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HYDRAULIC CHARACTERISTICS OF AN EMERGENCY CYLINDER GATE CLOSURE

BY

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GLOSSARY

a = wave speed (ft/s)

A_C = area of cylinder gate (ft^2)

A_N = area of needle valve (ft^2)

A_P = area of penstock (ft^2)

A_T = area of tower (ft^2)

C_{DC} = coefficient of discharge through cylinder gates

C_{DN} = coefficient of discharge through needle valves

C_M = negative characteristic

C_P = positive characteristic (ft)

dH = increment of head (ft)

dt = increment of time (t)

g = acceleration of gravity (ft/s^2)

H_E = elevation head of needle valves (ft)

H_N = needle valve head(ft)

H_P = head at beginning of penstock (ft)

H_R = reservoir elevation head (ft)

H_T = tower water elevation head (ft)

N = number of needle valves open

Q_C = discharge through cylinder gate (ft^3/s)

Q_N = discharge through needle valves (ft^3/s)

Q_P = discharge through penstock (ft^3/s)

Q_T = discharge through intake tower (ft^3/s)

HYDRAULIC CHARACTERISTICS OF AN EMERGENCY CYLINDER GATE CLOSURE

Background of Prototype Tests

In 1950 and 1953 prototype tests were conducted at Hoover Dam to determine if the intake tower cylinder gates could be closed with a differential head across the gates. The tests were designed to measure the hydraulic downpull force on the lower cylinder gate at fixed positions over a range of differential heads across the gate. Tests were not conducted on the upper cylinder gate.

The 1950 tests were conducted on the original cylinder gate (fig. 1). The bottom lip of the gate and the gate seat formed a shallow diverging nozzle downstream from the point of control. When a cavitation vapor cloud forms downstream from the control point, part or all of the gate bottom can be subjected to vapor pressure. For the tests, vertical gate openings of 3, 5, 6, 9, and 15 inches were tested under a reservoir elevation of 1168 ft. The tests were conducted by (1) establishing a fixed gate opening without flow, (2) controlling the penstock discharge by staging the opening of the downstream needle valves, and (3) recording tower water surface and hydraulic downpull at set intervals. A maximum hydraulic downpull force of 540 kips was measured during the tests. The maximum force occurred at the 5-in gate opening (fig. 2). Although the downpull forces measured during the tests were not felt to be excessive, all tests were halted with the tower water surface at about 1020. The tests were stopped due to observations of noise and vibration in the tower.

Based on the results of the 1950 tests, the bottom edge of the lower gates were modified to reduce hydraulic downpull forces during emergency closure

(fig. 3). Hydraulic downpull tests were conducted on the modified lower cylinder gate in 1953. The same test procedure was used as in 1950. Fixed gate openings of 3, 5, 9, and 12 inches were tested under a reservoir elevation of 1155 ft. A maximum hydraulic downpull of 130 kips at a 3-in gate opening was measured during the tests.

Noise and vibration present during the testing were considered substantially less than encountered during the unmodified gate tests. The tower water surface was allowed to drop to about elevation 940 ft. Tests were halted at that point due to turbulence in the tower water surface endangering test equipment.

Objectives of Current Emergency Closure Studies

A hydraulic analysis of an emergency closure of the cylinder gates was conducted to:

1. Predict the tower water surface elevation in response to emergency closure of the cylinder gates

2. Estimate hydraulic downpull on the gates under actual closure conditions

3. Determine how hydraulic downpull varies with the mode of operation

4. Identify possible hydraulic forcing functions capable of exciting the gate structure

Math Model

A math model of the hydraulics of the inlet tower, penstock, and needle valves was developed to partially meet the above-listed objectives. Penstock laterals and turbines were omitted. The model was developed for both single- and double-gate operation.

Previous mathematical studies conducted by Ball 1/ and physical model studies conducted by Colgate 2/ pointed to flow conditions under the gate at small openings exhibiting cavitation, and flow separation which could not be handled in detail. Although assumptions about the flow conditions under the gate must be made, where possible, assimilation of prior prototype data was used to define the boundary conditions of the model. The math model was developed as a transient model based on the method of characteristics. The intake tower, penstock, and outlets were sectioned as shown on figure 4. Above elevation 893 ft the intake tower was treated as a single boundary condition. The penstock was then broken into three 600-ft-long segments for transient computation. The downstream boundary condition was defined by four 72-in needle valves discharging free.

Tower Boundary Conditions

The upstream boundary condition was defined by the following equations:

1. Flow through the cylinder gate,

$$Q_C = C_{DC} A_C [2g(H_R - H_T)]^{0.5}$$

1/ Ball, J. W., Unpublished USBR Hoover Dam file No. 225, Book 1, 1955.
2/ Colgate, M., Unpublished USBR Hoover Dam file No. 225, Book 1, 1955.

2. Flow in the tower,

$$Q_T = [Q_p^2 - gA_T^2(H_T - H_P)]^{0.5} \quad \text{(neglect friction)}$$

3. Flow into penstock,

$$Q_P = \Sigma Q_C + Q_T$$

4. Definition of the change in the tower water surface,

$$dH = (Q_T/A_T)dt$$

5. Compatibility equation at the boundary,

$$H_P = C_M + \frac{aQ_P}{gA_P}$$

All unknowns can be found by simultaneous solution of the five boundary equations at time T. By expressing the equations in finite difference form using a second order approximation, the boundary equations can be solved at time T + dt. Prototype data avilable from the 1953 tests 1/ were used to estimate the coefficient of discharge through the cylinder gates at small openings. The same coefficient of discharge equations were used for both gates (fig. 5).

Downstream Boundary Conditions

The downstream boundary was defined by the simultaneous solution of two equations:

1/ Unpublished USBR Data Book, Hoover Dam file No. 225, Book 2, 1955.

1. Flow through the needle valve,

$$Q_N = NC_{DN}A_N\,[2g(H_N - H_E)]^{0.5}$$

2. Compatibility equation at boundary,

$$H_N = C_P - \frac{aQ_P}{gA_P}$$

There are no calibration curves available for the 72-in needle valves. An equation for the coefficient of discharge, figure 6, was developed from information on the 84-in Hoover needle valves in conjunction with 1953 prototype test data.

Hydraulic Downpull

Hydraulic downpull on the gates was calculated using pressures at the center of the gate opening. Hydraulic downpull was defined as the unbalanced force created by the difference between tower hydrostatic pressure and the calculated pressure profile, each acting on the horizontal area of the gate.

For the upper gate configuration, pressures were calculated at five locations inward on a radial line on the bottom of the gate leaf. The area between adjacent calculated pressure points was assumed to be acted on by a force equal to the average of the pressure times the area.

Insufficient prototype data are available to clearly define the gate loading due to cavitation or flow separation occurring along the gate bottom. Both conditions can affect the prototype hydraulic downpull forces under submerged conditions. The pressure distribution during cavitating conditions presents the greatest influence on hydraulic downpull forces.

Studies done by Colgate 1/ have shown the formation of a vapor cloud near the leading edge of the bottom results in a distorted pressure distribution over the downstream gate area. To bracket the pressure distribution on the upper gate, two separate cases were studied in the numeric model:

1. Assume cavitation does not distort the downstream pressure distribution.

2. Assume if cavitation forms at a point on the bottom of the gate, the entire downstream portion of the gate is subjected to vapor pressure.

During free discharge the gate was considered to be aerated. Minimum pressures under the gate were restricted to atmospheric pressure.

Cavitation has less influence on the lower cylinder gate. The modification to the lower gate forces the high-velocity jet to separate sharply from the gate bottom. The area of the pressure distribution affected by a vapor pressure cloud is significantly reduced. The pressure distribution on the lower gate was modeled by treating cavitation as a point source. Pressures downstream of the point of separation were calculated based on a linear pressure recovery up to hydrostatic conditions in the tower.

RESULTS

Simulated emergency gate closures were based on reservoir elevation 1210.0 ft. All emergency closures simulated by the model were based on a constant rate of cylinder gate closure. A total gate stroke of 9.17 ft in 12.33 minutes

was adopted. Steady-state conditions based on the initial discharge through the penstock were modeled before emergency closure of the cylinder gates was started.

Three cases of emergency cylinder gate closures were modeled. Both the upper and lower gates were modeled separately and during combined operation.

Tower Water Surface

Figures 7 through 9 show the dependence of tower water surface elevation on cylinder gate opening for upper, lower, and simultaneous dual-gate operation. The discharges shown represent steady-state penstock flow established by the discharge capacity of the needle valves at the beginning of the tests.

Case 1. - Upper gate closure with lower cylinder gage closed (fig. 7):

The upper cylinder gate remains submerged during full closure for initial discharges up to about 4000 ft^3/s. Severe cavitation on the gate is not predicted in this region of operation. At higher discharges a cavitation cloud is expected to occur on the bottom of the gate as the tower water elevation falls below 1075.0 ft. The tower water surface within the cavitating zone is falling at between 1.5 and 3.0 ft/s over the range of discharges shown. The rate of drawdown in the tower water surface limits the existence of severe cavitation on the gate to a period of 10.0 to 20.0 seconds.

Case 2. - Lower cylinder gate closure with upper cylinder gate closed (fig. 8):

The lower cylinder gate remains submerged during full closure for initial discharges up to 6000 ft^3/s. Fully developed cavitation is expected to occur for gate openings of less than 1.0 ft under differential heads of greater than 250 ft.

Case 3. - Simultaneous dual closure of both the upper and lower gates (fig. 9):

Operation of both gates produces rapid drawdown of the tower water surface over the final foot of cylinder gate closure. Both gates can be closed under submerged conditions for initial discharges less than 4000 ft^3/s. The lower tower gate remains submerged for flows up to 6000 ft^3/s. Strong cavitation occurs on the gates in zones similar to those identified for single-gate operation. Strong cavitation is expected to occur on the upper gate for a period of 5 to 10 seconds before the jet breaks free.

Hydraulic Downpull Forces

Case 1. - Upper cylinder gate closure with lower cylinder gate closed (figs. 10 and 11):

Figure 10 shows the predicted hydraulic downpull under the assumption of point cavitation. The gate operates under a nearly constant hydraulic downpull until the tower water surface starts falling rapidly. After the jet breaks free, hydraulic uplift on the gate can occur.

Hydraulic downpull forces, assuming cavitation subjects the entire downstream portion of the gate to vapor pressure, are shown on figure 11. Within the cavitation zone, large increases in the hydraulic downpull forces occur. A maximum hydraulic downpull of 375 kips occurs for initial discharge of 6100 ft^3/s at a 0.43-ft gate opening.

Case 2. - Lower cylinder gate closure with the upper cylinder gate closed (fig. 12):

The treatment of pressure recovery and cavitation on the modified gate produces smaller downpull forces than obtained for the upper gate. Highest hydraulic downpull forces act on the gate at gate openings of less than 1.0 ft. Maximum hydraulic downpull forces predicted fall under 300 kips.

Case 3. - Simultaneous dual closure of both the upper and lower cylinder gates (figs. 13-15):

Figures 13 and 14 show the hydraulic downpull forces acting on the upper cylinder gate during emergency closure of both upper and lower gates. Downpull forces given on figure 13 were formulated assuming cavitation does not distort the pressure distribution under the gate. In contrast, hydraulic downpull forces calculated assuming a full cavitation vapor cloud under the gate are shown on figure 14. Similar to upper gate operation alone, large spikes arise in the downpull force during operation in the cavitation zone. Again, due to rapid tower water surface drawdown, the large forces exist for short periods of time.

The range of predicted downpull forces on the lower gate during emergency dual-gate closure are shown on figure 15. The progressive buildup and

sharp decay of forces are similar to single-gate operation, but of lower magnitude.

COMMENTS ON FORCING FUNCTIONS

Steady closure of the cylinder gates used in the model does not produce transient pressures capable of exciting the gate. A review of literature and analysis of flow characteristics under the gate failed to identify a hydraulic forcing function capable of producing a sustained periodic transfer of energy between the flow and gate. Cavitation and separation on the gate can act as extraneous excitation, yielding damped aperiodic vibrations. Significant random tower vibration and turbulence within the tower water are expected as the tower water level approaches the level of the gates.

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[5] Schlicting, H., Boundary Layer Theory, McGraw Hill, 1968.

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[7] USBR unpublished data file No. 225, Hydraulic Downpull on Hoover Intake Tower Cylinder Gates, 1950-53.

[8] Wylie, B. E., and V. L. Streeter, Fluid Transients, McGraw Hill, 1978.

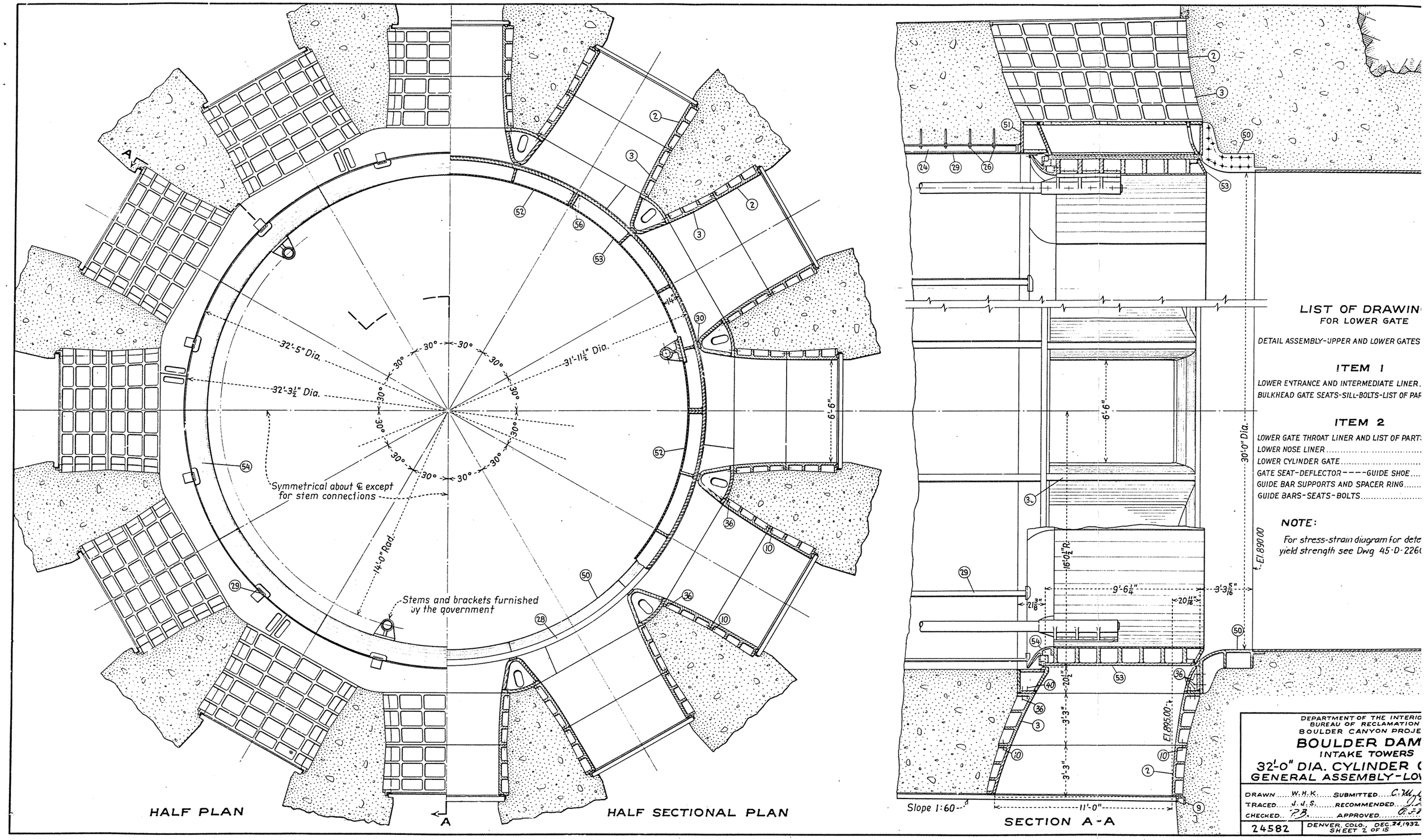


Figure 1. - Unmodified lower gate.

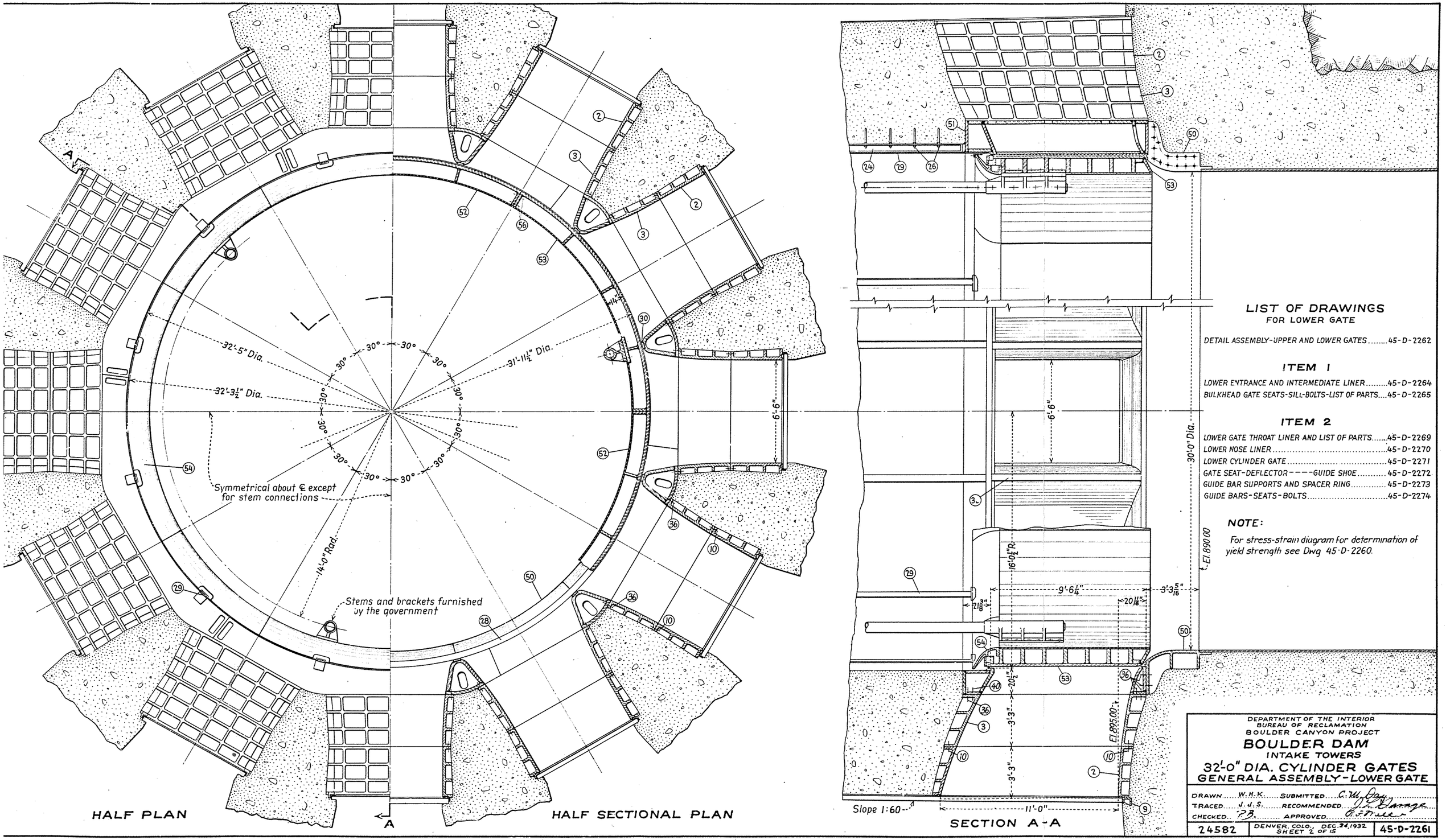
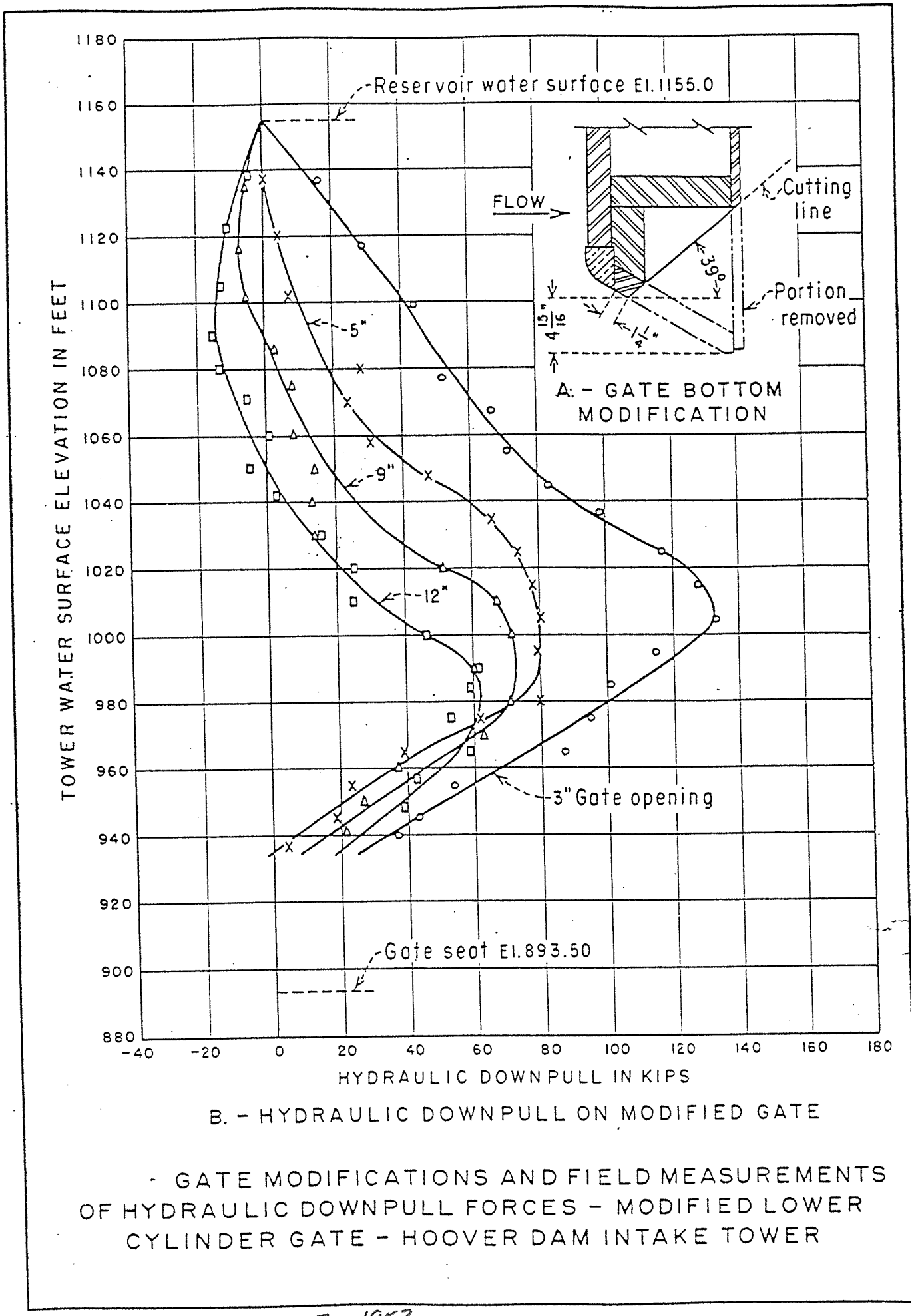
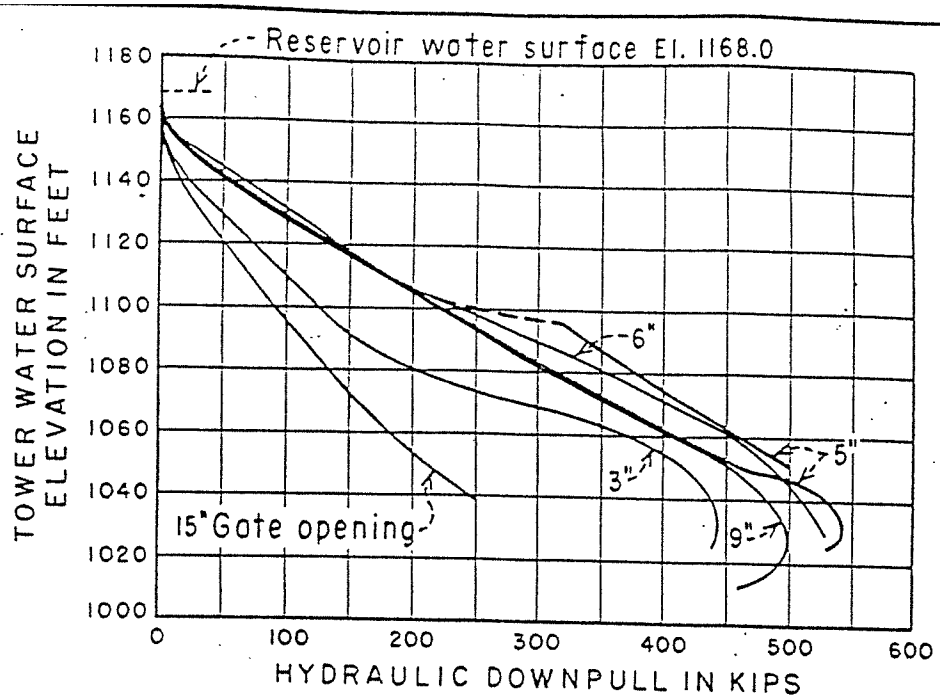


Figure 1. - Unmodified lower gate.

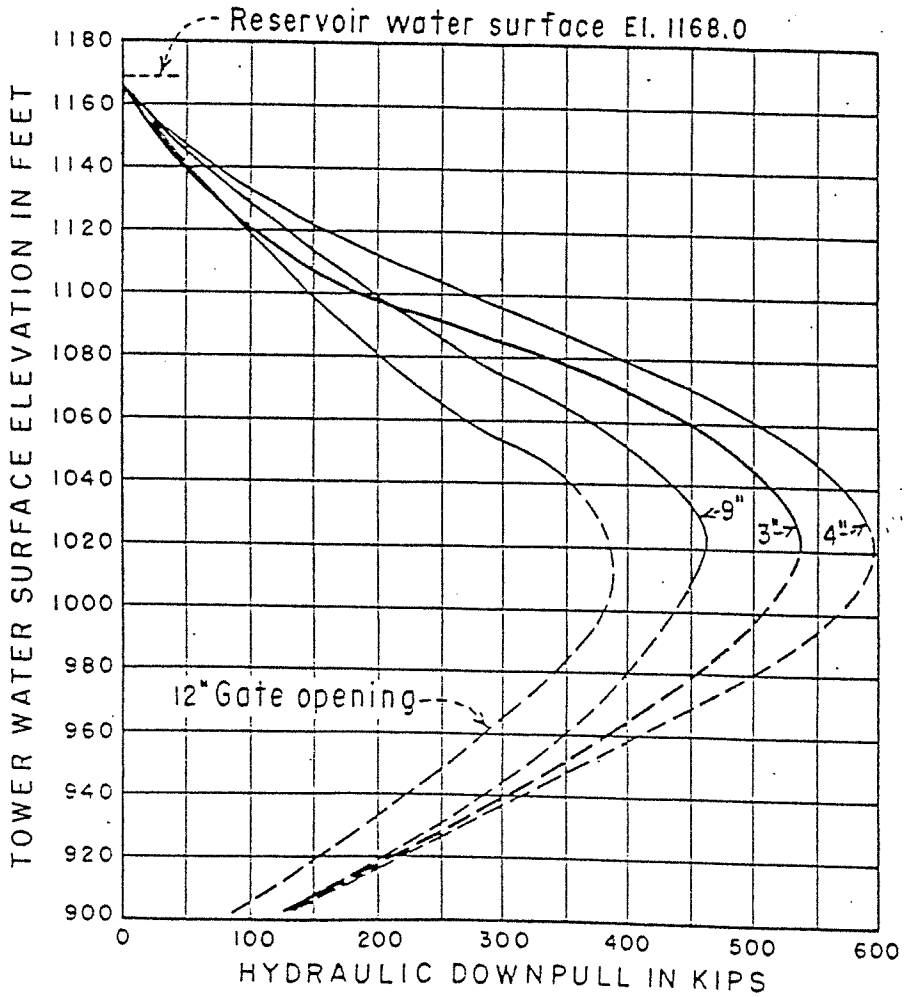


- GATE MODIFICATIONS AND FIELD MEASUREMENTS OF HYDRAULIC DOWNPULL FORCES - MODIFIED LOWER CYLINDER GATE - HOOVER DAM INTAKE TOWER

Figure ~~1~~ 3. - ~~1950~~ 1953 prototype test results.



A. - HYDRAULIC DOWNPULL FOR RECORDED GATE OPENINGS



B. - HYDRAULIC DOWNPULL FOR GATE OPENINGS ADJUSTED FOR STEM ELONGATION

FIELD MEASUREMENTS - HYDRAULIC DOWNPULL FORCES - LOWER CYLINDER GATE - HOOVER DAM INTAKE TOWER

Figure ~~1~~ 2. - ~~1923~~ 1950 prototype test results.

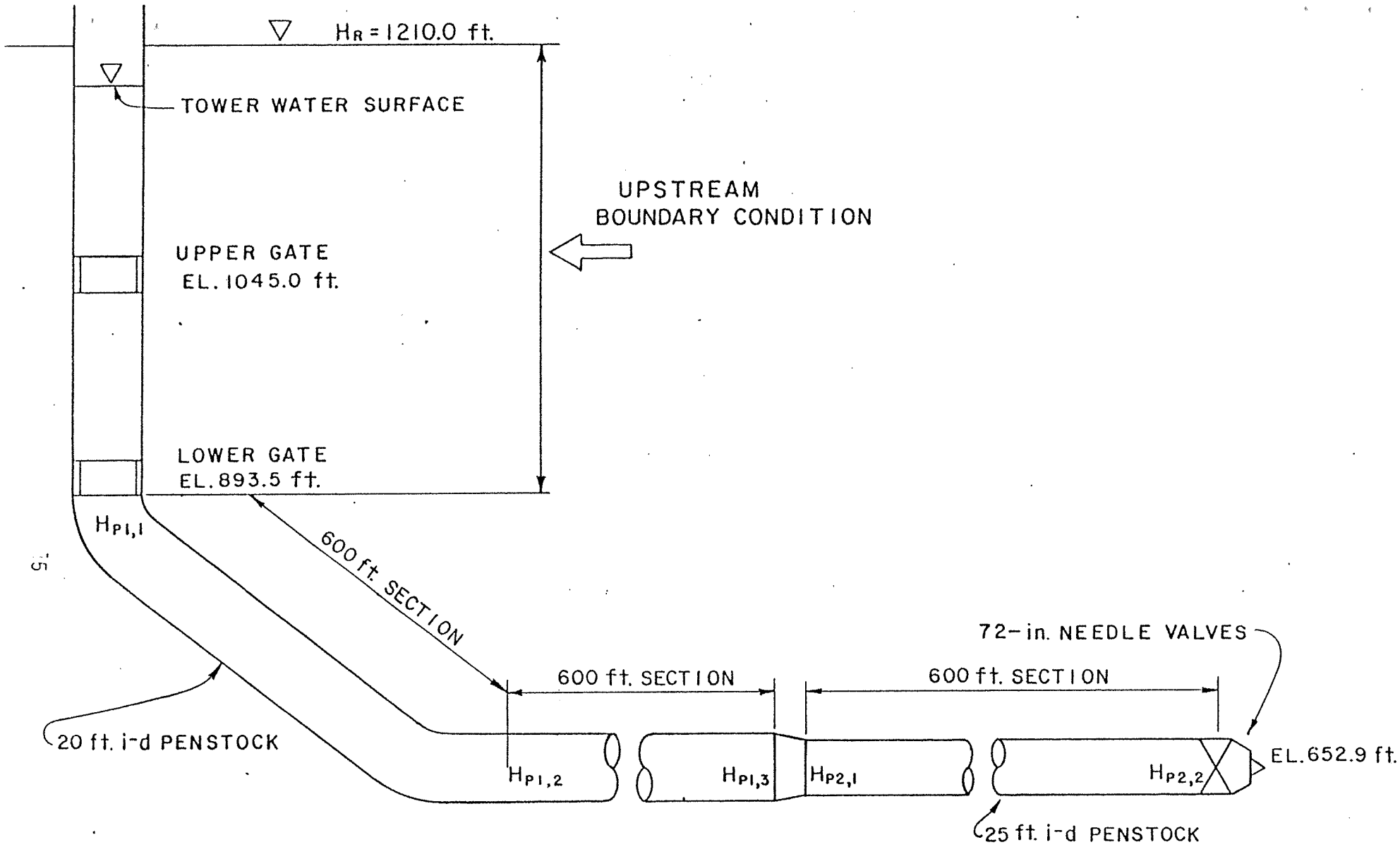


Figure 4. - Physical layout for math model.

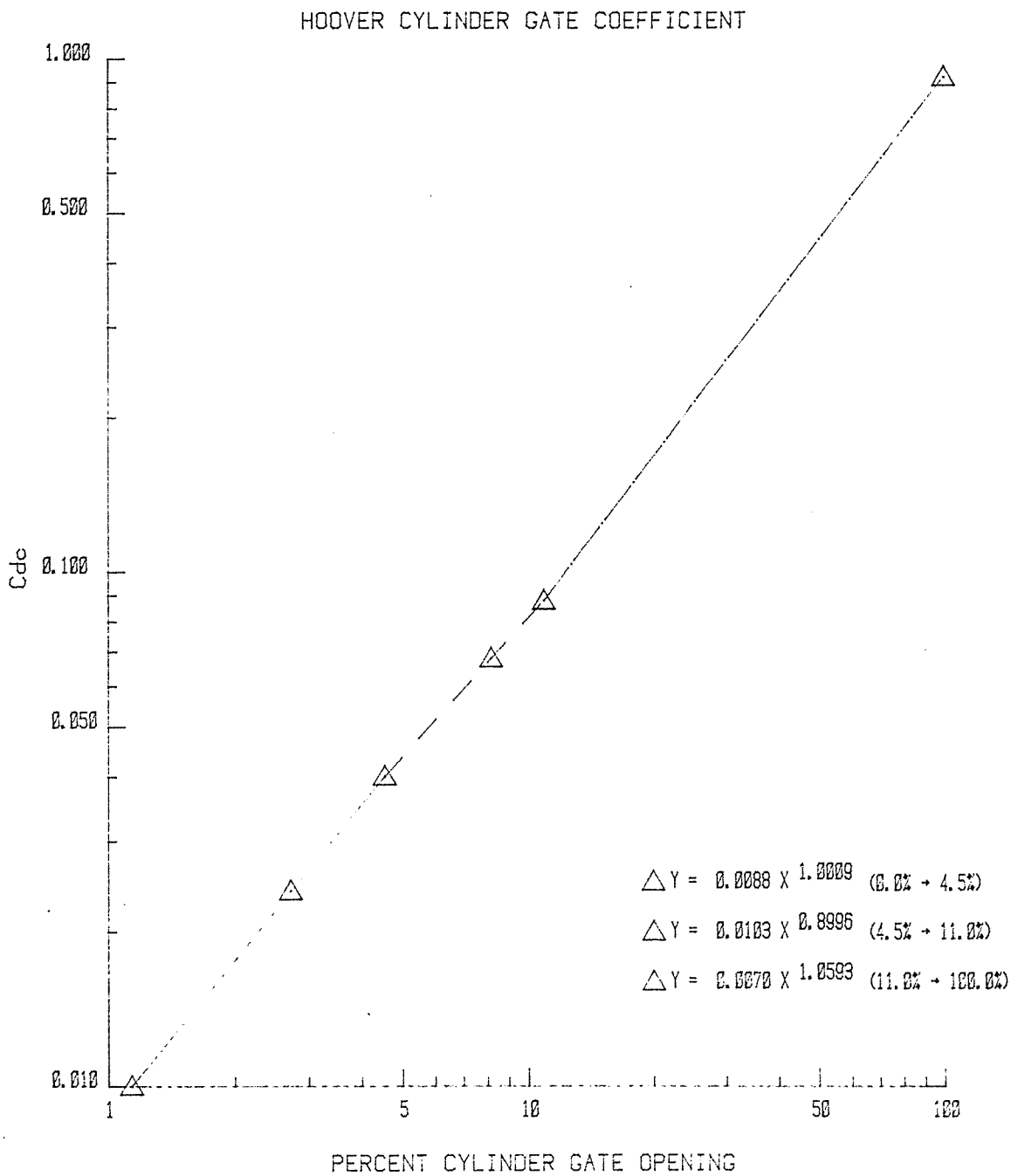


Figure 5. - Cylinder gate coefficient of discharge.

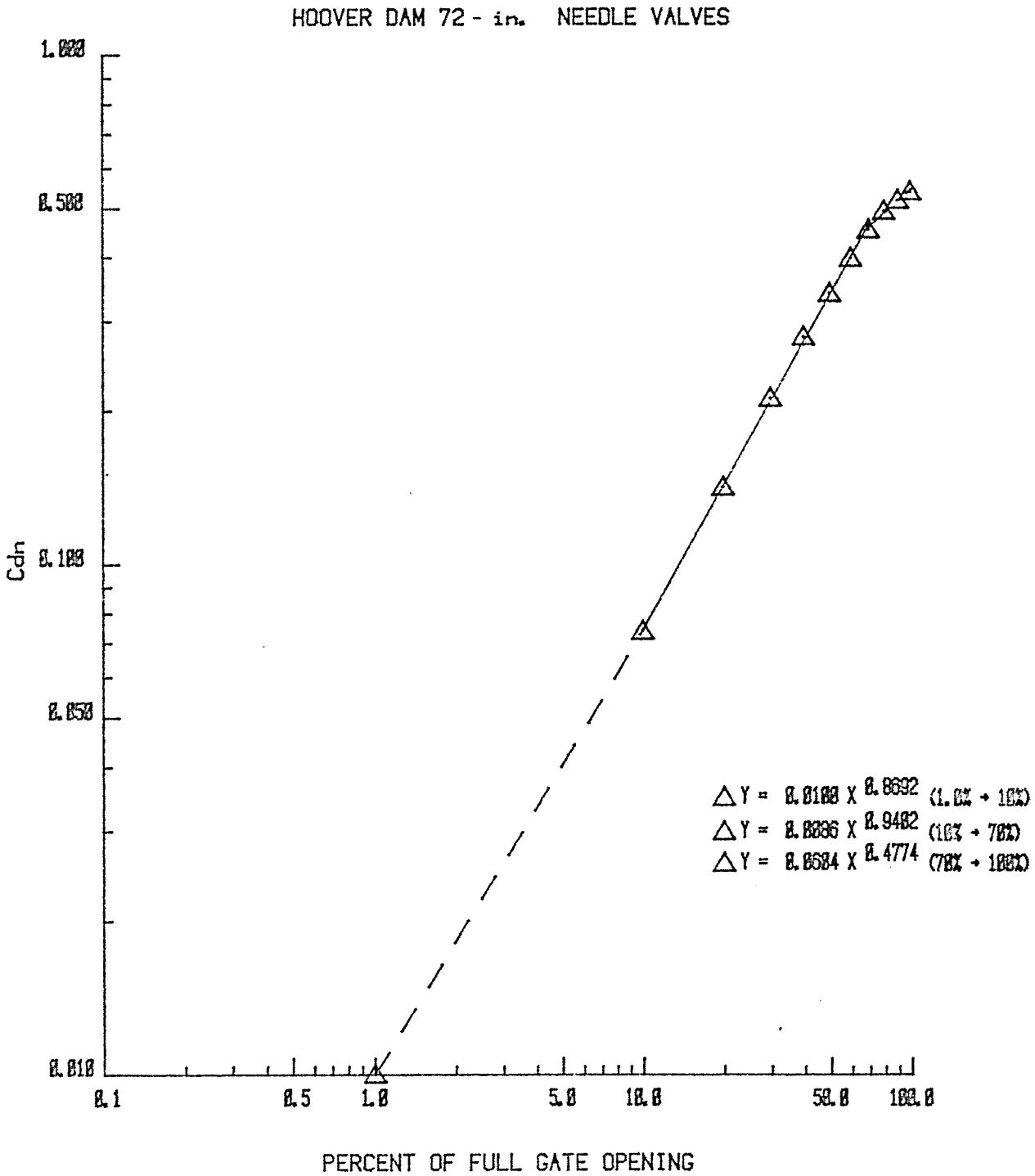


Figure 6. - Needle valve coefficient of discharge.

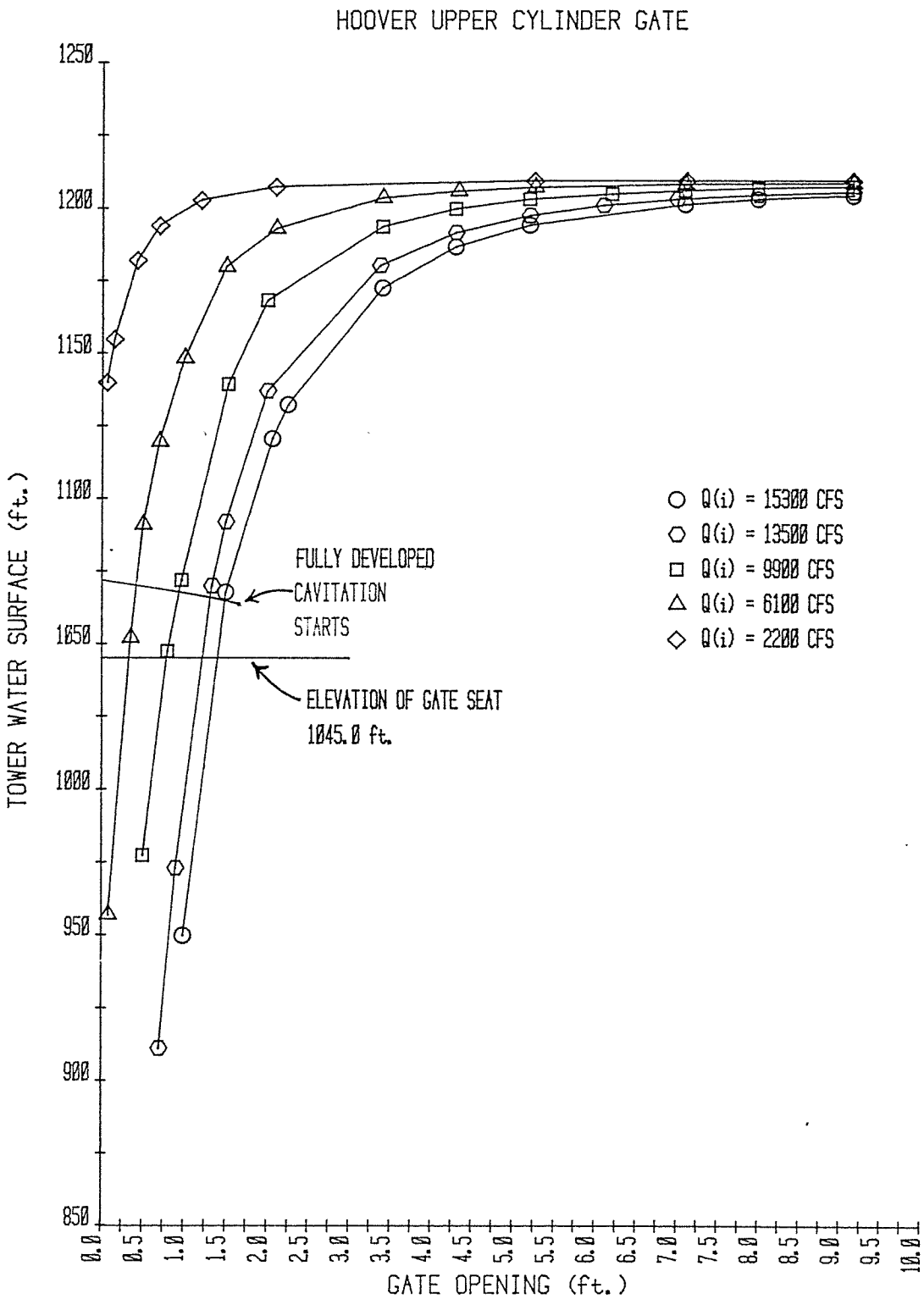


Figure 7. - Upper gate H_T vs. percent of gate.

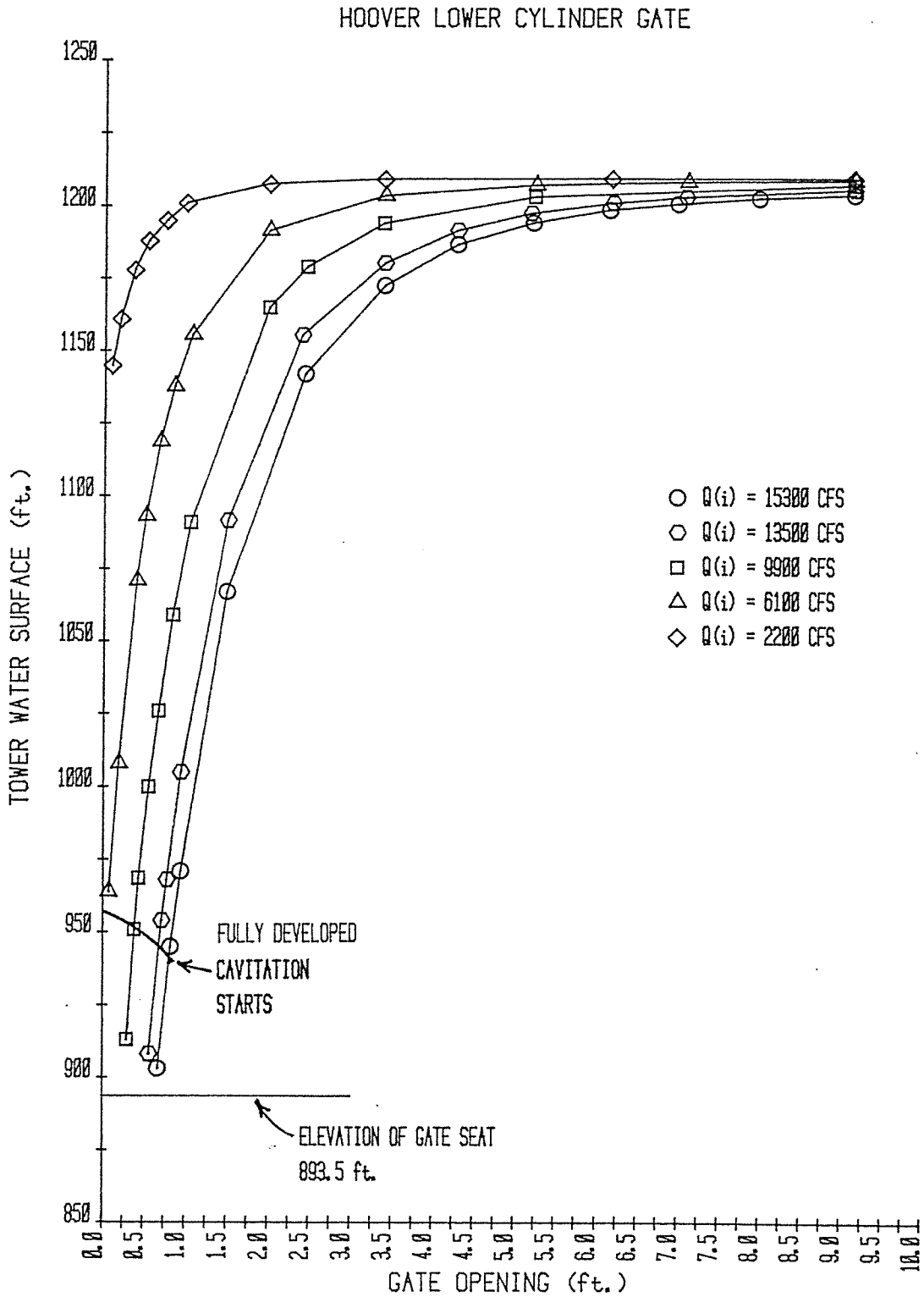


Figure 8. - Lower gate H_T vs. percent of gate.

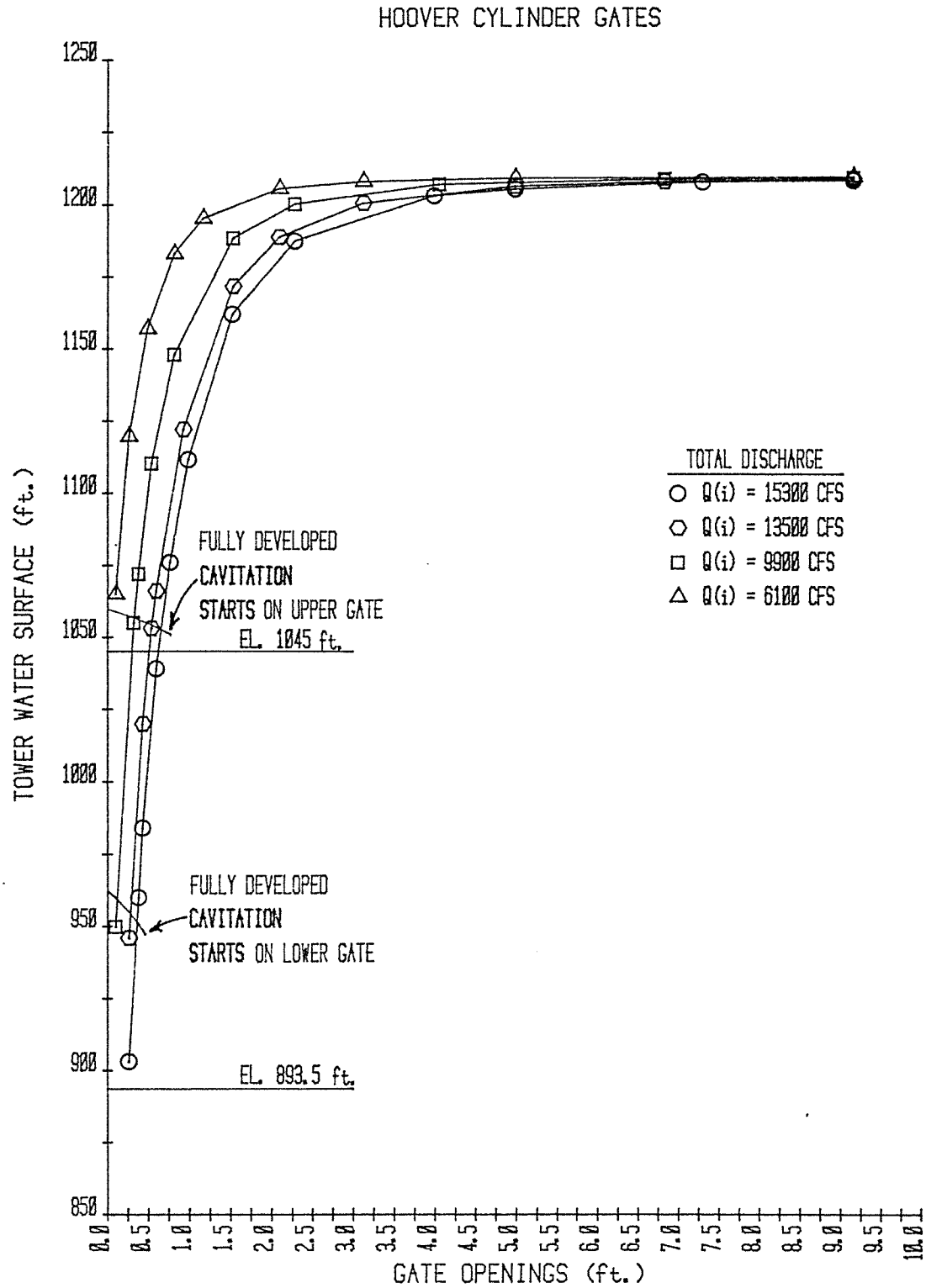


Figure 9. - Both gates H_T vs. percent of gate.

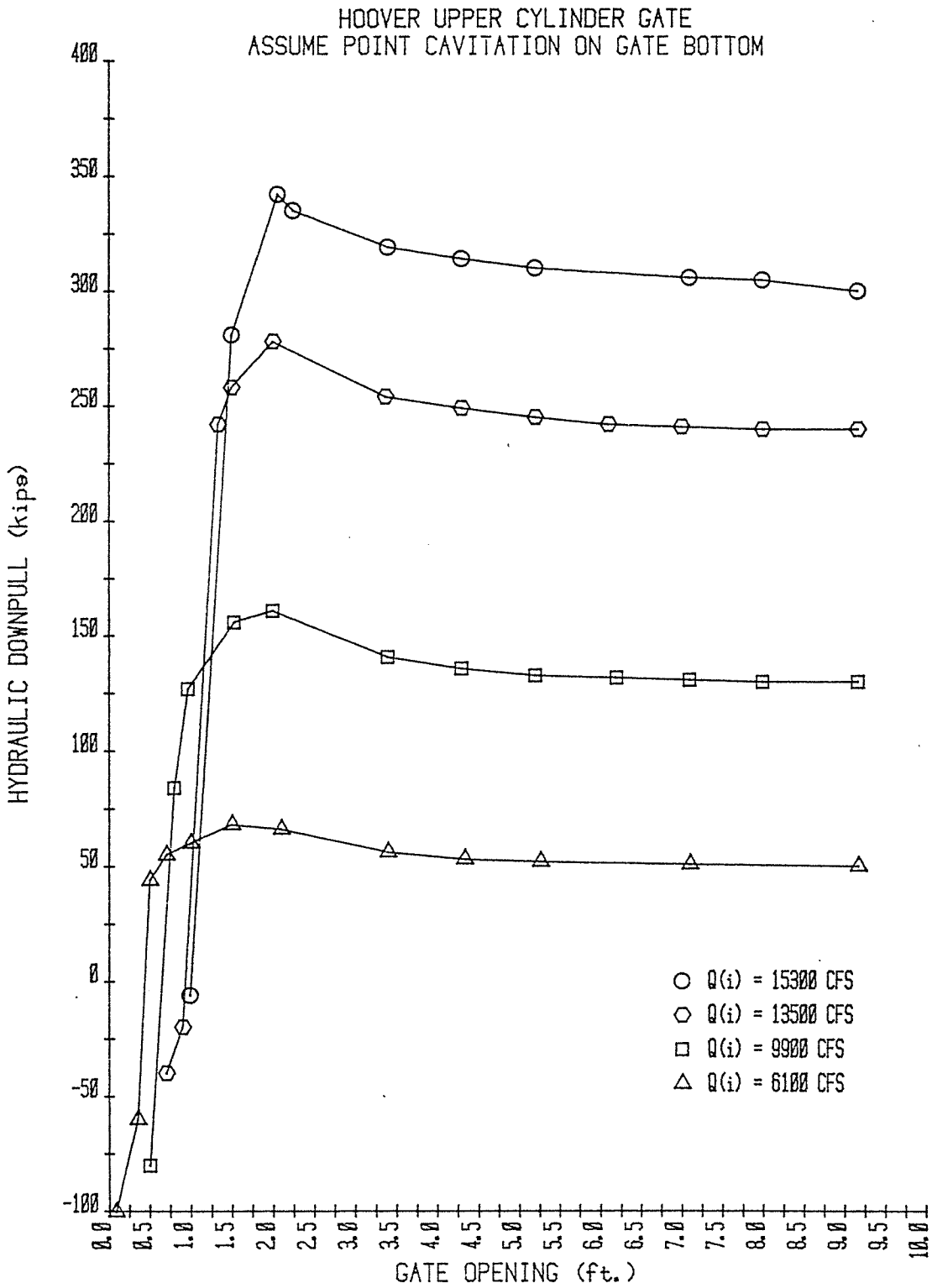


Figure 10. - Minimum predicted hydraulic downpull on upper gate.

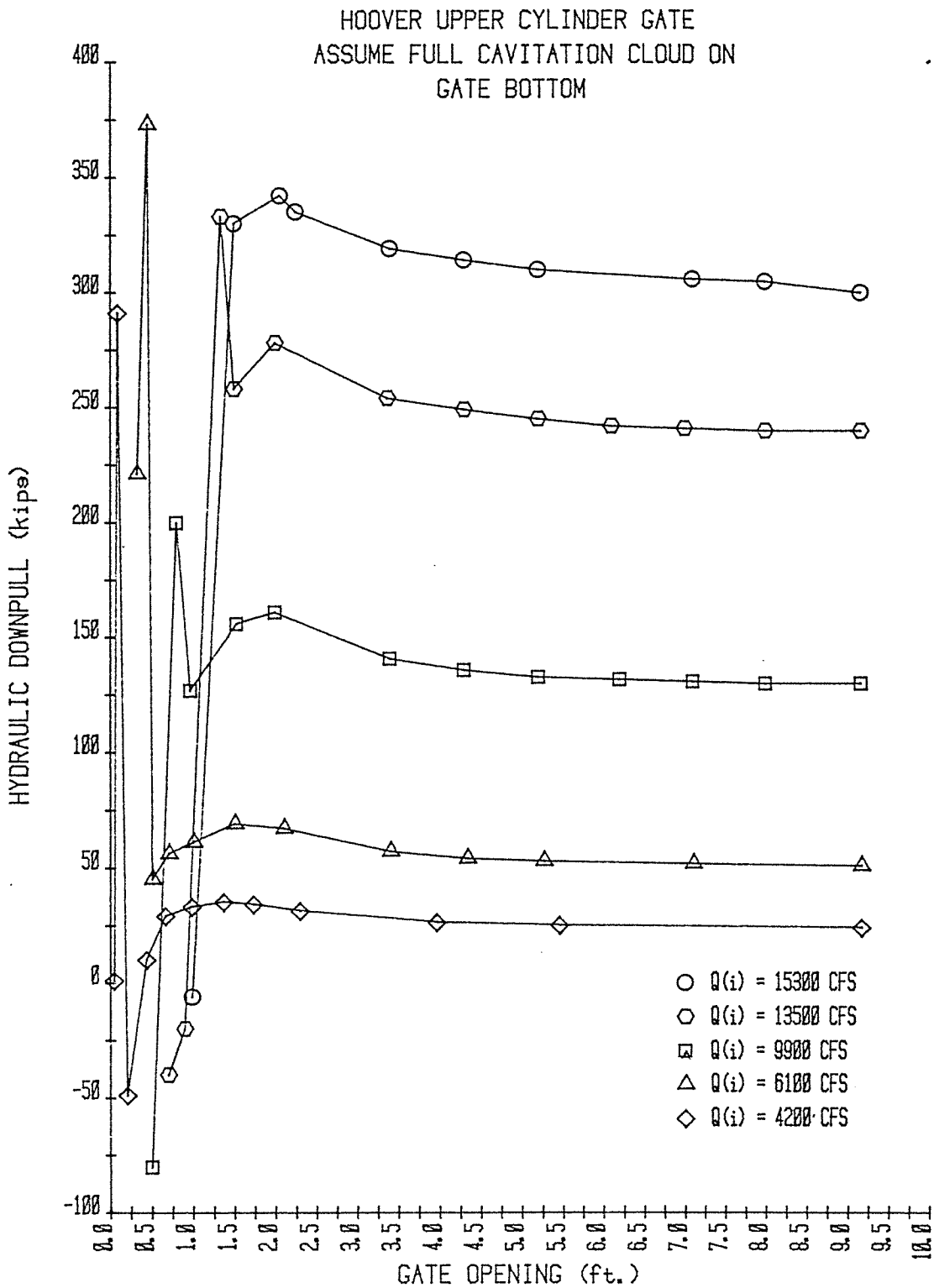


Figure 11. - Maximum predicted hydraulic downpull on upper gate.

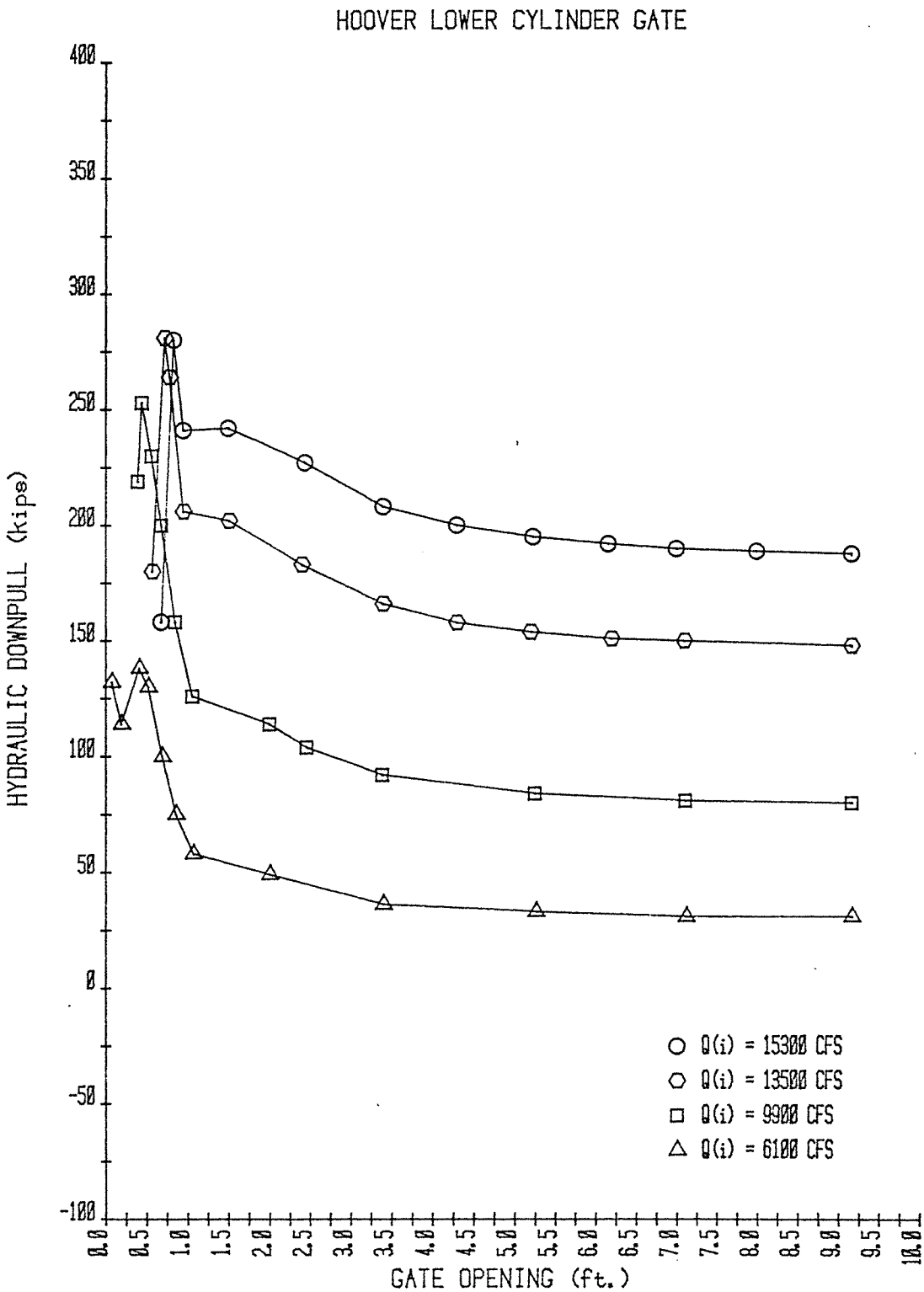


Figure 12. - Hydraulic downpull on lower gate.

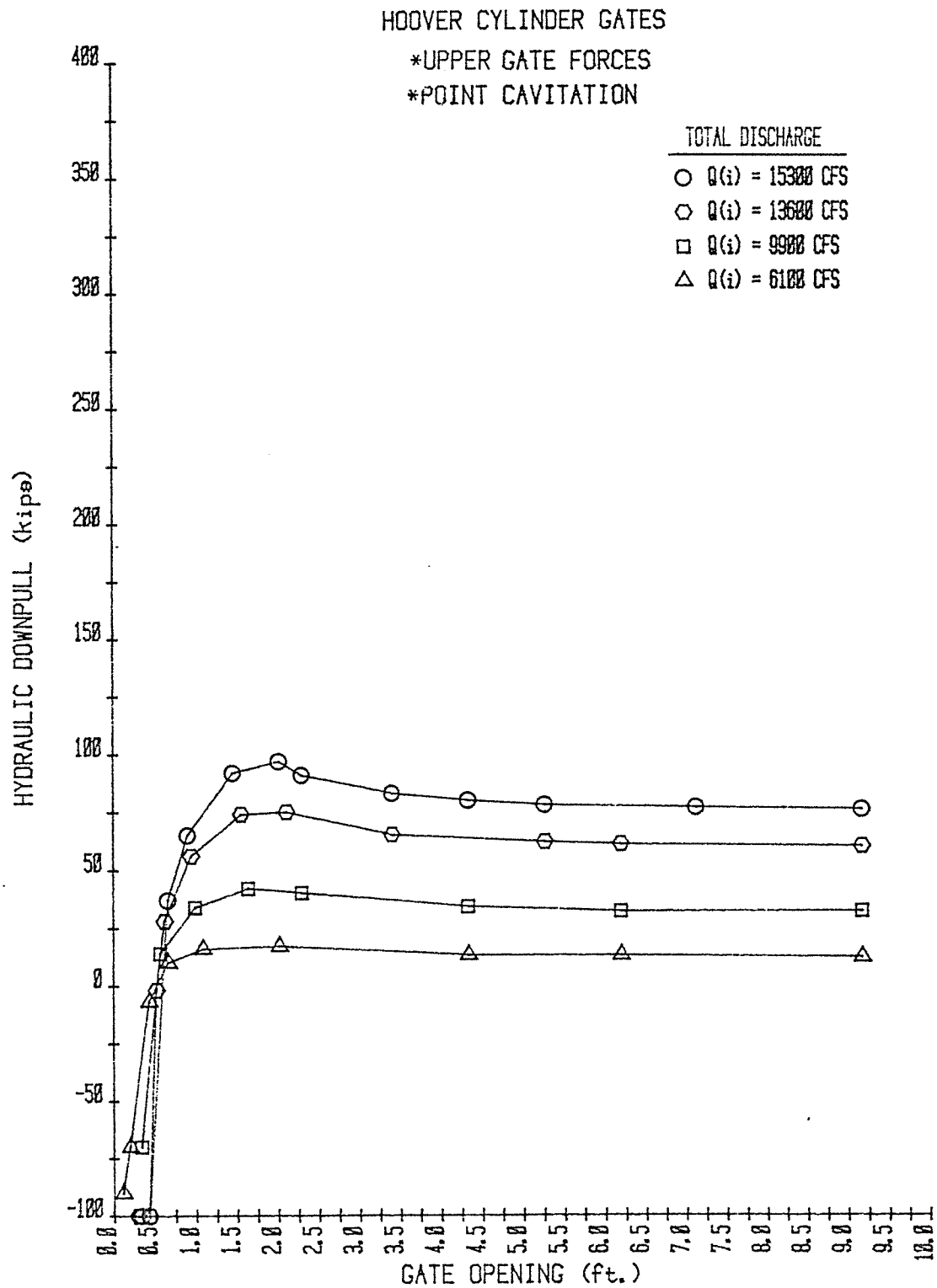


Figure 13. - Minimum predicted hydraulic downpull on upper gate - dual-gate operation.

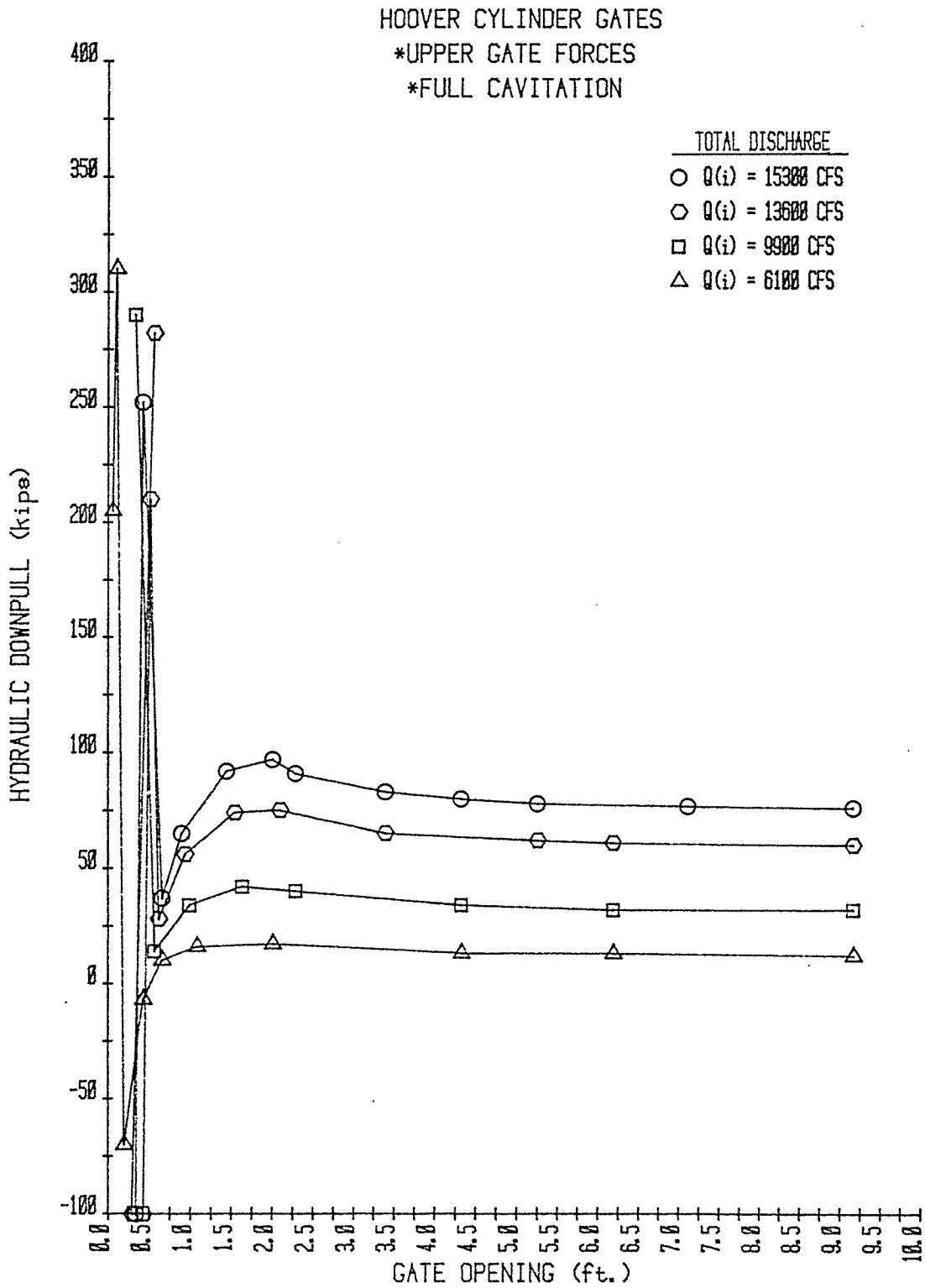


Figure 14. - Maximum predicted hydraulic downpull on upper gate - dual-gate operation.

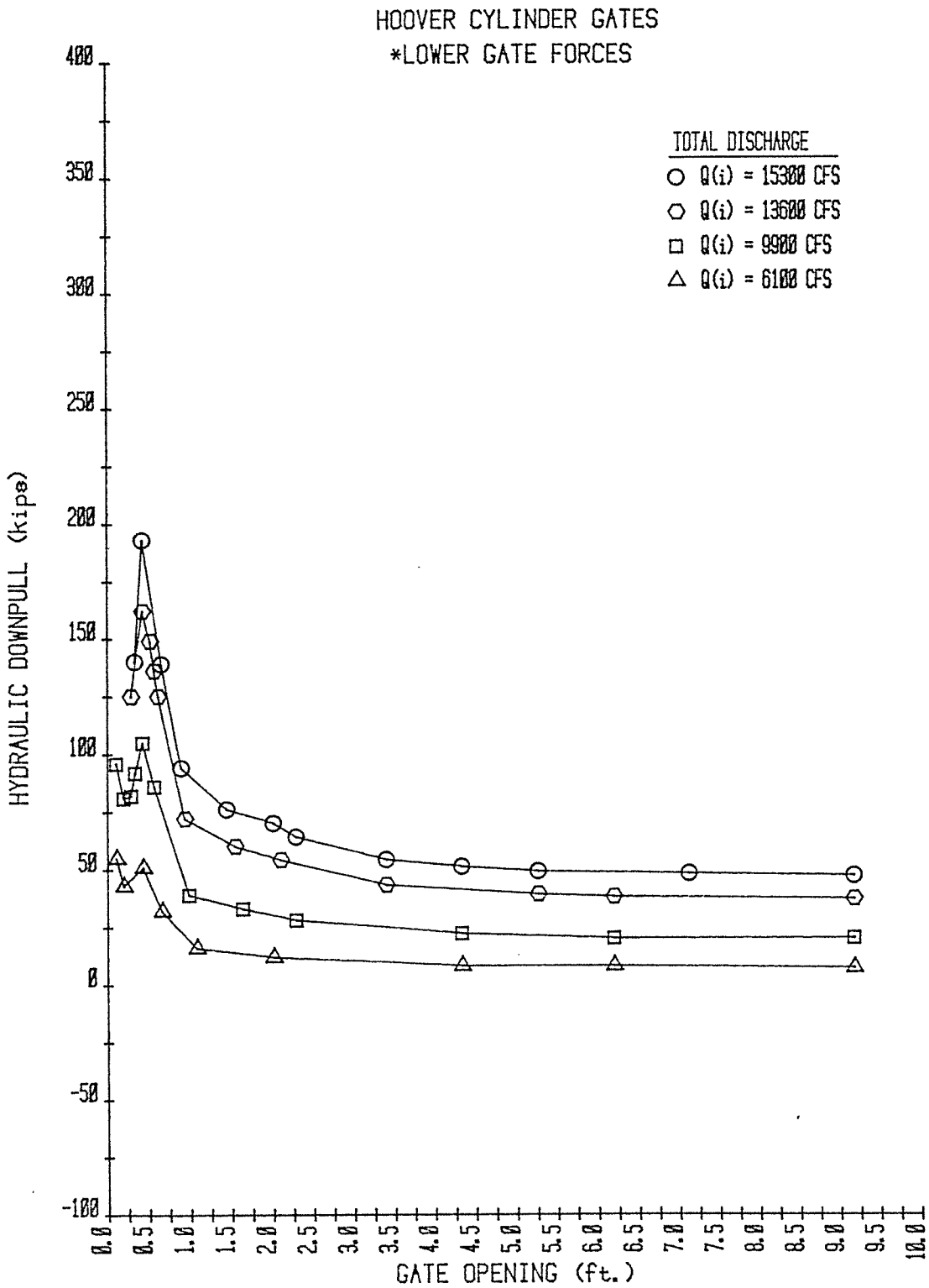


Figure 15. - Hydraulic downpull on lower gate - dual-gate operation.