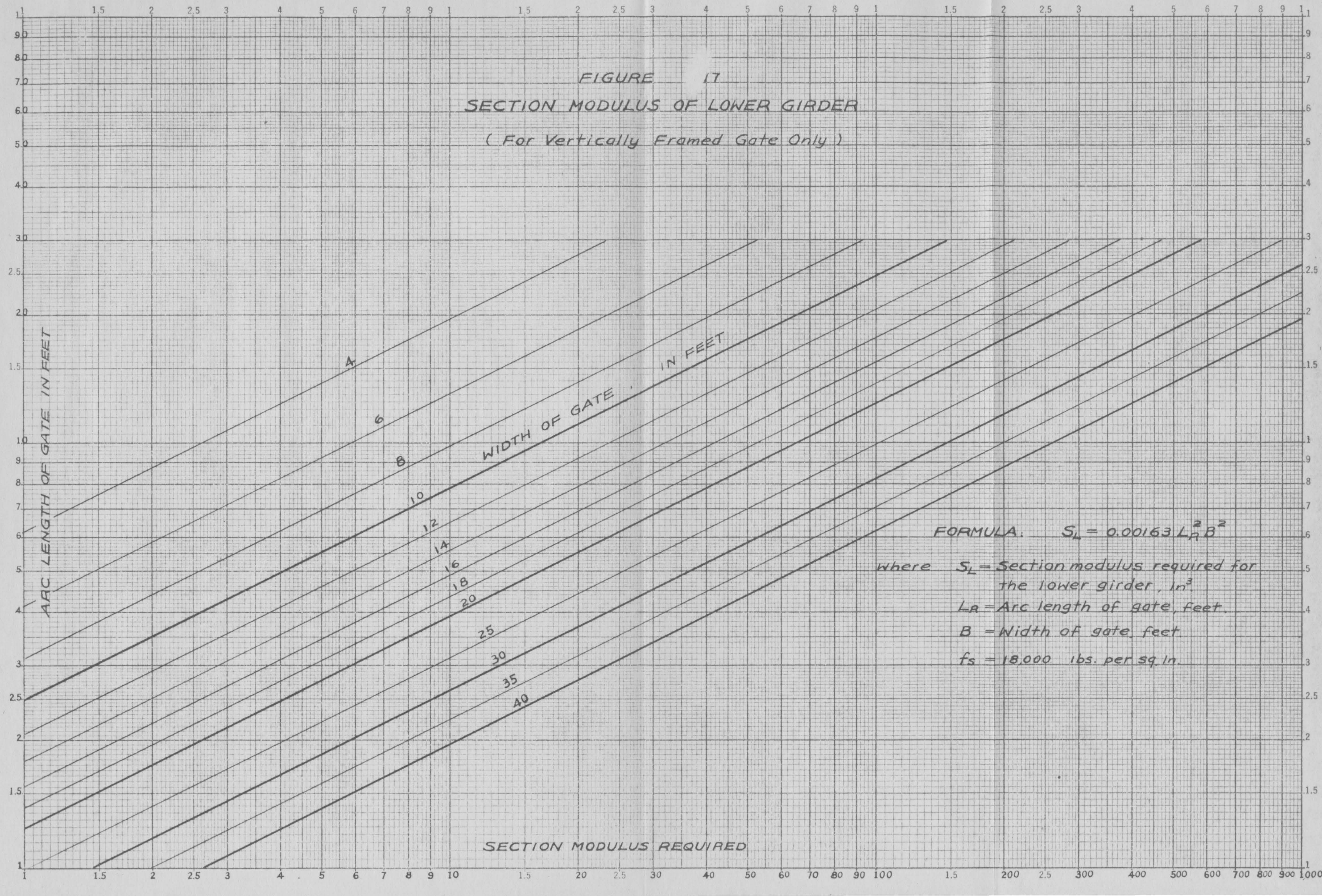


FIGURE 17
SECTION MODULUS OF LOWER GIRDER
(For Vertically Framed Gate Only)
ARC LENGTH OF GATE IN FEET
WIDTH OF GATE, IN FEET
4
6
8
10
12
14
16
18
20
25
30
35
40
FORMULA: $S_L = 0.00163\, L_R^2 B^2$
where S_L = Section modulus required for the lower girder, In^3.
L_R = Arc length of gate, feet.
B = Width of gate, feet.
f_s = 18,000 lbs. per sq. in.
SECTION MODULUS REQUIRED

T H E S I S

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A SYSTEMATIC APPROACH TO THE HYDRAULIC AND STRUCTURAL PRINCIPLES INVOLVED IN THE DESIGN OF LOW-HEAD RADIAL GATE

Submitted by

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In partial fulfillment of the requirements

for the Degree of Master of Science

Colorado A & M College

Fort Collins, Colorado

May, 1947

COLORADO A & M COLLEGE

May 28, 1947

I HEREBY RECOMMEND THAT THE THESIS PREPARED UNDER MY SUPERVISION BY Kuo-chang, Lin

ENTITLED A Systematic Approach to The Hydraulic and Structural principles involved in the Design of Low-head Radial Gate

BE ACCEPTED AS FULFILLING THIS PART OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF Science in Irrigation Engineering

MAJORING IN Irrigation Engineering

CREDITS 9

Robert L. Lewis
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Approved Robert L. Lewis
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Examination Satisfactory

Committee on Final Examination

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Robert L. Lewis

[illegible]
Dean of the Graduate School

Permission to publish this thesis or any part of it must be obtained from the Dean of the Graduate School

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One year's training with the U. S. Bureau of Reclamation has given the writer the golden opportunity to learn the modern practices in the design of radial gates. Acknowledgment is due to Mr. J. Larson and Mr. A. N. Miller, engineers of U. S. Bureau of Reclamation, who gave the writer a great amount of help during the period of training.

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May, 1947

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CHAPTER I - INTRODUCTION

A. Purpose.

The radial gate, or Tainter gate, is so called because its skin plate is formed by a segment of circular curve supported by a framework of horizontal or vertical purlins and stiffeners. The principle is based on the fact that as the skin plate is made concentric with the pin, the resultant of the water pressure will pass through the pin, thus creating no moment to be overcome in hoisting the gate. Because of their simplicity in construction and operation and because they are less expensive, radial gates are now widely used not only for small gates but also for spillway control installations.

No standard method of framing, however, has yet been developed. Review of a large number of radial gate installations reveals a striking diversity of ideas concerning the proper type of framing to employ. Trusses, tied arches, and simple and continuous girders have been used according to the designer's taste. No attempt has as yet been made to isolate the separate factors that are involved in the design of this type of gate, or to correlate these factors in a rational approach to the hydraulic and structural problems involved in design.

The purpose of this thesis is, therefore, to separate the individual factors involved in the problem, to examine each of these factors in light of known physical laws, to develop mathematical equations expressing these laws and their relation to the problem, and to correlate all of these factors in a rational and systematic process of analysis leading to an efficient and economical design.

B. Scope and Limitations

Review of the literature reveals that a radial gate which will serve satisfactorily, may be designed with almost any known type of structural framing. The best design, however, should be the one which is most economical and comparatively easy to fabricate, and which performs the gate function most satisfactorily. No systematic attempt to establish the most efficient type of framing has been made. A number of different types of gates are in use, each type performing its function satisfactorily. The true measure of efficiency of a radial gate is based upon the weight of material in the gate, the cost of fabrication and installation, and the cost of maintenance and operation.

The truss type of framing for supporting skin plate members and for end frames has been used in many installations in the past. It is believed that its use is a carry-over from wooden truss days. Since the truss design of any type requires an excessive amount of design, drafting, fabricating, erecting, inspecting and painting, and since fabricators usually bid higher per pound for truss work than they do for girders, there seems little reason to select trusses for the gate framework.

There is also the case in which additional horizontal supports are used between the vertical ribs with the skin plate spanning in two directions. However, due to the cylindrical curvature and the doubtful action of supports of differing rigidity, the use of plate as a two-way member leads to such complications that the entire design becomes baffling.

The exact method of analysis based on the theory of shells has been presented by Mr. Silverman in "Stresses in Sector Gates."[1] It is based upon the elastic theory of plates and shells and involves the use of mathematics beyond the knowledge of the usual designing engineer. This analysis is tedious and lengthy and therefore prohibitive from the standpoint of design costs.

The scope of this thesis is limited as follows:

1. The study will be limited to low-head radial gates. When gates are used for outlet works or as gate valves in the lock systems subjected to high pressures, the hydraulic problems involved differ considerably and will not be considered in this thesis.

2. Ordinary sizes of radial gates, commonly used for irrigation canal structures, vary from several feet to twenty feet both in height and width. Spillway gates usually range from thirty to forty feet in span as well as in height. It is generally believed that spans greater than sixty feet are not economical. Therefore, this investigation will be limited to heights less than thirty feet and spans less than forty feet.

3. Careful study of existing structures indicates that within the size range stated above, two general types of radial gates are most efficient. These types are the horizontally framed and the vertically framed structure. Only these two types will be investigated.

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[1] Silverman, I. K. Stresses in sector gates. Washington, 1941. 24 p. processed. (U. S. Bureau of Reclamation. Technical memorandum, no. 477.)

4. The allowable stresses for materials used in arriving at sizes of structural members are those specified by the American Institute of Steel Construction.

5. No attempt will be made to specify a particular type of framing or detailed design which will be most efficient and economical in any given set of circumstances. Such a study involves a cost analysis which varies with time and location and is not considered to be within the scope of this thesis.

CHAPTER II - HYDRAULIC PRINCIPLES INVOLVED IN THE ANALYSIS AND DESIGN OF RADIAL GATE

A. General Layout of Radial Gate from the Point of View of Hydraulics.

Three factors control the general layout and shape of a radial gate: the radius of gate, the height of pin and the location of gate sill. The location of gate sill is not a serious problem in ordinary installations, but may introduce serious difficulties when radial gates are to be used on spillway crests. No definite relation between these three factors is apparent. Final design must be a compromise, obtained by careful consideration of the hydraulic and structural principles involved.

1. Radius of Gate.

The radius of curvature not only affects the direction of the upward water pressure, but also has an important bearing on the relative dead load reaction at the trunnion or axis and upon the length and height of the pier and the weight of the struts. The longer the radius, the higher the elevation required for the runway and the larger the pier will be. On the other hand, too short a radius, or too greater an inclination of the chord from the vertical will require a heavier gate and develop complicated problems in the trunnion anchorage caused by the excessive uplift. From an analysis of existing structures, the radius of gate varies from 1 to $\frac{5}{4}$ times the height of gate. The statistical data upon which this statement is based are plotted as shown in Figure 1-a, in Appendix III.

2. Height of Pin.

The pin should be located above the ordinary high water level, and should be high enough to permit the gate to be raised above floating material carried by the extreme flood. But in the case of small gates installed in irrigation canals, where it is not necessary to provide for flood clearance, the pin is normally located between 1/2 - 3/4 of the height of the gate. If the pin is placed too high in relation to the radius and position of the gate, an undesirable uplift pressure in the trunnion anchorage will result. If it is too low, it will decrease the efficiency of the operation of gate. The values of height of pin for the existing structures are plotted in Figure 1-b, in Appendix III. An average value of height of pin equal to 3/4 the height of gate may be used for preliminary layout.

3. Location of the Gate When Used on Spillways.

The principal hydraulic requirements in the design of radial gates on a spillway crest are: that the location of the horizontal seal with respect to the crest of the ogee spillway section should be such as to eliminate any tendency for the water to leave the spillway surface and develop pressures less than atmospheric at partial gate openings; that the gate and its trunnions should clear the upper nappe of the overflowing sheet of water corresponding to the maximum flow, and that the lower edge of the gate should be shaped to aid uniform flow. The first requirement may be met by placing the seal somewhat downstream from the spillway crest. At partial gate openings, the overflowing water will be given a downward velocity component, so that the tendency of the flow to leave the spillway surface and create a negative pressure is minimized. The equation for the trajectory at partial gate openings may be derived as follows:

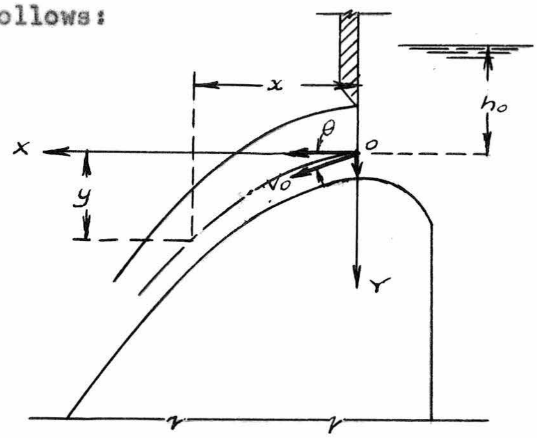


Fig. 2

Let V_o = initial velocity

h_o = head corresponding to the initial velocity

then, $$V_o = \sqrt{2\,g\,h_o}$$

since $$x = V_o t \cos\theta \quad ; \quad t = \frac{x}{V_o \cos\theta}$$

$$y = V_o t \sin\theta + \frac{1}{2} g\, t^2$$

$$= \frac{x \sin\theta}{\cos\theta} + \frac{1}{2} g \left(\frac{x}{\sqrt{2g\,h_o}\,\cos\theta}\right)^2$$

Hence, $$y = x \tan\theta + \frac{x^2}{4h_o \cos^2\theta} \qquad \text{..................(1)}$$

From this equation it is possible to check the flow condition at different gate openings to determine if the flow suits the dam profile. But, from the practical standpoint, the location of gate seal downstream from the spillway crest is limited because the height of gate increases with the distance away from the crest.

In designing radial gates on a spillway crest, various studies should be made with different locations of pin height and bottom seal and different lengths of radius of gate.

Their effects on both the spillway profile during partial gate openings and the vertical uplift acting on the trunnion should be studied. Hydraulic model tests are always helpful in determining the most desirable design.

B. Load Analysis.

The critical position, or loading condition which causes maximum stresses, for a non-submersible radial gate is ordinarily the normal closed position with the upstream face of the gate subjected to pressures caused by a full upper pool and an assumed unwatered downstream side. If the gate is of the overflow type, water loads caused by the weight of the overflowing sheet must be considered in addition to those caused by the static pressure on the upstream side. If the gate is of the submersible type, the critical position cannot be determined by simple inspection because of the flow conditions under and over the gate, but must be found from investigation of resultant loads over the range of possibly critical positions, tailwater considered according to reasonable assumptions.

1. Hydrostatic Pressure.

The hydrostatic pressure acting on the gate under normal closed position may be analyzed by a load diagram as shown in Fig. 3.

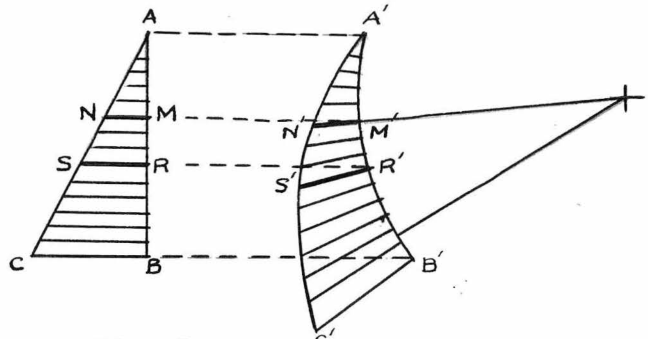


Fig. 3

This figure shows simply the load diagram for a linear foot of gate in the normal closed position, with no backwater and no overflow. The water loads acting radially on the curved back of the gate are represented to some convenient scale by the radial vectors of the load diagram proper, A'B'C', one vector being drawn for each linear unit of curved gate surface. The intensities of the pressure at the various points of application of the vectors, that is, the lengths of the vectors, are determined by the lengths of the horizontal lines at the elevations of these points on the diagram ABC. For instance, M'N' is made equal in length to MN, and R'S' to RS etc.

The total magnitude of hydrostatic pressure acting on the gate may be easily found by the method of integration:

Let ds = any infinitesimal segment of arc along the face of gate.

θ = angle measured from the x-axis to any point p_o along the arc.

p = unit water pressure at any point p_o.

Referring to Fig. 4, then

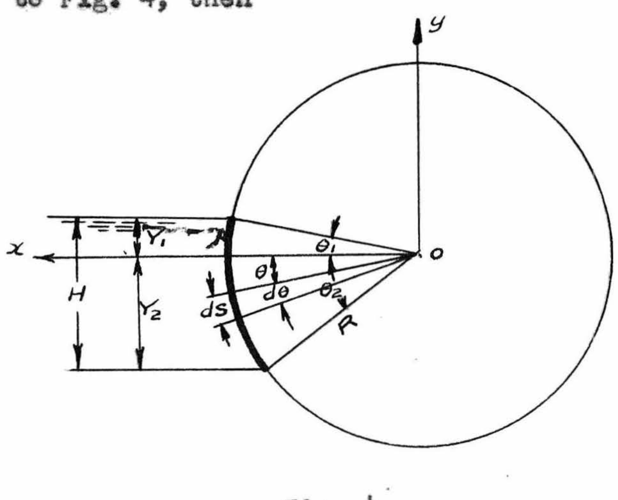


Fig. 4

$$ds = R\,d\theta$$

$$dP_1 = p\,ds = w\,R\,(\sin\theta_1 - \sin\theta)\,R\,d\theta$$

$$= w\,R^2\,(\sin\theta_1 - \sin\theta)\,d\theta$$

$$P_1 = w\,R^2\sin\theta_1\int_{-\theta_2}^{\theta_1} d\theta + w\,R^2\cos\theta\Big|_{-\theta_2}^{\theta_1}$$

$$= w\,R^2\left[\sin\theta_1\,(\theta_1 + \theta_2) + \cos\theta_1 - \cos\theta_2\right]$$

If $Y_2 = 0.75$ H, $R = 1.25$ H,

$$\sin\theta_1 = Y_1/H = 0.20\,; \qquad \theta_1 = \sin^{-1}0.2 = 11^\circ 32'$$

$$\sin\theta_2 = Y_2/H = 0.60; \qquad \theta_2 = \sin^{-1}0.6 = 36^\circ 52'$$

$$P_1 = w\,(1.25\,H)^2\left[0.2\frac{(48^\circ 24')\pi}{180^\circ} + \frac{\sqrt{24}}{5} - \frac{4}{5}\right]$$

$$= 0.349\,(1.25)^2\,w\,H^2 = 0.545\,w\,H^2$$

$$= 34\,H^2 \quad \text{(per unit width of gate)}$$

The pin load, therefore, is;

$$P = 34\,H^2\cdot\frac{B}{2} = 17\,B\,H^2 \quad \text{..................(2)}$$

Therefore, under this special arrangement, the total hydrostatic pressure acting on the gate is equal to $0.545\,w\,H^2$ comparing to the horizontal component pressure of $0.5\,w\,H^2$.

The next problem is to find the direction of the resultant pressure. Referring to Fig. 5, it is found that:

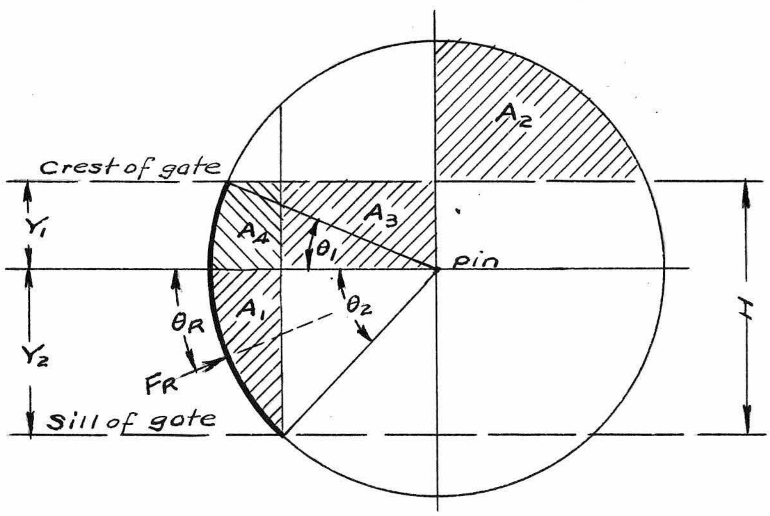


Fig. 5

$$A_1 = \frac{\theta_2}{90}\frac{\pi R^2}{4} - \frac{Y_2}{2}\sqrt{R^2 - Y_2^2}$$

$$A_2 = \frac{90 - \theta_1}{90}\frac{\pi R^2}{4} - \frac{Y_1}{2}\sqrt{R^2 - Y_1^2}$$

$$A_3 = Y_1\sqrt{R^2 - Y_2^2}$$

then, F_v = vertical component of total pressure = $62.4\ (A_1 + A_4)$

$$= 62.4\left(\frac{\pi R^2}{4} - A_2 - A_3 + A_1\right)$$

$$= 62.4\left(\frac{\pi R^2}{4}\frac{\theta_1 + \theta_2}{90} - \sqrt{R^2 - Y_2^2}\,\frac{2Y_1 + Y_2}{2} - \sqrt{R^2 - Y_1^2}\,\frac{Y_1}{2}\right)$$

F_h = horizontal component = $62.4\ \frac{H^2}{2}$

F_R = resultant = $\sqrt{F_v^2 + F_h^2}$

$\theta_R = \tan^{-1}\frac{F_v}{F_h}$

By substituting the values of "R", "Y", "θ_1" and "θ_2", it is found:

$$\theta_R = \tan^{-1}\frac{0.188}{0.5} = \tan^{-1} 0.376 = 20^\circ 36'$$

Hence, if a line is drawn passing through the point of reaction at the trunnion pin by making an angle of $20^\circ 36'$ with the horizontal, its intersecting point with the direction of the horizontal component ($\frac{H}{3}$ distance above the bottom) will give the point of application of the total resultant pressure.

2. Method of Computing the Water Pressure under Partial Gate Openings.

When the gate is in a partially opened position, flow passes through it at very high velocities. Due to the bending of stream lines, the distribution of pressure along the gate no longer follows the hydrostatic law. It can be computed by means of flow nets.

The procedure may be outlined briefly as follows:

1. Draw flow nets by free hand sketching according to the following characteristics: that the stream lines and equipotential

lines should be always perpendicular to each other, that each rectangle they form should have a definite ratio between the adjacent sides, (it is advisable and a common practice to draw the net as a series of curvilinear squares); and that the equipotential lines should be perpendicular to all the boundary lines because the boundaries are alao a part of the stream line system.

b. Compute the discharge under such partial gate openings by the orifice discharge equation.

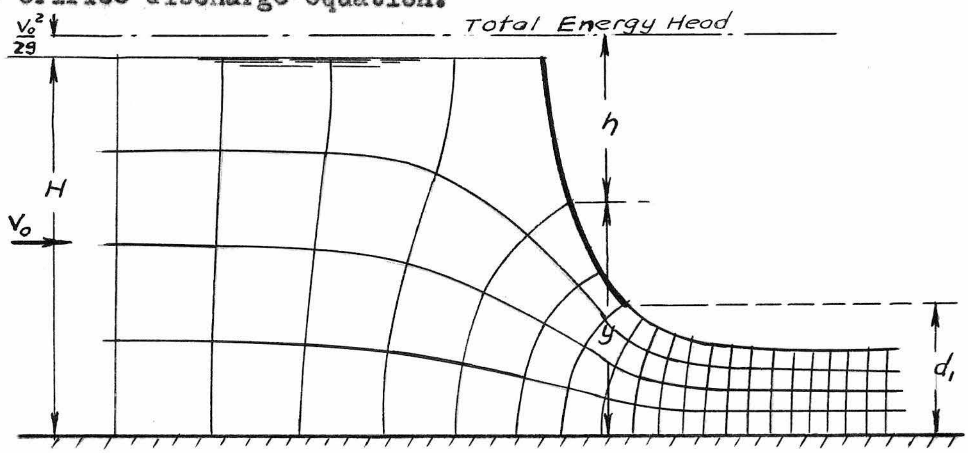


Fig. 6

$$q = c\,d\sqrt{2\,g\,(H - \frac{d_1}{2})} \quad \ldots\ldots\ldots\ldots\ldots\ldots(3)$$

where c discharge coefficient usual varying from 0.6 to 0.7

H upstream head water depth in feet

d_1 depth of gate opening in feet

Hence, velocity head of approach $= \frac{V_o^2}{2g} = \frac{q^2}{2g\,H^2}$, which should be added to the hydrostatic head "H" to give the total energy head.

c. Compute the velocity at points along the gate face.

$$\text{Velocity} = \frac{\text{Quantity of flow in one stream tube}}{\text{The width of stream tube at the point considered}}$$

d. By Bernoullis' theorm:

$$\frac{P}{w} + \frac{V^2}{2g} + y = \frac{V_o^2}{2g} + H$$

$$\frac{P}{w} = (H + \frac{V_o^2}{2g}) - y - \frac{V^2}{2g}$$

$$= h - \frac{V^2}{2g}$$

where h = depth of the point considered below the total energy line

Plot these values at different points along the gate. It is the required pressure diagram under such height of openings.

III. STRUCTURAL PRINCIPLES INVOLVED IN THE ANALYSIS AND DESIGN OF RADIAL GATE - HORIZONTALLY FRAMED

The horizontally framed radial gate is so termed because its skin plate is supported by a series of unequally spaced horizontal beams. Two vertical side beams, supporting these horizontal beams, are in turn supported at each end by side frames, by meams of which the water load is transferred into the piers through the trunnion castings. The complete assembly of a horizontally framed gate, therefore, consists of skin plate, horizontal beams, side beams, pin bearing and bracket, side rollers, seals and wall and sill plates. The individual items will be discussed separately in detail as follows:

A. Skin Plate.

The skin plate is essentially a semi-continous beam running vertically with the horizontal beams acting as supports. There is some arch action in the skin plate due to curvature. However, if the radius is selected in accordance with the principles developed in Chapter II of this thesis, this arch action is so small that may be neglected without introducing any serious error. This assumption will simplify the design and fabrication considerably. Some investigators have attempted to consider the plate as a two-way member by fitting in additional supports. However, due to the cylindrical curvature andthe doubtful action of supports of differing rigidity, it may lead to such complications that the entire design becomes baffling. Paragraph 43 of the "Theory of Plates and Shells" [1] by Timoshenko demonstrates the difficulties of using even a flat plate on supports of varying rigidity.[1] Moreover, fabricators have advised that the cost of a face structure having supports in two directions would be higher by at least 10 percent than that for one with one-way supports. This higher unit cost removes the major incentive for two-way spanning.

The maximum bending moment used for design is:

$$M = \frac{1}{10} W L \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (4)$$

where, M = maximum bending moment for semi-continuous beams

W = total water load on a one-inch strip of plate

L = the distance between the flanges of the horizontal beams in inches

A thickness of face plate is, therefore, selected to give a reasonable spacing of the horizontal beams, usually not less than twelve inches, (15" preferable). The bottom horizontal beam is placed approximately three inches above the gate sill to allow the bottom rubber sealing strip to be bolted to the beam. The beam spacing increases progressively towards the top of the skin plate as the water load decreases, so as to make the skin plate stresses almost uniform in intensity.

From Equation (4), $M = \frac{1}{10} W L$

and, $W = w L; \quad w = 0.434 H$

The resisting moment of the skin plate with a thickness of "t" is $M_R = f_s S = \frac{1}{6} f_s t^2$

By equating these two;

$$10 \; f_s S = w L^2$$

1 Timoshenko, Stephen. Theory of Plates and Shells. New York, McGraw-Hill book co., 1940 (Engineering societies monograph)

$$L = \sqrt{\frac{10 f_s S}{w}} = \sqrt{\frac{10 S \times 18{,}000}{0.434 H}}$$

$$= \sqrt{\frac{414{,}746 S}{H}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (5)$$

If expressed in terms of the thickness of the skin plate, then

$$L = \frac{263 t}{\sqrt{H}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (6)$$

For practical purposes it will make the design more systematic if a system of curves is plotted with "H" as ordinates and "L" as abscissas, and the thickness of skin plate "t" as a parameter as shown in Figure 7, in Appendix III. For any plate thickness thus chosen, the allowable spacing of horizontal beams could be easily determined for different values of "H". The value "t" used in Equation (6) should be the effective thickness. One-sixteenth inch is added to the required effective thickness to compensate for anticipated corrosion.

B. Horizontal Beams.

The horizontal cross beams are designed as uniformly loaded simply supported beams. The maximum bending moment is:

$$M = \frac{1}{8} W' L^2 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (7)$$

where W' = water load per foot length of beam

L = distance between the center line of side beams, ft.

Hence the section modulus required is

$$S = \frac{M}{f_s} = \frac{\frac{1}{8} W' L^2 \times 12}{18{,}000}$$

$$= \frac{W' L^2}{12{,}000} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (8)$$

in which $W' = \frac{w b h}{12}$ $\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (9)$

b = spacing between the horizontal beams in inch

h = average water head acting on the beam, feet.

Equations (8) and (9) are plotted as two families of curves as shown in Figure 8, in Appendix III. If the spacing between the horizontal beams, the average head acting on the beam and the span of the beam are known, the section modulus required may be easily found from these charts.

The reaction of the gate sill (F) upon the lower beam was determined from a number of analyses of gates and is assumed as:

$$F = 0.0376\ W \quad \text{(for full width of gate)}$$

where W is the total water load acting on the gate.

The total load on the lower beam is the summation of the water load and the sill reaction "F". It is desirable for ease of construction to have as few different beam sizes as possible.

C. Side Beams.

The side beams, for ease of construction and assembly with the arms, are of welded steel plates which vary in depth of cross-sections. The theoretical location of the center line of arm connections on the inside of the skin plate is so placed that the negative bending moment of both cantilever sections is equal in magnitude to the maximum positive moment at the central span. Theoretically, this method of arrangement will give the most economical design. The criterion may be derived as follows:

Let U = uniformly increasing load due to depth of water distributed on arc length "L_R".

$$= 62.4\ \frac{H}{L_R} = 62.4\ \frac{H}{1.25\ H}\ \frac{(48^\circ 20')\pi}{180}$$

$$= 62.4 \ / \ 1.057 = 60 \text{ lbs per cu. ft. approximately}$$

Z = distance along arc from the center of upper arm to the section at interior span where vertical shear is equal to zero, in other words, section of maximum moment.

For simplicity, the arc of the face of gate is developed into a straight line and a unit width of gate is taken, as shown in Fig. 9.

<u>Approximate Solution for Equal Moments for two Supports</u>

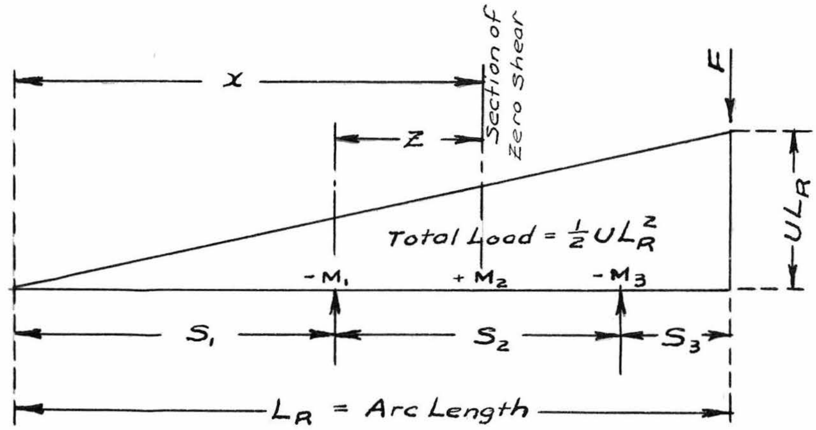


Fig. 9

From figure:

$$M_1 = -U\,S_1\,\frac{S_1}{2}\,\frac{S_1}{3} = -\frac{1}{6}\,U\,S_1^3$$

$$M_2 = R_1\,Z - \frac{1}{6}\,U\,x^3$$

$$M_3 = R_1\,S_2 - \frac{U\,(\,S_1 + S_2\,)^3}{6}$$

Since, by criterion; $-M_1 = +M_2 = -M_3$

$(-M_1) = (M_2)$; $\quad \frac{1}{6}\,U\,S_1^3 = R_1\,Z - \frac{1}{6}\,U\,x^3$

$$R_1\,Z = \frac{U}{6}\,(\,S_1^3 + x^3\,) \quad \ldots\ldots\ldots\ldots\ldots(a)$$

$(-M_1) = (-M_3)$; $\quad -\frac{1}{6}\,U\,S_1^3 = R_1\,S_2 - \frac{U}{6}\,(\,S_1 + S_2\,)^3$

$$R_1\,S_2 = \frac{U}{6}\left[(\,S_1 + S_2\,)^3 - S_1^3\right] \quad \ldots\ldots\ldots(b)$$

Again, by equations of equilibrium:

$\Sigma V = 0$; $\quad R_1 + R_2 = \frac{1}{2}\,U\,L_R^2 + F \quad \ldots\ldots\ldots\ldots\ldots(c)$

$\Sigma M = 0$; $\quad R_1S_2 - \frac{U(S_1 + S_2)^3}{6} = -FS_3 - \frac{US_3^2}{6}\left[2L_R + S_1 + S_2\right]$

$$R_1S_2 = \frac{U}{6}(S_1 + S_2)^3 - \frac{US_3^2}{6}\left[2L_R + S_1 + S_2\right] - FS_3 \quad \ldots\ldots(d)$$

Since shear is zero at section at "Z" distance from the center line of upper arm, it may be written as

$$R_1 = \frac{U}{2}\ (S_1 + Z)^2 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(e)$$

and

$$L_R = S_1 + S_2 + S_3 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(f)$$

We have above altogether six unknowns: S_1, S_2, S_3, R_1, R_2, and Z, but we have six available equations.

After solving these six equations, the following results are found:

$$\begin{array}{rcl} S_1 = 0.3858\ L_R & ; & R_1 = 0.4188\ P \\ S_2 = 0.4912\ L_R & ; & R_2 = 0.6188\ P \\ S_3 = 0.1230\ L_R & ; & -F = 0.0376\ P \\ \hline 1.0000\ L_R & & 1.0000\ P \end{array}$$

where P = pin load for half width of gate.

$$Z = \sqrt{\frac{2R_1}{U}} - S_1 = 0.2613\ L_R$$

Therefore,

$$M_1 = \frac{US_1^3}{6}\ \frac{B}{2} = \frac{U\ S_1^3\ B}{12}\ (\text{ft-lb}) = U\ S_1^3\ B\ \ (\text{in-lb})$$

$$= 3.45\ L_R^3\ B\ \ (\text{in-lbs.})\ \ldots\ldots\ldots\ldots\ldots(10)$$

Section Modulus required $= M_1/f_s$

$$= 0.0001914\ L_R^3\ B \quad \ldots\ldots\ldots\ldots\ldots\ldots(11)$$

which is plotted as shown in Figure 10, in Appendix III.

From this analysis, it is found that the maximum bending moment in the side beam is $M_{max.} = M_1 = M_2 = M_3 = 3.45\ L_R^3\ B$. The theoretical location of the arms is given as a ratio of the length of arc, and these distances are measured along the inside of the face plate. The distance from the gate sill to the center line of lower arm beam connection is $0.1230\ L_R$ and the distance along the inside of the face plate between the center line of the lower and upper arm is $0.4912\ L_R$. The reaction of the center line of the arm connections are given as a ratio of the water load and are 0.6188 P for the lower arm and 0.4188 P for the upper arm. For more than two supports, the same criterion could be used by balancing the moments of two cantilevers and two or more intermediate spans.

Approximate Solution for Equal Moments for Three Supports

After solving 9 simultaneous equations, we get the following results :

$$\begin{array}{llcll} S_1 & = 0.2870\ L_R & ; & R_1 & = 0.2312\ P \\ S_2 & = 0.3650\ L_R & ; & R_2 & = 0.4021\ P \\ S_3 & = 0.2800\ L_R & ; & R_3 & = 0.4167\ P \\ S_4 & = 0.0680\ L_R & ; & -F & = -0.0500\ P \\ \hline & 1.0000\ L_R & & & 1.0000\ P \end{array}$$

Therefore;
$$M_{max.} = \frac{1}{6} U S_1^3 \frac{B}{2} = 1.42\ L_R^3\ B \quad \text{(in-lb)} \quad \ldots\ldots(12)$$
$$P = \frac{U L_R^2}{4} B \quad \ldots\ldots\ldots(13)$$

As the maximum bending moment in the side beams, either for two supports or three supports, is found, it is easy to compute the actual stresses for the section furnished. The stresses in the side beams are usually very low. It is because the size of side beams are not governed by the stresses, but by the requirements such as the minimum thickness of flanges, the depth of web required for connections, etc. The values that are computed from the formula or found by charts in Fig. (10), therefore, serve only as a guide.

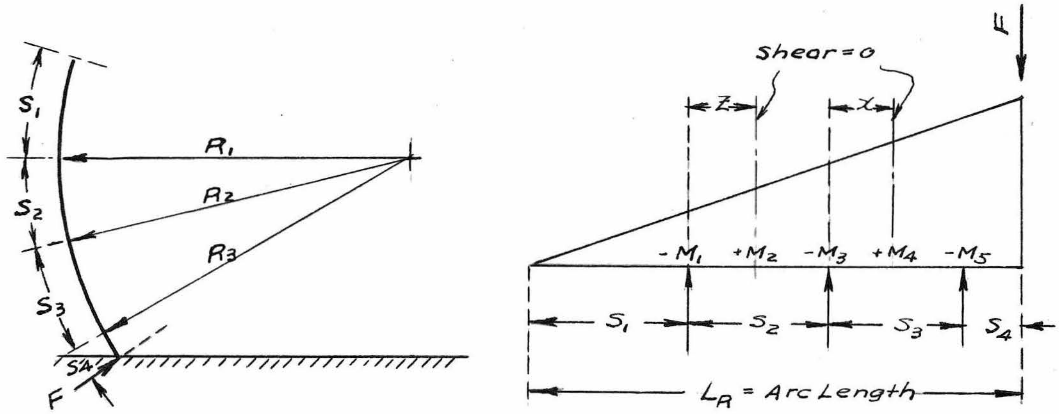


Fig. 11

D. Side Arms.

The arms are fastened to the side beams with rivet bolts to facilitate erection in the field. The arms are designed as columns with L/r ratio not to exceed 120, where r = least radius of gyration. The lower arm carries 0.6188 P, and the upper arm, 0.4188 P. Usually the size of arm is not governed by the direct thrust, but by the least radius of gyration required. In this case, bracings are advisable to use in the plane of arms for lateral supports.

The pin load acts on a radial line through the center line of the pin and normal to a point on the face plate located approximately H/3 above the gate sill ($\theta_R = 20^\circ 36'$). The pin load when water is level with the top of gate under maximum loading condition, may be determined either from Equation (2) or (13). Figure 12 in Appendix III is plotted from Equ. (2) with pin load as the abscissa, height of gate "H" as the ordinate and the width of gate "B" as a variable.

E. Pin Bearings.

The size of pin required depends upon the size of arms and the pin load. The pin is designed both for bearing and bending, and the larger pin size required is selected. For bearing, the diameter of pin required to carry the pin load is

$$D = \frac{P}{3{,}500\ C} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(14)$$

For bending, the diameter of pin required is

$$D = \sqrt[3]{\frac{4\ P\ (\ C + 3\ )}{\pi\ f_s}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(15)$$

where D = diameter of pin in inches

C = width of bracket in inches

Therefore the allowable pin load may be expressed in terms of "D" and "C" as follows:

$$P\ (\text{ for bearing })\ =\ 3{,}500\ C\ D \ \ldots\ldots\ldots\ldots(16)$$

$$P\ (\text{ for bending })\ =\ \frac{4{,}663\ D^3}{0.75 + \frac{C}{4}} \quad \ldots\ldots\ldots\ldots(17)$$

Based on Equation (16) and (17), the allowable pin loads for different sizes of pins and different widths of brackets can be plotted as shown in Figure 13, in Appendix III. It may be noted that for certain size of pin and width of bracket, bearing will control the design while in another combination, bending will be the governing factor. The adopted allowable pin load should be the smaller value.

F. Pin Bearing Bracket.

The pin bearing brackets are designed on the principle that the maximum pressure on the concrete shall not exceed 500 lb. per sq. in. under any load condition.

The thickness of the bracket plate is computed by the bending moment equation:

$$M = \frac{1}{8} P L (1 - 4k) \quad \text{.................}(18)$$

where P = pin load ; $k = \frac{p'}{L}$ (see Fig. 14)

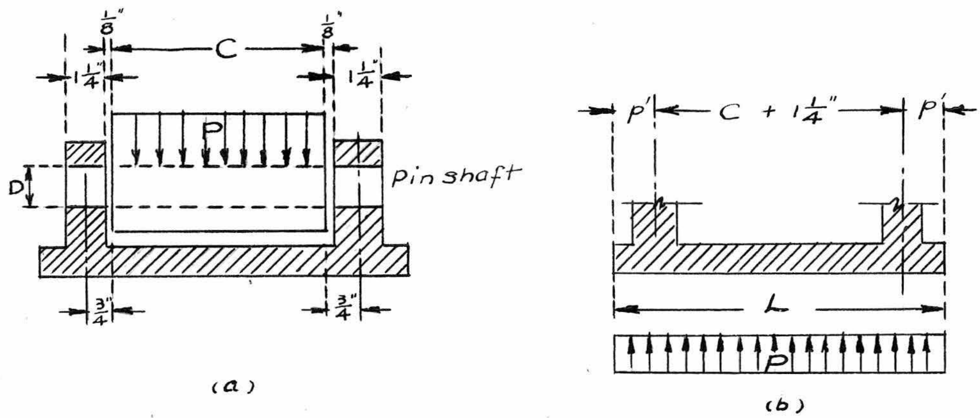


Fig. 14

G. Anchorage.

Since the loads transmitted to the piers by the trunnion pins tend to put the concrete in tension and tear away a part of of the pier, the pin loads must be carried forward into the pier and distributed through bond and bearing by special devices. Radial gates, with the trunnions downstream, are actually uneconomically placed, the strut frames being in compression and the pins tending to put the pier concrete in tension. Lighter struts and simpler pier bearings could be used if the gate were reversed and the trunnions placed upstream. However, no practical method of avoiding serious drift and silt accumulation, preventing the operation of radial gate in the reversed position, has yet been devised.

Anchorage may be classified into two general types. For gates of smaller sizes installed for canal structures, the wall bracket type is commonly used. It is satisfactory as long as the pin load is small. However, for gates installed on spillways with several spans separated by piers, the design of anchorages and piers requires great care and due consideration of the relative elastic properties of steel and concrete. In the past, some radial gates have been supported on trunnion pins which extended through the anchorage members so that one common pin served two gates. This is a costly arrangement as the shears and moments for entire gate are carried by a solid steel forging costing several times as much per pound as ordinary structural steel.

A simple box girder built up of heavy plates welded together will serve the same purpose much more effectively than a through pin and cost a fraction of the price of the solid shaft required for that design. The simplest form of anchorage consists of two rolled or built-up girder beams placed horizontally and welded to the cross-girder. This type should be adequate for all gates of moderate size. The girders are placed so that at least 8 inches of concrete will cover the steel nearest to the face of the piers. The cross-girder may be run through the webs of the anchor girders or any other adequate joint detail may be used. The anchor girders should extend somewhat upstream from the face of the gate and terminate in a heavy horizontal anchor designed to take the entire anchorage tension in bearing on the pier. It should be born in mind that for the condition of one gate fully loaded with the adjacent gate raised, there will be a severe torsion on the frame formed by the cross and anchor girders. For this condition, the tension in the near anchor beam is approximately doubled over its normal value. It is essential, therefore, that the framework be designed to resist both this torsion plus the normal tension, and also all side thrust, and that this stress be taken entirely on the steel itself without dependence on the concrete of the pier in the immediate vicinity of the trunnion.

IV. STRUCTURAL PRINCIPLES INVOLVED IN THE ANALYSIS AND DESIGN OF RADIAL GATE - VERTICALLY FRAMED

A vertically framed radial gate consists of curved vertical ribs to support the skin plate, horizontal cross-girders and side frames transferring the thrust through the trunnion castings to the pier.

A. Skin Plate.

Skin plate is designed as continuous beams with each span equal to the spacing between vertical ribs. For simplicity, the formula, $M = \frac{1}{12} W b$, is used, where "b" is the distance from center to center of vertical ribs instead of measuring from flange to flange as in Equation (6). The required thickness of plate varies from top to bottom according to the intensity of pressure to obtain a better distribution of stress. In practice, three or four changes in thickness of plate are not uncommon. When link or stud-link hoisting chain is used, it is essential that the skin plate be reinforced along the line of chain contact.

B. Vertical Ribs.

The vertical ribs are usually angles or channels, determined in spacing by the desirable skin plate thickness and the load to which the plate is subjected.

The basic assumption is that the curved vertical ribs act as beams simply supported by the horizontal cross girders. Although there is considerable rigidity at the joints between the ribs and girders, yet they are not sufficiently restrained in the usual design to act as arches. The stresses in the ribs actually should be somewhere between that of simple beams and the arches. Therefore, the design in accordance with the simply supported beam assumption is not altogether exact, but it is reasonably so, and, of course, has the merit of being conservative.

Moreover, since the radius of curvature of the ribs is generally quite large compared to the depths of the ribs themselves, the increase in compressive stresses in bending caused by the curvature is usually so slight as to be disregarded.

The same principle as used in the design of side beams for horizontally framed gate, will also be applied here by placing the horizontal girders at such places that the negative moments at two supports will be equal in magnitude to the positive moment at the interior span.

Let b = spacing between vertical ribs in inches

then $$M_{max.} = \frac{1}{6} U S_1^3 b = \frac{1}{6} U (0.3858 L_R)^3 b$$

$$= 0.575 L_R^3 b$$ (for two supports expressed in in-lb)

$$S = \frac{M}{f_s} = \frac{0.575}{18,000} L_R^3 b = 0.0000319 L_R^3 b \quad ....(19)$$

which is plotted as shown in Figure 15, in Appendix III.

But for gates of larger size, the use of two-strut side frames may not be rigid enough, because it has long cantilevered sections. In this case three strut side frames will be preferable, and the cantilevers at the top of the gate should be stiffened to reduce the stresses due to lateral deflection. The method of analysis for vertical ribs when three-strut side frames are used, has already been presented in Chapter III. For statically indeterminate continuous structures, the method of moment distribution may provide a precise solution with relatively simple computations.

C. Horizontal Cross-girders.

The horizontal cross-girder may be of standard I-beam, built-up girder, or truss, depending upon the amount of water pressure to which it is subjected and the span of the gate.

The horizontal girders, once the rib reactions have been determined, may easily be analyzed as beams simply supported by the struts. In the case where two horizontal girders are used, the reactions of the vertical ribs may be found by the criterion developed in Chapter III.

$$R_U = 0.4188 \left(\frac{1}{2} U L_R^2 \right) b$$

$$R_L = 0.6188 \left(\frac{1}{2} U L_R^2 \right) b$$

The vertical ribs are so spaced so closely that these concentrated loads may be replaced by an equivalent uniform load without introducing much error; that is

$$W_u = R_U / b = 0.4188 \left(\frac{1}{2} U L_R^2 \right) = 12.6 L_R^2 \quad \text{lbs. per ft.}$$

$$W_L = R_L / b = 0.6188 \left(\frac{1}{2} U L_R^2 \right) = 19.6 L_R^2 \quad \text{lbs. per ft.}$$

Therefore, for the upper girder:

$$M_U = \frac{1}{8} W_U B^2 \times 12 = \frac{1}{8} 12.6 L_R^2 B^2 \times 12 = 18.9 L_R^2 B^2 \quad \text{in-lbs.}$$

$$S_U = M_U / f_s = 0.00105 L_R^2 B^2 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (20)$$

For the lower girder:

$$M_L = \frac{1}{8} W_L B^2 \times 12 = \frac{1}{8} 19.6 L_R^2 B^2 \times 12 = 29.4 L_R^2 B^2$$

$$S_L = M_L / f_s = 0.00163 L_R^2 B^2 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (21)$$

Equations (20) and (21) are plotted as shown in Figure 16 and 17 respectively, in Appendix III. Experience has shown that two horizontal girders should be used for gate height up to 25 feet, three girders, from 25 feet to 35 feet, and four or more for deeper gates. It is desirable to keep the number of these frames at a minimum to simplify construction and facilitate painting and other maintenance.

The plane of the arms may be swung inward from the pin to intersect the gate face approximately at the outer fifth-points. The arrangement effects considerable reduction in the weight of the horizontal members by converting them into one fixed and two cantilever beams of equal bending moment and at the same time removes the arms from ice danger. But the anchorage must be designed for the lateral thrust thus generated due to the sloping side frames.

D. The principles involved in the design of struts, pin bearings, and anchorages are the same as for the horizontally framed radial gate. Hence it will not be repeated here.

V. CONCLUSIONS

The individual factors which must be considered in the design of radial gate are (1) the proper radius of gate; (2) the height of pin with respect to the total height of gate; (3) the hydrostatic pressure involved; (4) the hydrodynamic pressure involved; (5) the general type of framing to be used; and (6) the principles of design of the structural elements involved including the skin plate, the structural support for the skin plate, the side frames which permit rotation of the gate, and the trunnion pins and anchorage which support the entire gate structure.

Determination of the proper radius of gate and the height of pin are functions of the total height of the gate. Local circumstances peculiar to each gate installation play an important part in determining the proper values of these two quantities. A critical study of existing installations which have been proven most satisfactory show a very definite relationship between the height of gate and each of these factors. The relations are presented graphically in Figure 1-a and 1-b.

The necessary size and strength of the individual structural elements comprising the gate are dependent upon the hydrostatic pressures, the hydrodynamic pressures and the general type of framing to be used. They are also closely interrelated so that no one element can be designed without consideration of the other elements. The thickness of the skin plate is a function of the hydrostatic and hydrodynamic pressures and the spacing of the primary members. The relationship of these factors is presented in Figure 7. Size and strength of the primary members is a function of the hydraulic pressures, the type of framing used, the width of gate and the spacing between these members. The relationship of these factors is presented in Figure 9, 10, 15, 16, and 17. The size of side frames and trunnion pins is a function of the hydraulic pressures and the height and width of the gate. The relationship of these factors is presented graphically in Figure 12 and 13.

The graphically representations presented in the figures mentioned above make it possible to determine the effect of each of these factors involved in the problem upon all of the other factors. With these data, it is possible for the designer to approach each individual problem systematically, to make a preliminary design for each of the two types of framing discussed in the thesis, to compare them and select the one best suited to his needs quickly and easily and with due consideration for all the pertinent factors. To illustrate the use of these charts, examples of their use in design are presented in the Appendix II.

APPENDIX I

NOTATIONS AND DESIGN DATA

A. Notations.

The symbols introduced in this paper are defined as follows :

b	= spacing between the members supporting the skin plate in inches.
B	width of gate in feet.
C	width of pin bracket in inches.
D	diameter of pin in inches.
f_s	allowable working stresses in lb. per sq. in.
F	assumed reaction of gate sill = 0.0376 W (for full width of gate.)
H	height of gate or head in feet.
L_R	length of arc for radius R, expressed in feet.
P	pin load in pounds.
R_1, R_2	reactions of arms.
S	section modulus in cubic inches.
w	unit weight of water = 62.4 pounds per cu. ft.
W	total water pressure acting on gate.
Y	height of pin in feet.

B. Design Data.

			allowable stress ($lb./in.^2$)
Skin plate	bending	....	18,000
Rolled sections	bending	....	18,000

		allowable stress ($lb./in.^2$)
Rolled sections	shear .... $\frac{V}{A} = \frac{(8,000)^2}{(\frac{h}{t})^2}$	
	with a maximum of	13,000
Pin (S.A.E. 1045)	bending	23,750
	shear	14,000
	bearing on bronze bushing	3,500
Bracket	tension	14,000
	compression	14,000
	shear	10,000
	bearing	14,000
Cast steel castings	....	10,000
Anchor bolts	....	6,000
Bearing on concrete	$0.25\ f_c'$	500
Arms	compression	

For axially load, columns with values of L/r not greater than 120 .... $17,000 - 0.485 \frac{L^2}{r^2}$

Seal friction 40 lb. per foot of seal strip.

Minimum thickness of face plate = $\frac{1}{4}''$, allowing $\frac{1}{16}''$ for corrosion.

APPENDIX II

EXAMPLES OF DESIGN

Given Data :

Height of gate = 20 feet

Width of gate = 16 feet

A. Horizontally Framed.

1. Skin Plate.

Use $\frac{5''}{16}$ skin plate, allowing $\frac{1''}{16}$ for corrosion, the effective thickness of skin plate $= \frac{1''}{4}$.

2. Determine the Spacing Between Horizontal Beams.

Since H = head = 20'

From Fig. 1-a and 1-b,

Y = height of pin $= \frac{3}{4} H = \frac{3}{4} \times 20 = 15'$

R = radius to inside of skin plate

$= 1.25\,H = 1.25 \times 20 = 25'$

then,

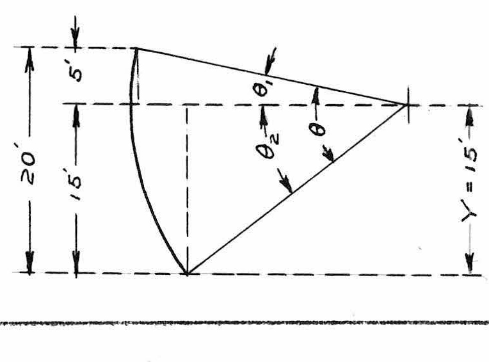
$$\sin \theta_1 = \frac{5}{25} = \frac{1}{5}$$

$$\theta_1 = \text{arc}\sin \frac{1}{5} = 11^\circ\ 32'$$

$$\sin \theta_2 = \frac{15}{25} = \frac{3}{5}$$

$$\theta_2 = \text{arc}\sin \frac{3}{5} = 36^\circ\ 52'$$

$$\theta = \theta_1 + \theta_2 = 48^\circ\ 24'$$



L_R = length of arc = θR

$$= \frac{48^\circ\ 24'}{180} \times \pi \times 25 = 21.12' = 21' - 1\tfrac{1}{8}"$$

Plot the profile of gate and use Equation (8), or the charts in Fig. 7 in Appendix III as a guide, determine the most desirable arrangement for horizontal beams. After several trials, the spacing used, from bottom to top, are 21", 22", 23", 24", 25", 26", 28", 32" respectively. The bottom beam is placed $5\frac{3}{4}"$ above the gate sill to allow the rubber seal to be bolted to the beam, and the span of top portion is $3' - 10\frac{3}{4}"$.

3. Design of Sizes for Horizontal Beams.

Bottom Beam :

The water head acting on the center of beam = 19.58'

Total water pressure on beam = $19.58 \times 62.4 \ \frac{5.75 + 10.5}{2}$

= 1,660 lb. per ft. width

Beam span from C. to C. of side beam = 16' − 17" = 14.6'

M_1 = bending moment due to water pressure = $\frac{1}{8} w L^2$

$$= \frac{1}{8} \times 1{,}660 \times 14.6^2 \times 12 = 531{,}000 \text{ "\#}$$

The reaction of gate sill = 0.0376 W

$$= 0.0376 \left(\frac{1}{2}\, 60 \times 21.12^2 \right)$$

= 503 # per ft. width.

M_2 = bending moment due to sill reaction

$$= \frac{1}{8} \times 503 \times 14.6^2 \times 12 = 161{,}000 \text{ "\#}$$

Total moment = $M_1 + M_2$ = 531,000 + 161,000 = 692,000 "#

Use 12WF 31, section modulus furnished = 39.4 in.^{3}

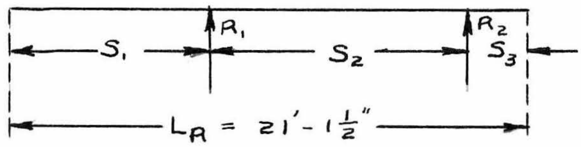
$$f_s = \frac{M}{S} = \frac{692{,}000}{39.4} = 17{,}300 < 18{,}000 \ \#/\text{in.}$$

For other beams, the method of design is just the same.

Hence it will not be repeated here.

4. Design of Side Beam.

Assume two-arm side frames are used.

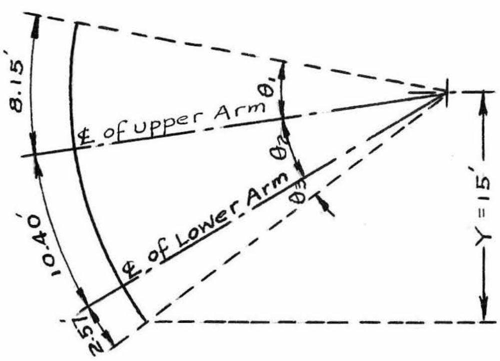


From the criterion developed in Chapter III :

$S_1 = 0.3858\ L_R = 0.3858 \times 21.12 = 8.15'$

$S_2 = 0.4912\ L_R = 0.4912 \times 21.12 = 10.40'$

$S_3 = 0.1230\ L_R = 0.1230 \times 21.12 = 2.57'$



$$\theta_1 = \frac{S1}{R}\ \frac{180}{\pi} = \frac{8.15 \times 180}{25 \times \pi} = 18^\circ\ 40'$$

$$\theta_2 = \frac{S2}{R}\ \frac{180}{\pi} = \frac{10.40 \times 180}{25\pi} = 23^\circ\ 47'$$

$$\theta_3 = \frac{S3}{R}\ \frac{180}{\pi} = \frac{2.57 \times 180}{25\pi} = 5^\circ\ 55'$$

From Equation (10);

$M_{max.} = U\ S_1^3\ B = 60 \times 8.15^3 \times 16 = 519{,}000$ "#

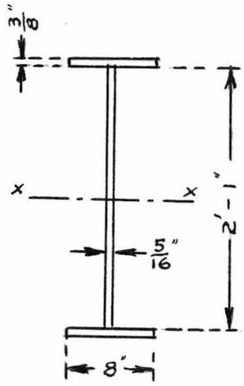
Section modulus required $= \dfrac{M}{f_s}$

Section modulus required $= \frac{519{,}000}{18{,}000} = 28.8$ in.^{3}

Or by Fig. 10, for $L_R = 21.12'$, $B = 16'$, same result is found.

Use $8'' \times \frac{3}{8}''$ plate as flanges; and $\frac{5}{16}''$ plate for web.

From Fig. 18, the depth of side beam at the support = 2'-1"



Find I_{x-x} :

Flanges; $2 \times 8 \times \frac{3}{8} \times (12\ \frac{11}{16})^2 = 968$

Web: $\frac{1}{12} \times \frac{5}{16} \times 25^3 = 407$

I_{x-x} .... 1375 in.^{4}

Section modulus furnished = 106.75 in.^{3}

> 28.8 in.^{3} as required.

Check for shear :

$F = 0.0376\ W = 503$ # per ft. width of gate.

$= 503 \times 8 = 4024$ # for half width of gate.

Water load from bottom to the center line of R_2

$$= 60 \times 8 \times \frac{18.52 + 21.12}{2} \times 2.57 = 24{,}580\ \#$$

$R_2 = 0.6188\ P = 0.6188 \times 8 \times 13{,}380 = 66{,}240$ #

Maximum shear at $R_2 = R_2 - (4{,}024 + 24{,}580) = 37{,}636$ #

The allowable shear = web area x allowable unit shearing stress $= \frac{5}{16} \times 25 \times 10{,}000 = 78{,}000 > 37{,}636$ #/in.^{2}

$$\left(\text{For } \frac{h}{t} = \frac{25''}{\frac{5}{16}} = 80;\ \frac{V}{A} = 10{,}000\ \#/\text{in.}^2\right)$$

5. Design of Arms.

P = total water pressure acting on side beam

$$= \frac{UL_R^2}{4} B = \frac{60 \times 21.12^2 \times 16}{4} = 107{,}048\ \#$$

Same result is found from Fig. 12 for H = 20', B = 16'.

R_1 = reaction of upper arm = 0.4188 P = 44,832 #

R_2 = reaction of lower arm = 0.6188 P = 66,240 #

For economy ~~design~~, bracings are here used in order to reduce the unsupported length of the arm. From Fig. 18, the unsupported length of arm = 11'-10 $\frac{7''}{16}$. Since maximum ratio of L/r = 120, the least radius of gyration of "r" required = $\frac{L}{120}$ $= \frac{11.87 \times 12}{120} = 1.19$ in.

The allowable compression stress, $f_c = 17{,}000 - 0.485 \left(\frac{L}{r}\right)^2$

$$= 17{,}000 - 0.485\,(120)^2 = 10{,}030 \ \#/\text{in.}^2$$

Area of arms required $= \frac{66{,}240}{10{,}030} = 6.60$ in.^{2}

use 8 WF 31 rolled sections, which give area = 9.12 in.^{2} ; r = 2.01".

Same size of beam will be used for the upper arm.

6. Design of Pin Bearings.

The total water load acting on pin = P = 107,048 #

From Equation (14) by using C = 9.0"

$$D = \frac{P}{3{,}500\ C} = \frac{107{,}048}{3{,}500 \times 9.00} = 3.4''$$

From Equation (15);

$$D = \sqrt[3]{\frac{4P\,(3 + C)}{\pi f_s}} = \sqrt[3]{\frac{107{,}048\,(3 + 9.0)}{0.7854 \times 23{,}750}}$$

$$= 4.1''$$

D = diameter of pin = 5 $\frac{3}{4}$" will be used.

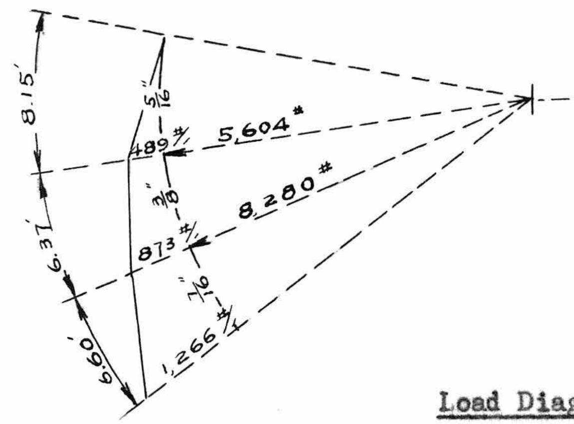
From Fig. 13, for D = 5 $\frac{3}{4}$" , C = 9.0", the allowable pin load = 181,000 > 107,048 #.

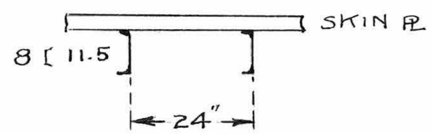
For details and method of connections, see Fig. 18.

B. Vertically framed.

1. Design of Skin Plate.

Assume three different thicknesses of plate are used from top to bottom of the gate. Their arrangements and load diagram used in design are as shown in the following figure.





Load Diagram

Assume the spacing between the vertical ribs supporting the skin plate $= b = 24"$

For 7/16" skin plate:

$$M = \frac{1}{12} w b^2 = \frac{1}{12} \left(\frac{60 \times 21.12}{144}\right) \times 24^2 = 417 \text{ "\#}$$

Section modulus furnished, allowing 1/16" for corrosion

$$= \frac{1}{6} t^2 = \frac{1}{6} x\left(\frac{3}{8}\right)^2 = 0.0234 \text{ in}^3.$$

$$f_s = \frac{417}{0.0234} = 17{,}800 \text{ lbs. per sq. in.} < 18{,}000$$

For 3/8" skin plate:

$$M = \frac{1}{12} \left(\frac{60 \times 14.52}{144}\right) \times 24^2 = 290 \text{ "\#}$$

$$\text{Sec. modl furnished} = \frac{1}{6} \left(\frac{5}{16}\right)^2 = 0.0163 \text{ in}^3.$$

$$f_s = \frac{290}{0.0163} = 17{,}800 \text{ lbs. per sq. in.} < 18{,}000$$

For 5/16" skin plate:

$$M = \frac{1}{12} \left(\frac{60 \times 8.15}{144}\right) \times 24^2 = 163.5 \text{"\#}$$

$$\text{Sec. mod. furnished} = \frac{1}{6} \left(\frac{1}{4}\right)^2 = 0.01042 \text{ in}^3.$$

$$f_s = \frac{163.5}{0.01042} = 15,700 \text{ lbs. per sq. in.} < 18,000$$

<u>2. Design of Vertical Ribs.</u>

$M_{max.} = 0.575\ L_R^3\ b = 0.575\ (21.12)^3 \times 24 = 130,000$ "#

Section modulus required $= \frac{130,000}{18000} = 7.22$ in^3.

From Fig. 15, same results is also found.

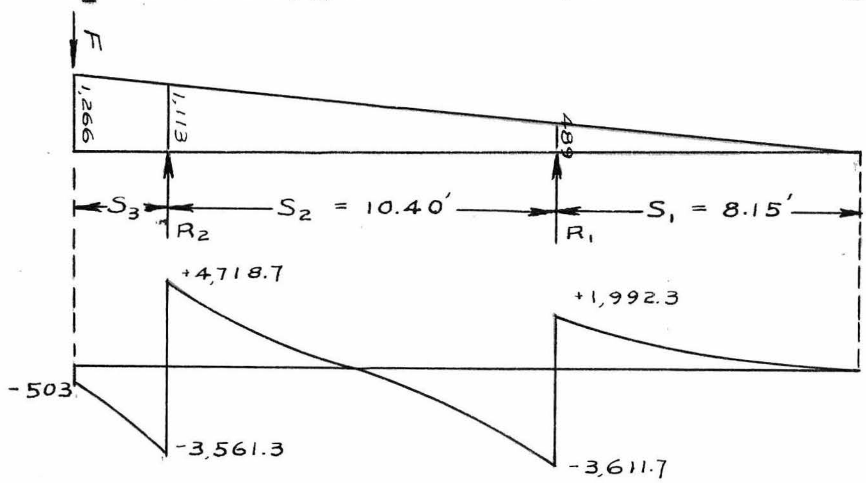
Use 8 [11.5; S furnished = 8.1 in^3.

Check shear:

$F = 0.0376\ W = 503$ lbs. per foot width of gate

$R_1 = 0.4188 \times 13,380 = 5,604$ lbs per foot width of gate

$R_2 = 0.6188 \times 13,380 = 8280$ lbs per foot width of gate



<u>Shear Diagram</u>

(1' spacing of beam)

Maximum shear for vertical ribs = $4,718.7 \times 2 = 9,437.4$ #

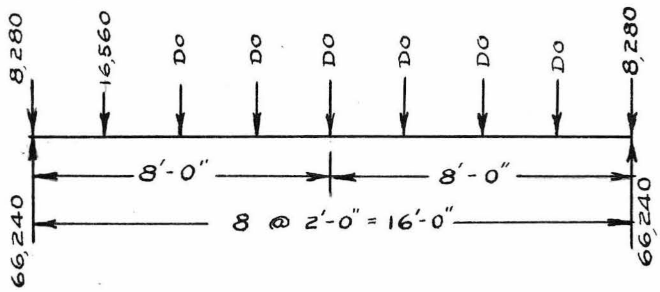
Shear on web $= \frac{9,437.4}{0.22 \times 6.375} = 6,750$ lbs per sq. in.

For $\frac{h}{t} = \frac{6.375}{.22} = 29$, the allowable shearing stress is equal to 13,000 lbs. per sq. in. which is greater than 6,750.

<u>3. Design of Horizontal Cross-girders.</u>

Lower girders:

Vertical ribs reaction = 8,280 x 2 = 16,560 #



Maximum moment = (66,240 - 8,280) x 8 - 16560(2+4+6)

= 463,680 - 198,720 = 264,960 '#

Section modulus required = $\frac{264,960 \times 12}{18,000}$ = 176.6 in^3.

Or from Fig. 17, for L_R = 21.12', B = 16', same result is found.

Use 21 WF 89; S furnished = 182.8 in^3.

Shear on web = $\frac{57,960}{.537 \times 18}$ = 6,000 < 13,000 lbs. per sq.in.

Upper girder:

Vertical rib reaction = 5,604 x 2 = 11,208 #

Max. moment = (44,832 - 5,604) x 8 - 11,208(2 + 4 + 6)

= 179,328 '#

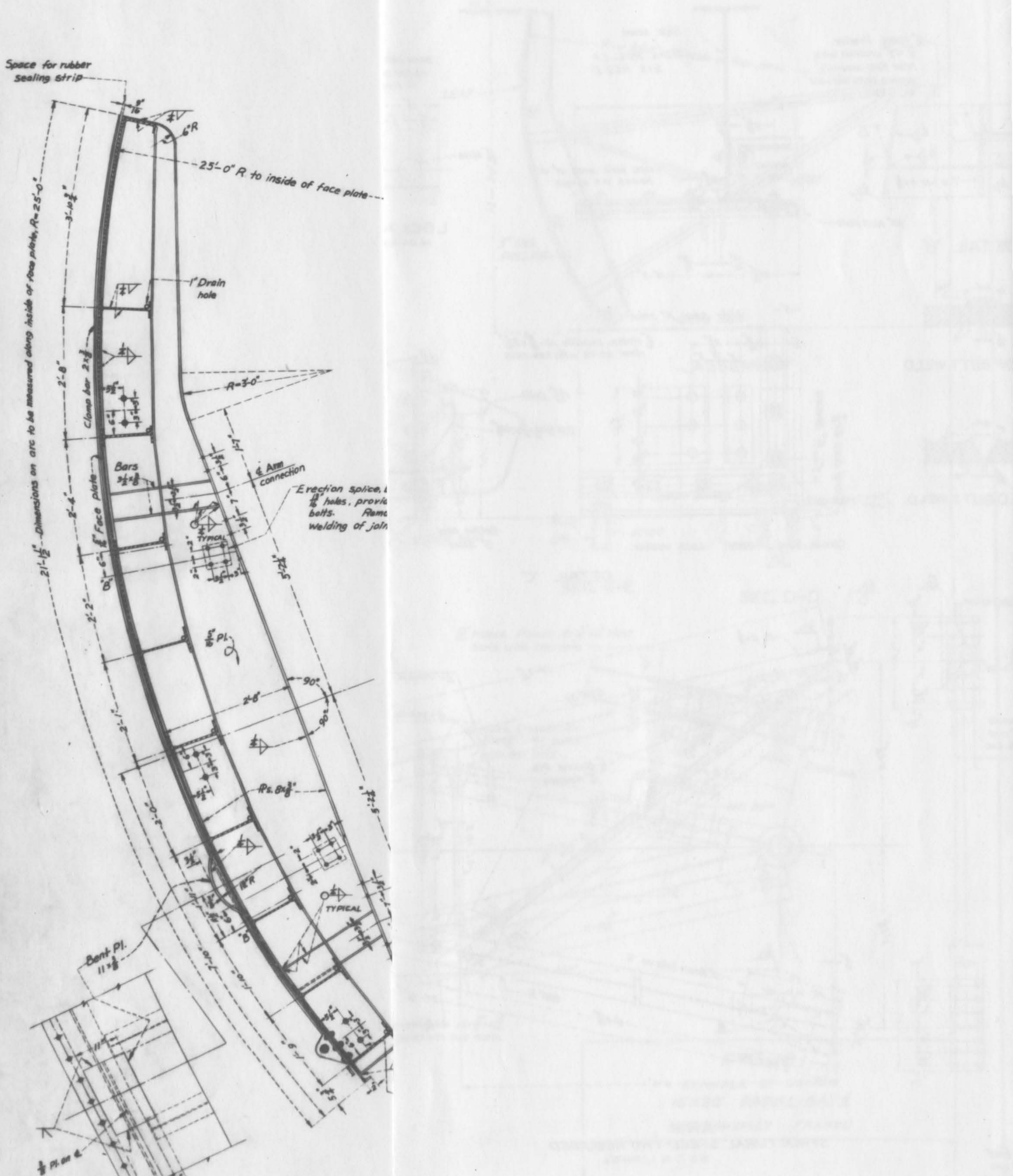
Section modulus required = $\frac{179,328 \times 12}{18,000}$ = 119.5 in^3.

which is also found by means of Fig. 16.

Use 21 WF 63; S furnished = 128.0 in^3.

Shear on web = $\frac{39,228}{0.410 \times 18.625}$ = 5,150 < 13,000 #/in^2.

The design of arms, pin bearings and bracket are the same as for the horizontally framed radial gate.



SECTION A-A

STRUCTU

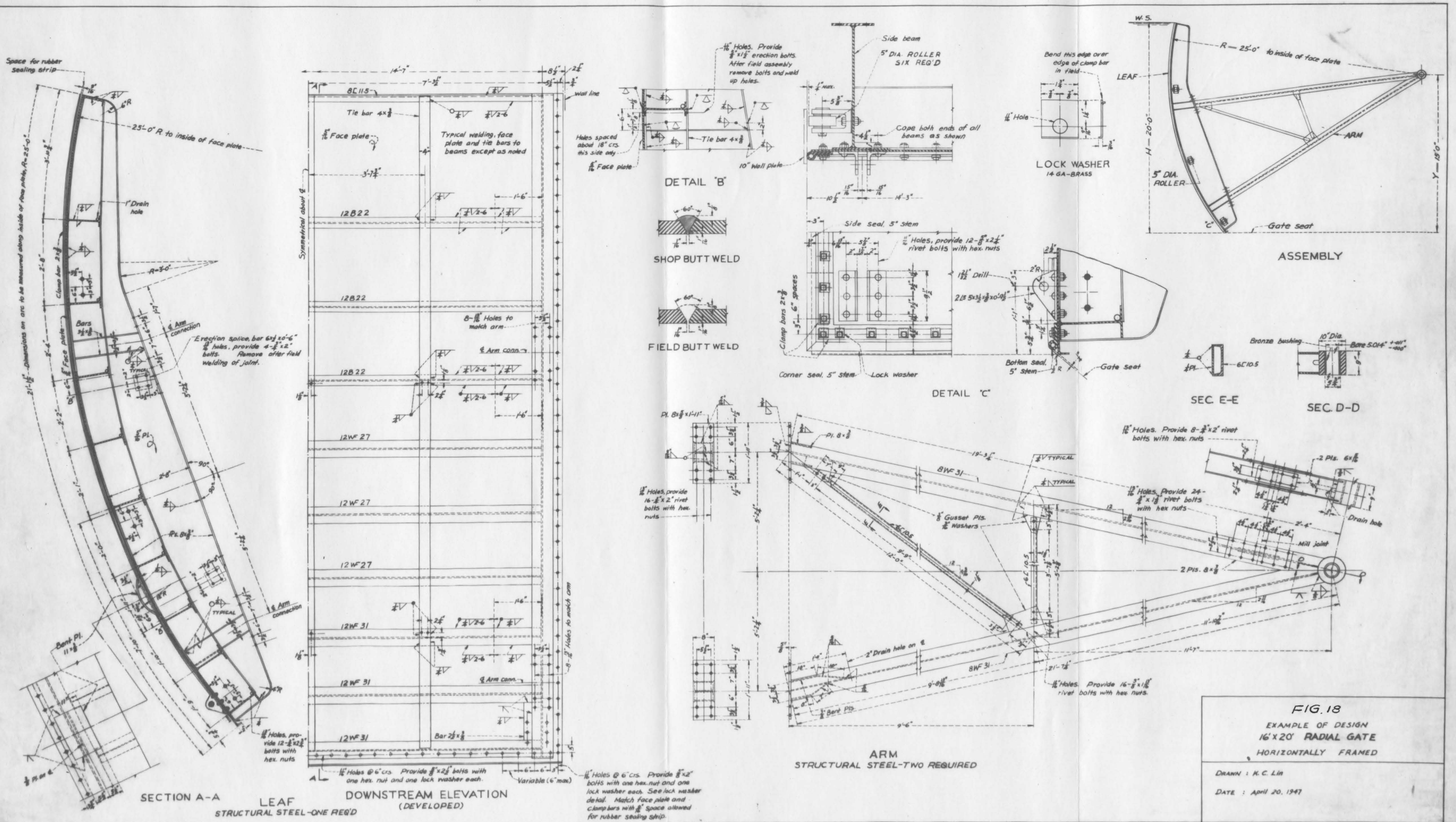


FIG. 18

EXAMPLE OF DESIGN

16'×20' RADIAL GATE

HORIZONTALLY FRAMED

DRAWN : K. C. Lin

DATE : April 20, 1947

APPENDIX III

DESIGN CHARTS

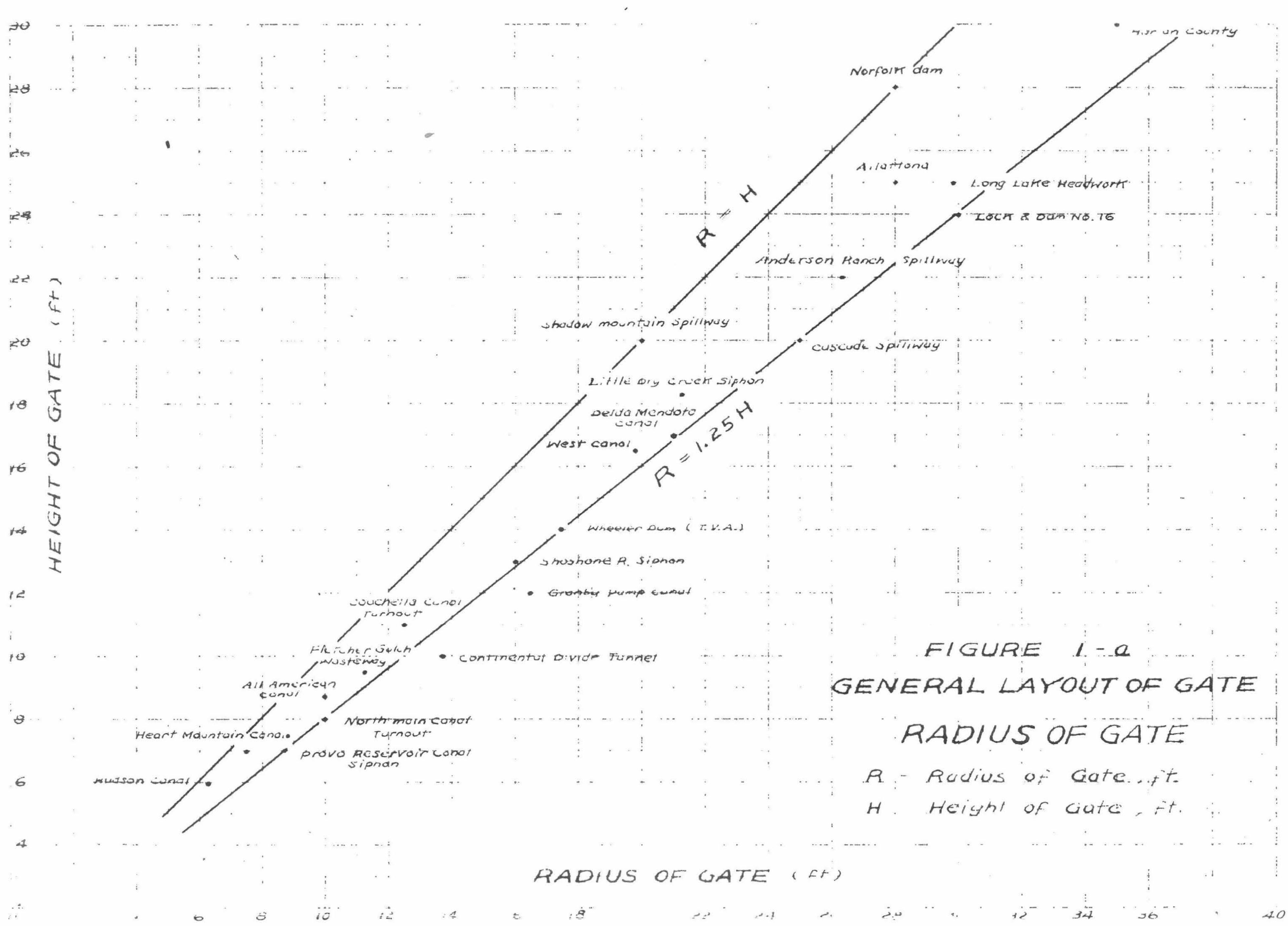


FIGURE 1-a
GENERAL LAYOUT OF GATE
RADIUS OF GATE

R - Radius of Gate, ft.
H. Height of Gate, ft.

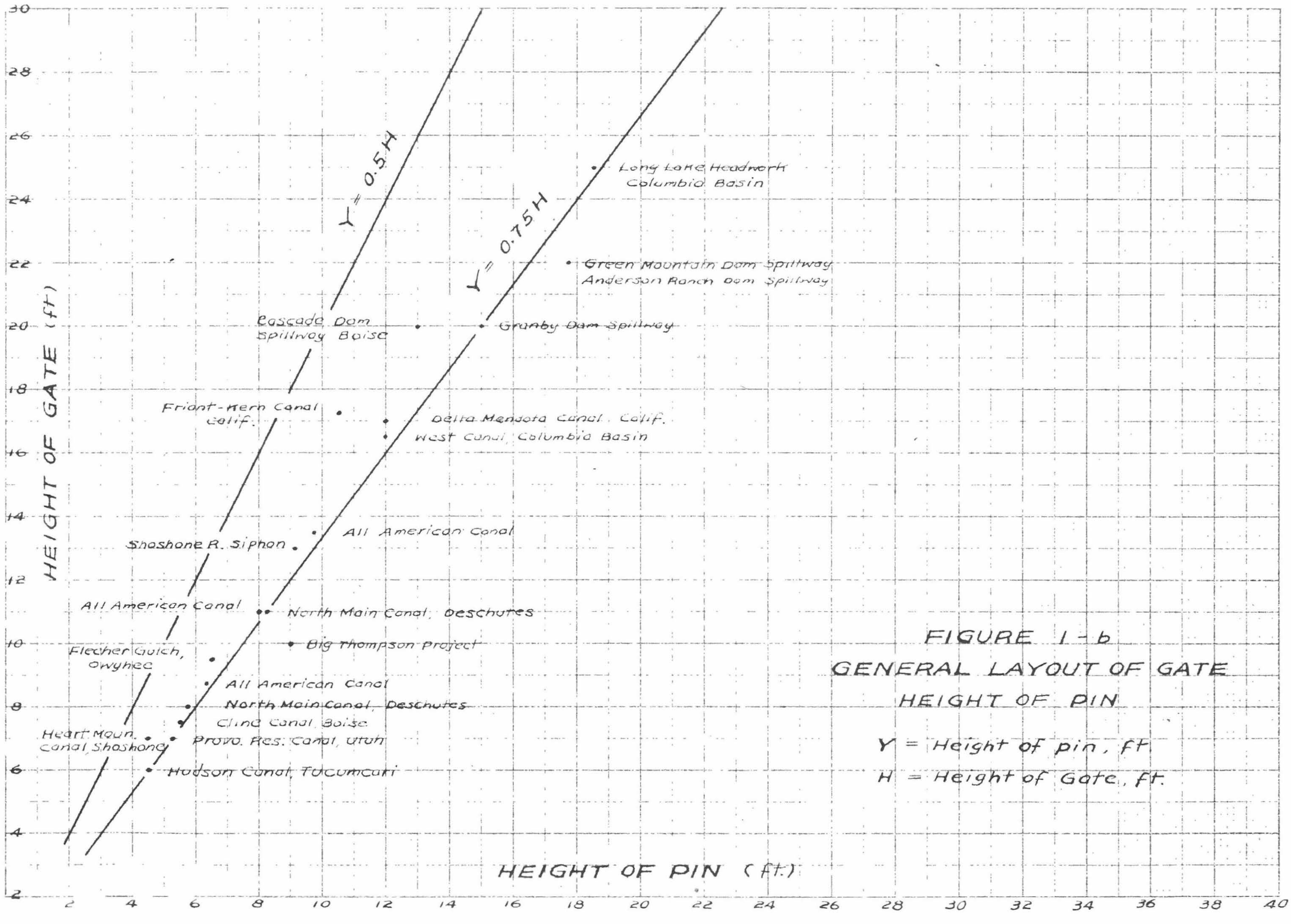


FIGURE 1-b

GENERAL LAYOUT OF GATE

HEIGHT OF PIN

Y = Height of pin, ft.

H = Height of Gate, ft.

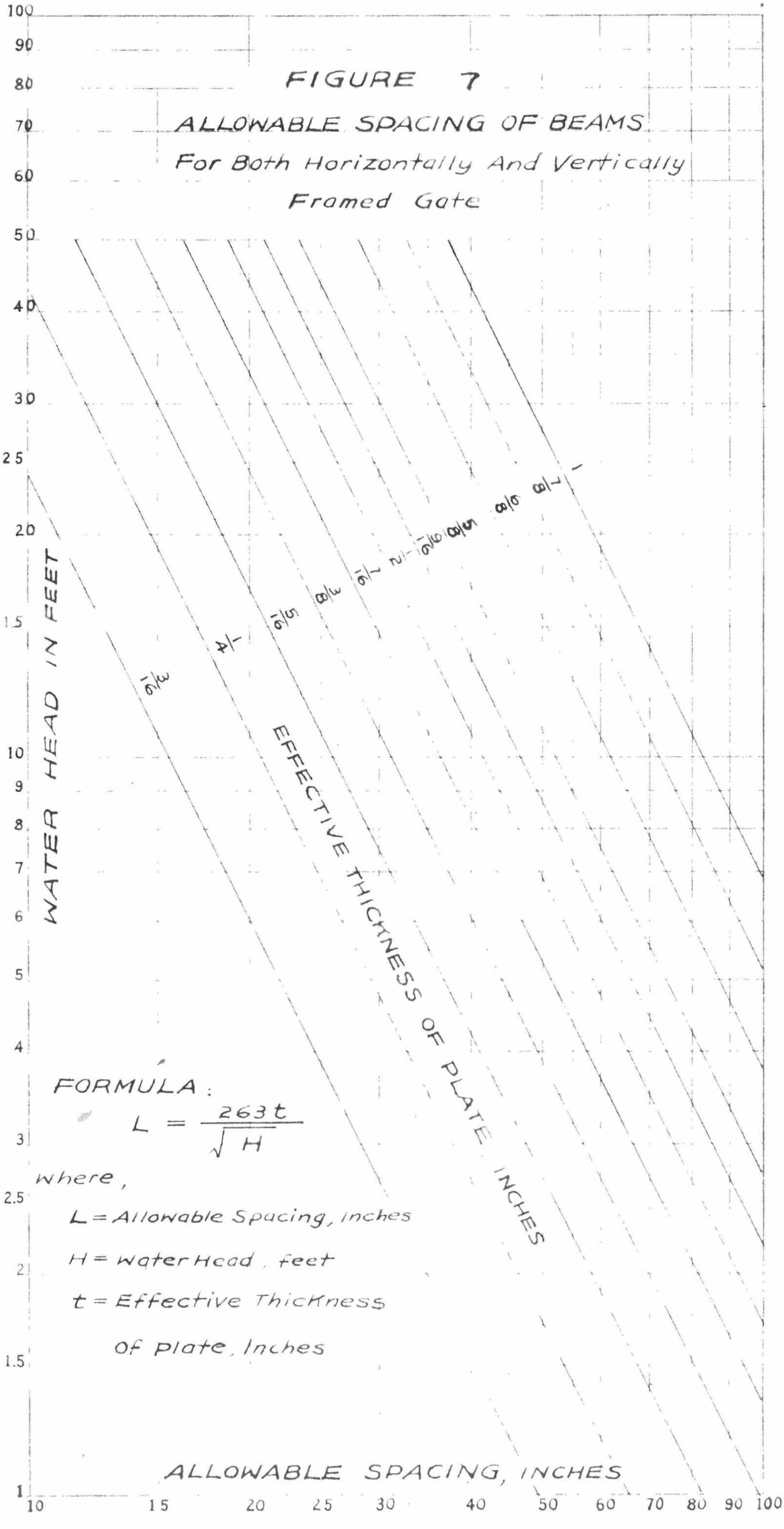


FIGURE 7
ALLOWABLE SPACING OF BEAMS
For Both Horizontally And Vertically Framed Gate
WATER HEAD IN FEET
EFFECTIVE THICKNESS OF PLATE INCHES
3/16
1/4
5/16
3/8
7/16
1/2
9/16
5/8
3/4
7/8
1
FORMULA:
$L = \frac{263t}{\sqrt{H}}$
where,
L = Allowable Spacing, inches
H = Water Head, feet
t = Effective Thickness of plate, Inches
ALLOWABLE SPACING, INCHES
100
90
80
70
60
50
40
30
25
20
15
10
9
8
7
6
5
4
3
2.5
2
1.5
1
10
15
20
25
30
40
50
60
70
80
90
100

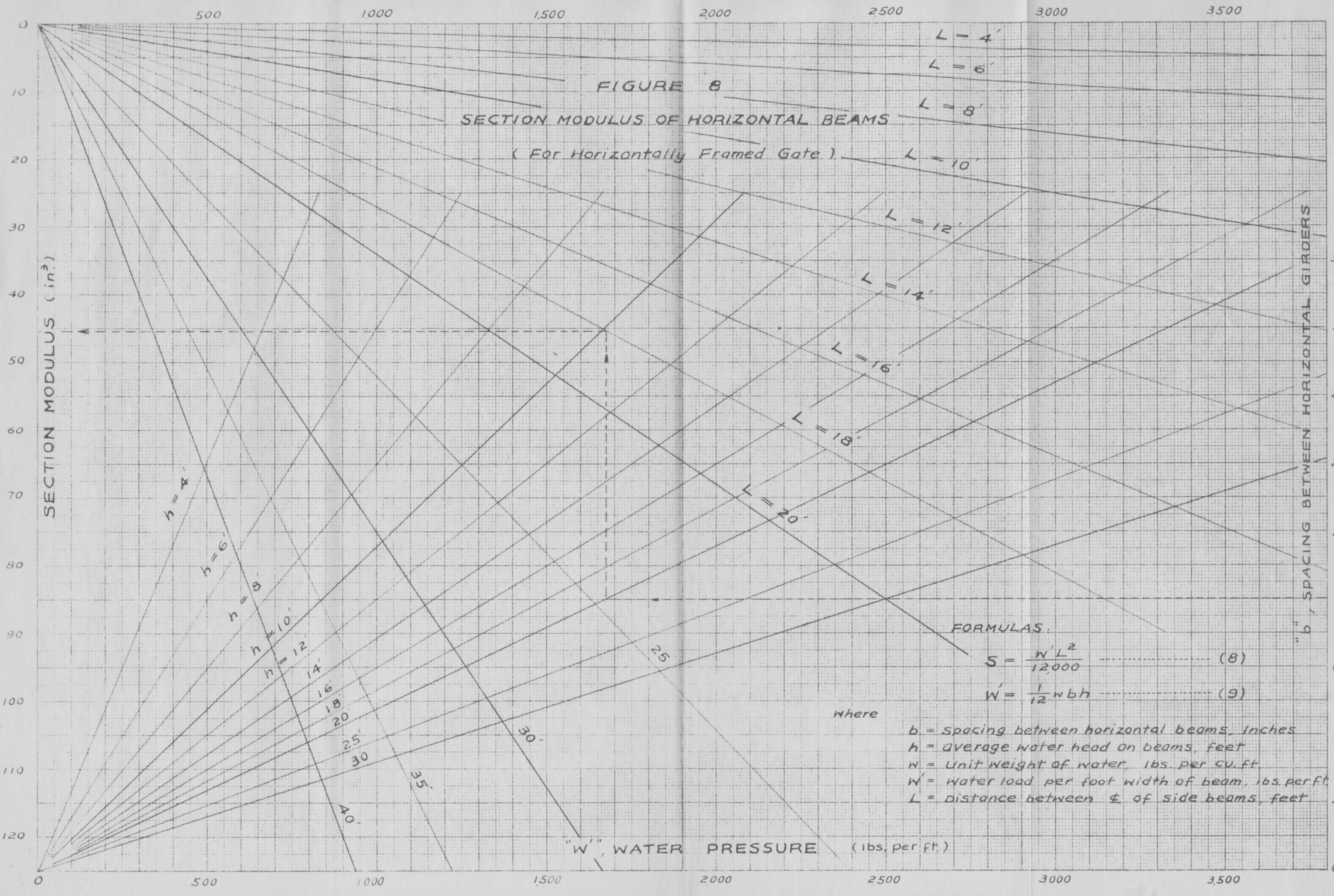


FIGURE 8

SECTION MODULUS OF HORIZONTAL BEAMS

(For Horizontally Framed Gate)

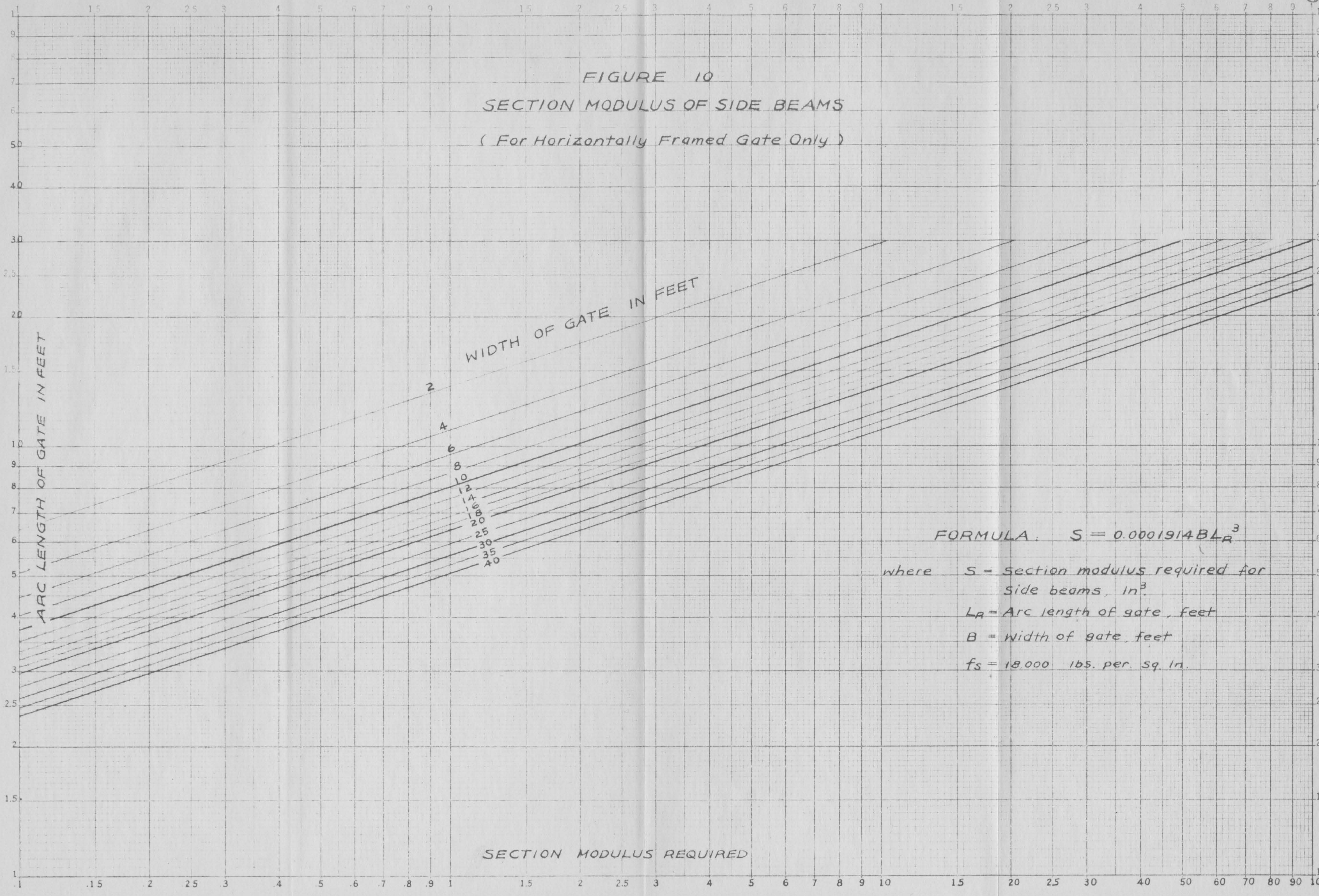


FIGURE 10
SECTION MODULUS OF SIDE BEAMS
(For Horizontally Framed Gate Only)
WIDTH OF GATE IN FEET
2
4
6
8
10
12
14
16
18
20
25
30
35
40
ARC LENGTH OF GATE IN FEET
SECTION MODULUS REQUIRED
FORMULA. $S = 0.0001914 B L_R^3$
where S = section modulus required for side beams, In^3.
L_R = Arc length of gate, feet
B = width of gate, feet
f_s = 18,000 lbs. per sq. in.

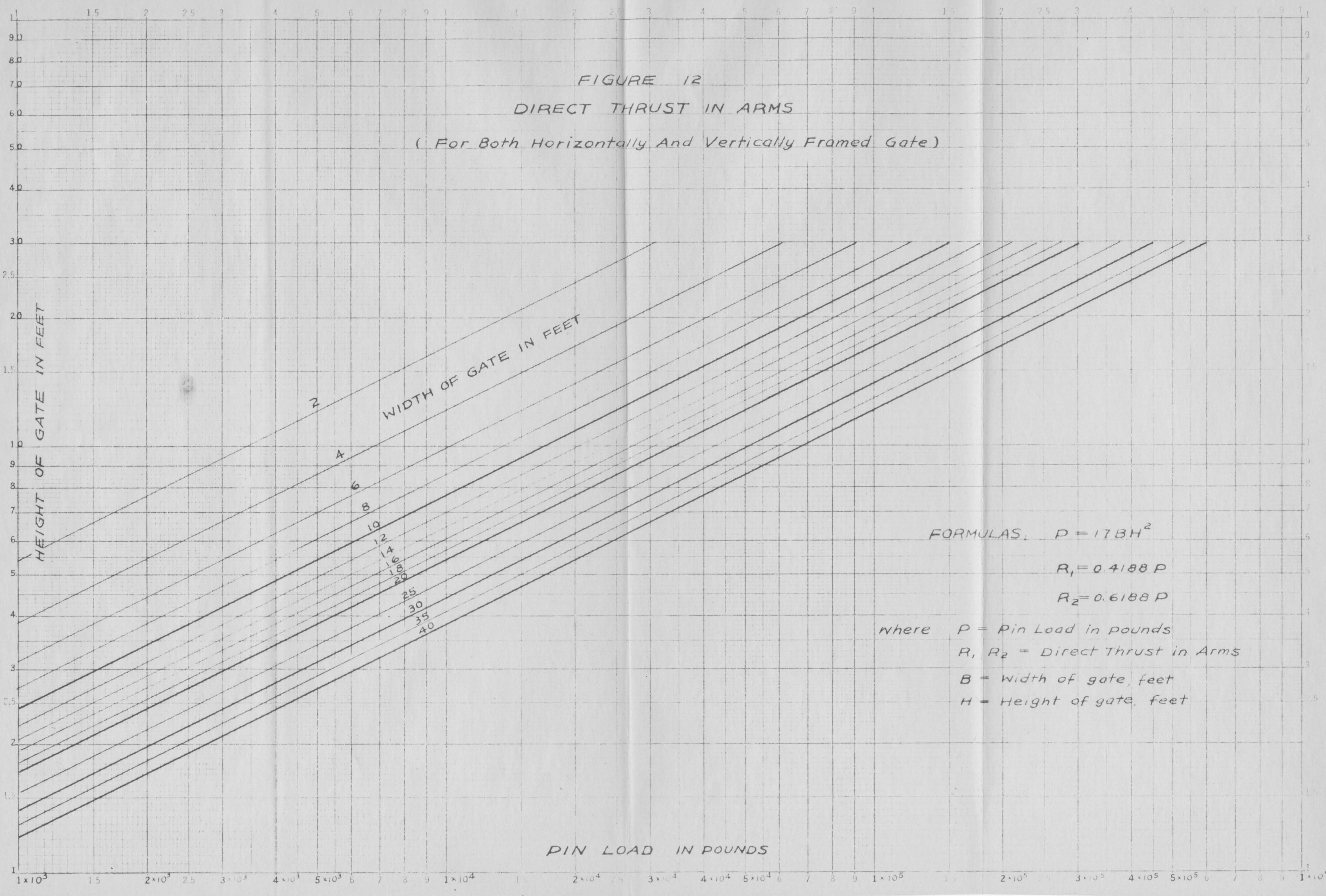


FIGURE 12
DIRECT THRUST IN ARMS
(For Both Horizontally And Vertically Framed Gate)

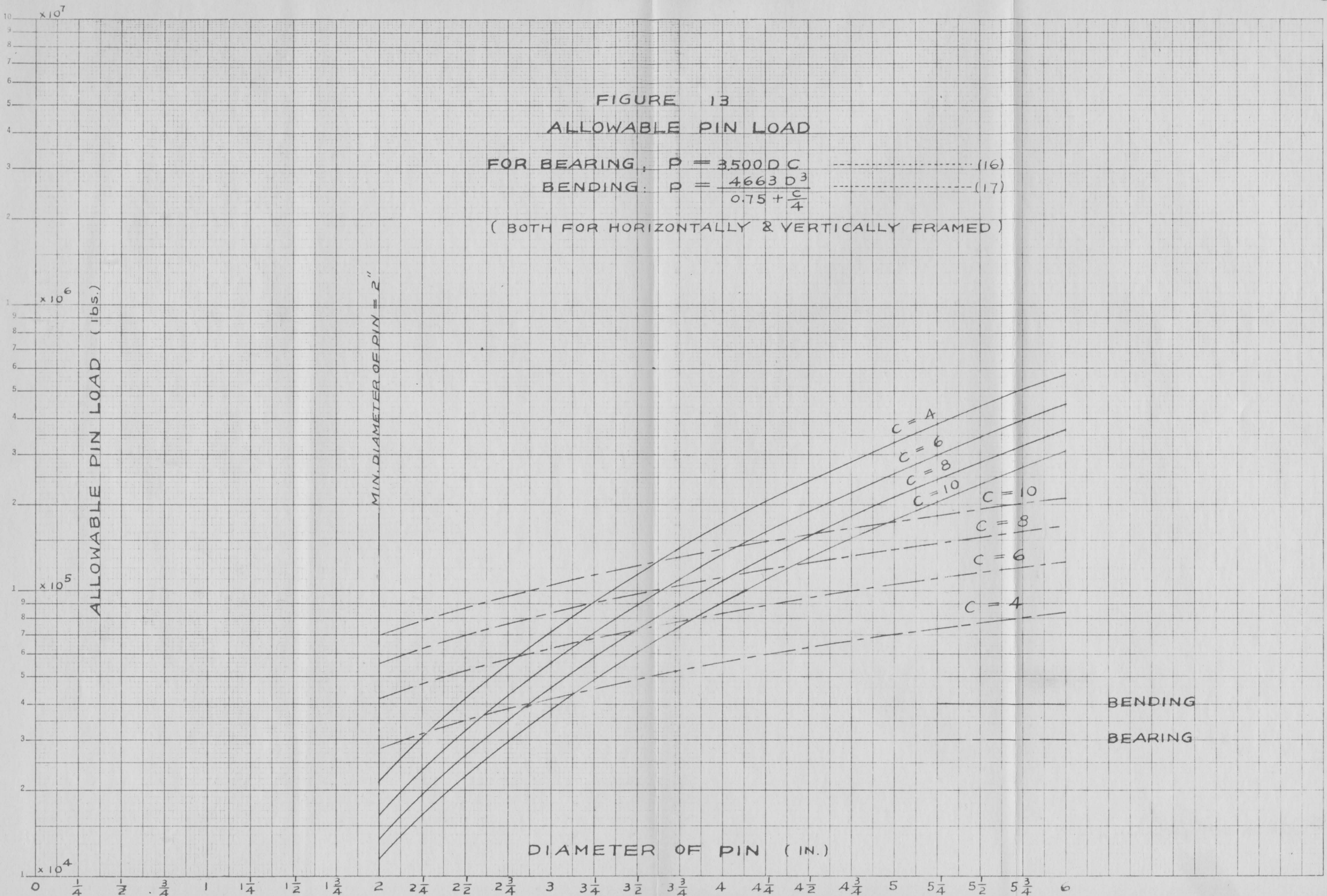


FIGURE 13
ALLOWABLE PIN LOAD
FOR BEARING, P = 3500 D C ---- (16)
BENDING: P = 4663 D³ / (0.75 + C/4) ---- (17)
(BOTH FOR HORIZONTALLY & VERTICALLY FRAMED)
MIN. DIAMETER OF PIN = 2"
ALLOWABLE PIN LOAD (lbs.)
DIAMETER OF PIN (IN.)
C = 4
C = 6
C = 8
C = 10
BENDING
BEARING
x 10⁷
x 10⁶
x 10⁵
x 10⁴

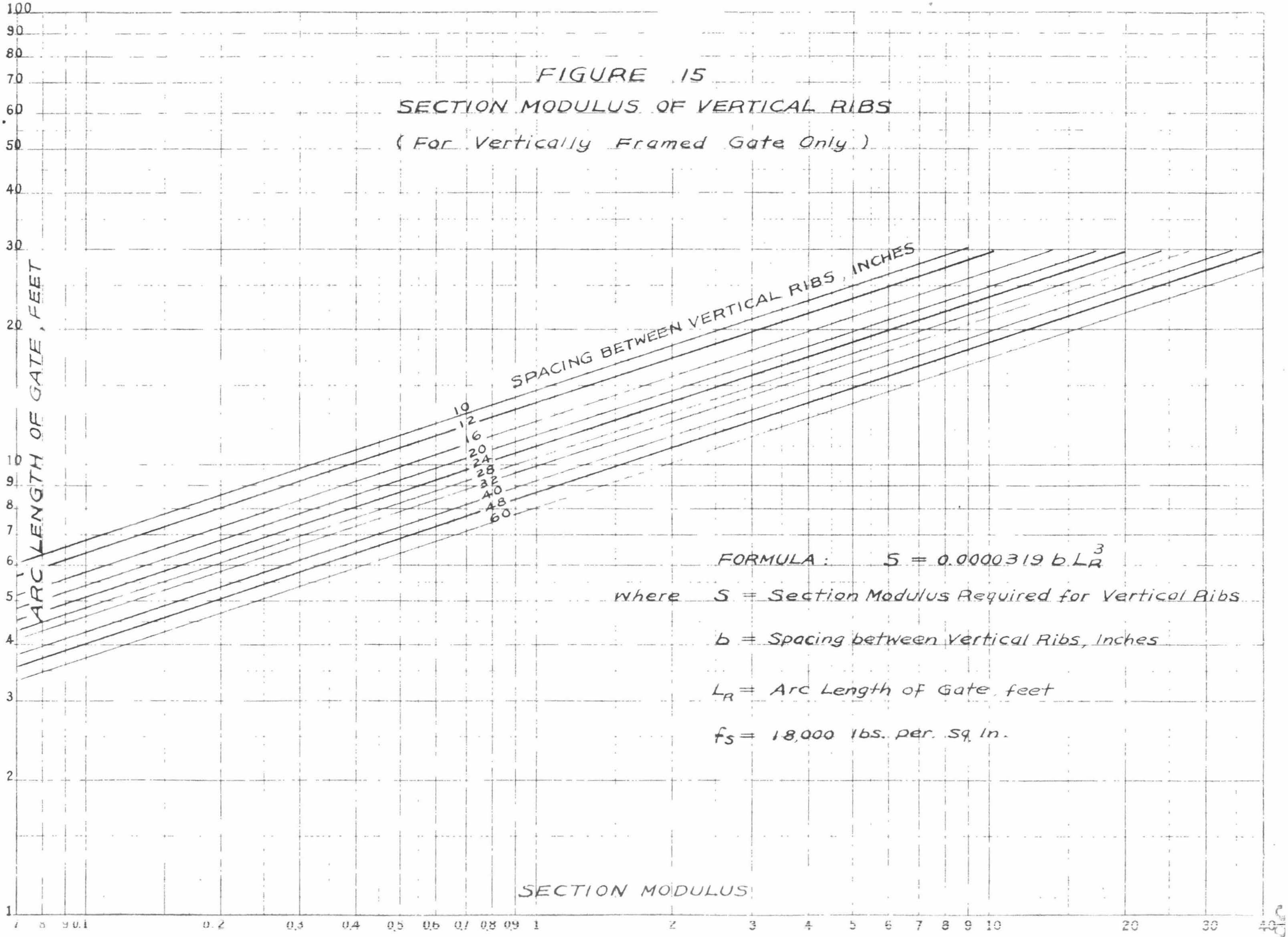


FIGURE 15
SECTION MODULUS OF VERTICAL RIBS
(For Vertically Framed Gate Only)
SPACING BETWEEN VERTICAL RIBS, INCHES
10
12
16
20
24
28
32
40
48
60
ARC LENGTH OF GATE, FEET
FORMULA: $S = 0.0000319\, b\, L_R^3$
where S = Section Modulus Required for Vertical Ribs
b = Spacing between Vertical Ribs, Inches
L_R = Arc Length of Gate, feet
f_s = 18,000 lbs. per. sq. in.
SECTION MODULUS
100
90
80
70
60
50
40
30
20
10
9
8
7
6
5
4
3
2
1
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
2
3
4
5
6
7
8
9
10
20
30
40

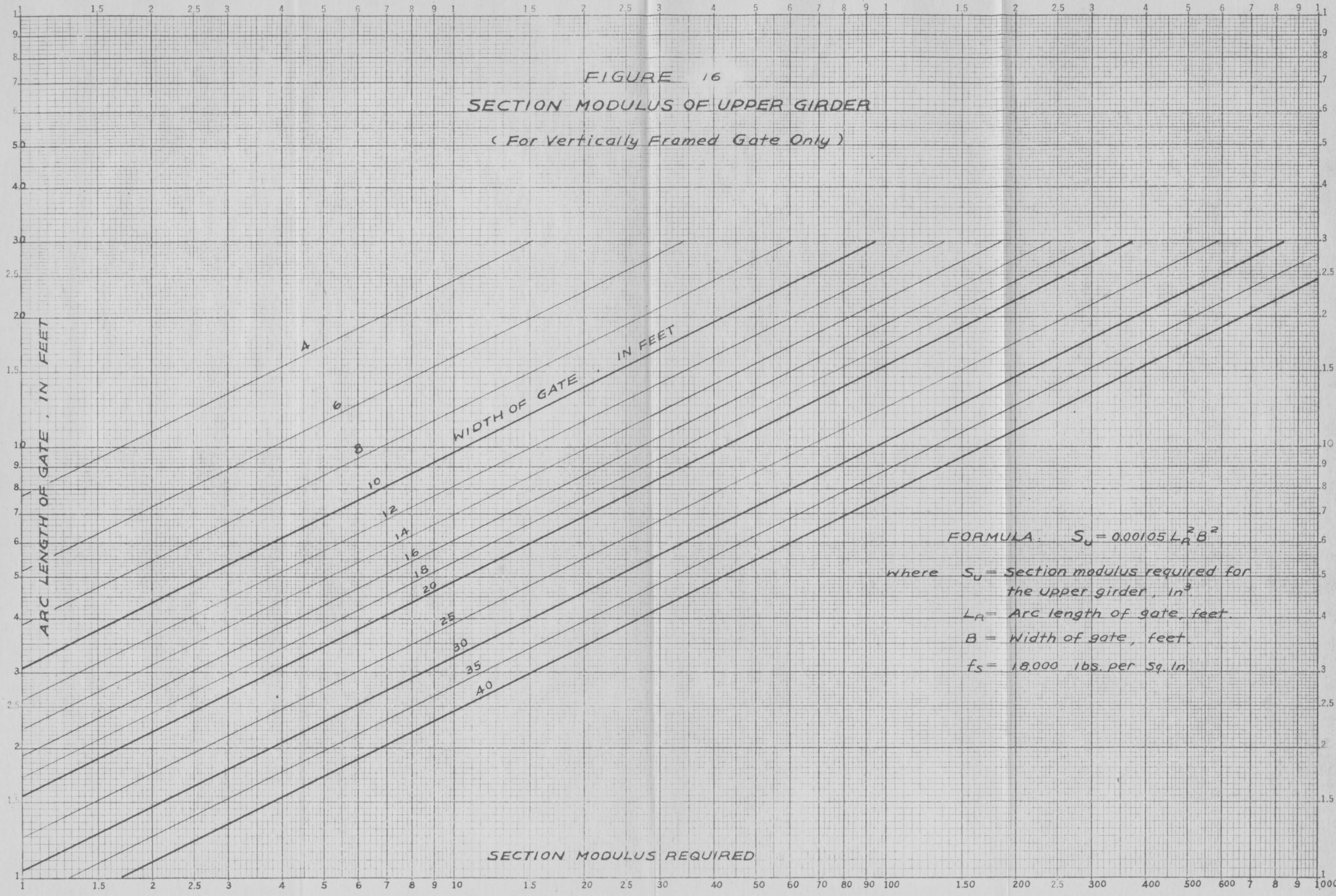


FIGURE 16
SECTION MODULUS OF UPPER GIRDER
(For Vertically Framed Gate Only)

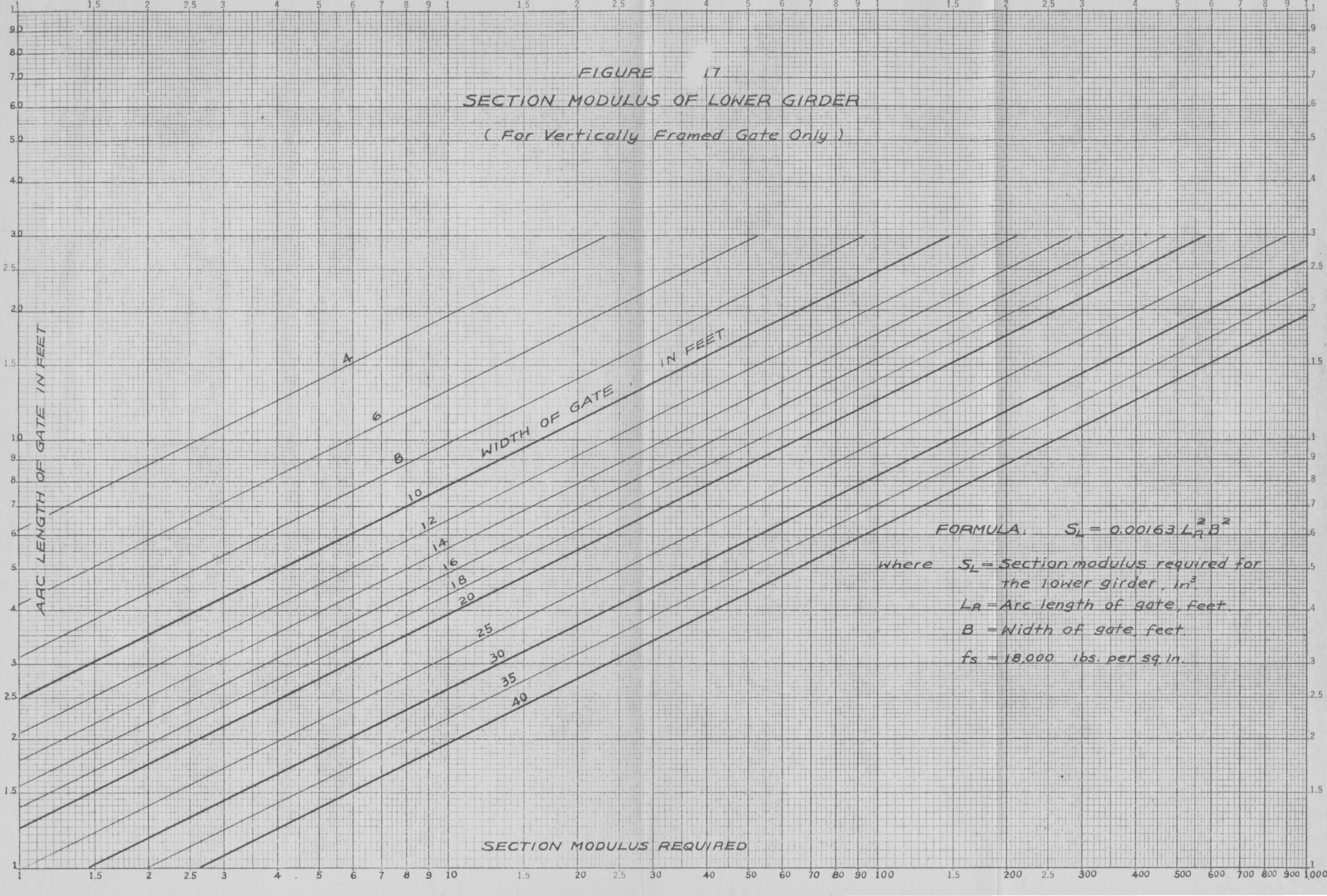


FIGURE 17

SECTION MODULUS OF LOWER GIRDER

(For Vertically Framed Gate Only)

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