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16. ABSTRACT

Vertical stilling wells are economical and ideally suited to dissipate high energy pipe flow. Model studies established general design criteria for vertical stilling wells using a standard sleeve valve. Dimensionless parameters based on design discharge, Q, and valve diameter, D, were established to aid the designer in determining optimum well size for a specific need. Over 100 tests were conducted with 2 laboratory models to determine stilling well geometry. The wave runup measured along the side slope of the downstream channel was used for all tests as the criterion for the efficiency of energy dissipation of each well configuration. Generally, a well depth-to-width ratio of 1.5 will give the best results. The corner angle configuration yields a smoother tailwater surface than the corner fillet and is a more economical design. Pressure distribution tests have not pinpointed the cause of possible concrete erosion in the stilling well but possibly such erosion may be alleviated or completely eliminated by placing the standard sleeve valve on the floor and by removing the pedestal and the pipe stand sleeve supports. A graphical method of presentation aids the designer in sizing a vertical stilling well. Three design examples are included. Has 9 references.

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HYDRAULIC MODEL STUDIES OF VERTICAL STILLING WELLS

by
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February 1973

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Division of General Research
Engineering and Research Center
Denver, Colorado

UNITED STATES DEPARTMENT OF THE INTERIOR * BUREAU OF RECLAMATION
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PURPOSE

For many years the Bureau of Reclamation has utilized the vertical stilling well as an efficient means of energy dissipation. The relative protection against abrasion and cavitation erosion provided by this energy dissipator and its potential to receive and still discharges from manifolded outlets more economically than a stilling basin have also been recognized. In the past, individual model studies have been used to develop each specific stilling well design. However, the economics of today do not justify such individual studies on small structures. Since no two structures were exactly alike, attempts to generalize the design from the individual studies were futile. Therefore, a research program was established to develop general design criteria for the vertical stilling well. This report reviews the laboratory work to date and presents design rules to aid the designer in determining optimum well geometry for his specific need.

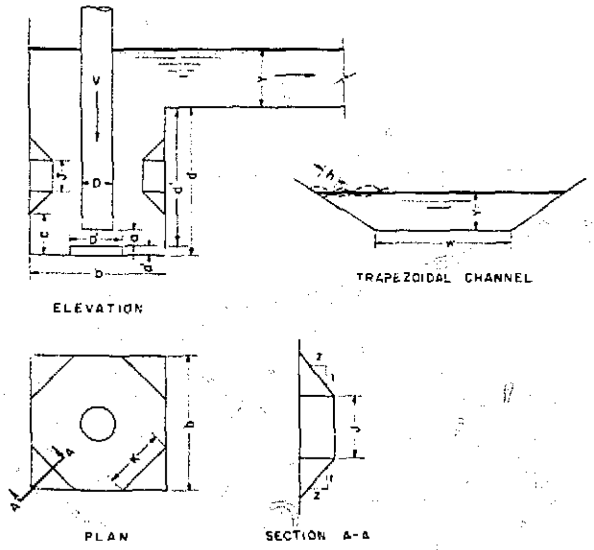


Figure 1. Hydraulic and structural variables (corner fillet design)

CONCLUSIONS

1. General design criteria have been established to determine well size based on design discharge, Q, and diameter of the standard sleeve valve, D.

2. Dimensionless parameters have also been established for the corner fillet and corner angle configurations. Optimum values for the parameters are as follows:

Corner fillet	*Corner angle*
C/b = 0.100	T/b = 0.053
J/b = 0.210	L/b = 0.333
K/b = 0.417	$\alpha = 45^\circ$
Z = 1.4	C/b = 0

The well dimensions are defined in Figures 1 and 2.

3. The corner angle configuration yields a smoother tailwater surface than the corner fillet configuration and is a more economical design.

4. The present method of supporting the pipe stand and standard sleeve valve should be modified to eliminate cavitation-generating obstructions in the high-velocity jet leaving the standard sleeve valve.

5. Some concrete erosion of prototype stilling well walls and floors has been reported. This may be attributed to the high-velocity roller which develops in the zone between the pedestal and the stilling well wall. It is therefore recommended that the standard sleeve valve be placed on the floor of the stilling well with the floor properly protected against possible cavitation or abrasion damage.

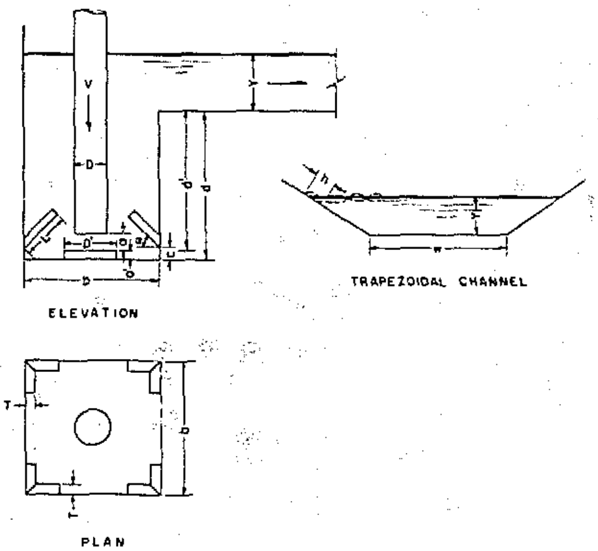


Figure 2. Hydraulic and structural variables (corner angle design)

6. The cause for the erosion of concrete in some of the present vertical stilling wells has not been positively identified. However, with removal of the pedestal and the pipe stand sleeve valve support, such erosion may be alleviated or completely

eliminated. Because of such experience designers have elected, on recent designs, to protect the walls with stainless clad steel plate. Studies indicate that protection may be required to a height 1.5 D (inlet pipe diameter) above the valve seat.

APPLICATION

Design criteria for sizing the vertical stilling well are established and will be quite useful where the standard sleeve valve is used. Additional studies will be required to properly size the stilling well where a multijet (ported) sleeve valve is desired.

INTRODUCTION

Mechanics of Operation

Vertical stilling wells (Figures 1 and 2) are ideally suited for dissipation of high-energy pipe flow. However, the energy dissipation characteristics of the well are quite complex. The pipe discharge enters the stilling well along a vertical axis through a control valve fastened to the floor of the well at the terminus of the pipe. The high-velocity jet, which leaves the valve seat in a radial-horizontal pattern, converges in the four corners of the well. The convergence of the radial flow results in very intense vertical flow in the corners. The corner fillets direct this vertical flow from the lower corners into the center of the well creating a roller action which adds to the turbulence and energy dissipation. The flow rises vertically in the well where it is stilled and then discharged with a smooth water surface into a horizontal canal or chamber.

Previous Investigations

As early as 1947, the Hydraulics Laboratory of the Bureau of Reclamation studied designs of the vertical stilling well[1*, 2, 3]. The discharge control in the early stilling wells utilized an in-line valve. The possibility of occurrence of cavitation downstream of the regulating valve was recognized and recommendations were made to develop a suitable cavitation-free control valve[1, 2].

Modifications to the original Masonville Siphon turnout structure[1] included: Placing a 1-foot-high (0.305-meter) pedestal on the stilling well floor directly beneath the discharge pipe, lowering the discharge pipe to within 1 foot (0.305 meter) of the pedestal, and various modifications to the baffle wall between the stilling well and the weir box immediately downstream from the stilling well. The various stilling well configurations investigated in the blowoff structure for the Soap Lake Siphon[2] were valuable in setting the trend for later designs. The configurations investigated in the model well included: cylindrical floor pedestal, pedestal with teeth, circular shelf above floor, square blocks in corners of floor, triangular corner shelves, corner floor blocks with corner fillets on walls, octagonal well, circular wall, baffle wall, and corner fillets. The configuration yeilding the most satisfactory water surface was the corner fillet design. The octagonal well also produced a satisfactory water surface but the corner fillets offered a simpler design. The criterion used to measure the efficiency of energy dissipation was the wave runup along the 1.5 to 1 side slope of the downstream channel.

The idea of using a circular stilling well was also investigated in the laboratory. Data from the studies suggest a problem with surface boils around the wall of the stilling well. Attempts to place a circular baffle in the well to alleviate the rough surface resulted in surface boils around the downspout, creating a rougher surface than before. The unpublished results of these tests confirmed that the circular well was less effective than a square well.

In the early 1950's a suitable sleeve valve was developed by the Bureau of Reclamation for the Wanship Dam stilling wells. The effective energy dissipation characteristics of the vertical stilling well combined with the new "sleeve valve" design resulted in an economic and efficient energy dissipator. Data collected by D. Colgate during the period February to May 1954 and reported by H. T. Falvey[4] related the required tailwater depth in the vertical stilling well to the total head on the valve and the design discharge. A procedure was presented in the report whereby other geometrically similar stilling wells could be sized using a scale factor.

The development of the sleeve valve greatly improved the potential of the vertical stilling well as an energy dissipator. The sleeve valve placed the vertical stilling well in competition with other high-head energy dissipators. The success of the vertical stilling well prompted the Bureau of Reclamation to initiate a research program to develop general design criteria covering a wide range of heads and discharges. In the period from 1962 to 1970, studies involving several investigators were performed to optimize the design of the vertical stilling well. Although unpublished, the work was significant in developing the generalized design criteria published in this report.

*Numbers designate references at end of text.

THE INVESTIGATION

Physical Description of 3-foot Model

A 3-foot (0.915-meter) square model (Figure 3) constructed for the previous studies was utilized for some of the tests reported herein. The original model stilling well, constructed of wood with sheet metal lining, was 4 feet by 4 feet (1.22 by 1.22-meter) in plan with a maximum available depth of 6 feet (1.83-meter). In later studies, the well was changed to a 3- by 3-foot (0.915- by 0.915-meter) well by placing plywood false walls in the larger well. Various diameter downspouts ranging from 6 to 12 inches (15.24 to 30.48-cm) were tested. The distance between the downspout and the stilling well floor could be varied through the use of an adjustment mechanism consisting of a dresser coupling and three threaded rods supporting the downspout, which were connected with sprockets and a link chain, Figure 3.

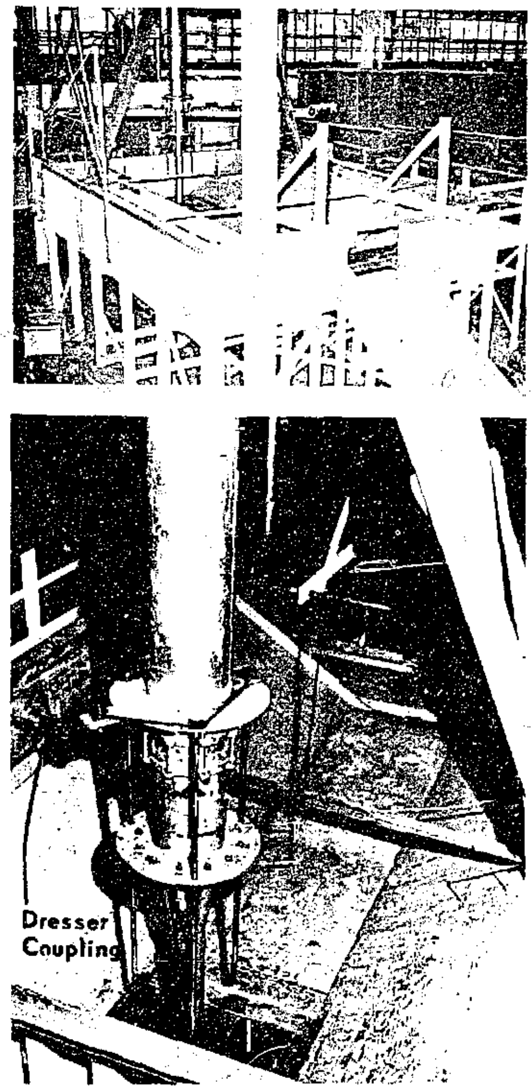


Figure 3. View of 3-foot model. Photos P801-D-73020 and P801-D-73021

The downstream portion of the model consisted of a trapezoidal channel with 1.5 to 1 side slopes. The bottom width of the channel, w, was 3 feet (0.915-meter), the same as the well width, b. Flow was supplied to the model by a 12-inch (30.48-cm) centrifugal pump and was measured by one of a bank of Venturi meters permanently installed in the laboratory. The tailwater elevation was controlled by an adjustable tailgate. This model was used to confirm the tests conducted on the 9-inch (22.9-cm) model.

Physical Description of 9-inch Model

A 9-inch (22.9-cm) square plexiglass model (Figure 4) was constructed to a 1:4 scale of the large model and used for the majority of the tests by the author. The plexiglass model had several obvious advantages over the larger model. The research program called for a thorough study of the stilling well geometry. Variations in the well depth, valve opening, and fillet size and location were easily made in the small model. The capability to observe and photograph the flow patterns in the well proved very helpful throughout the investigation.

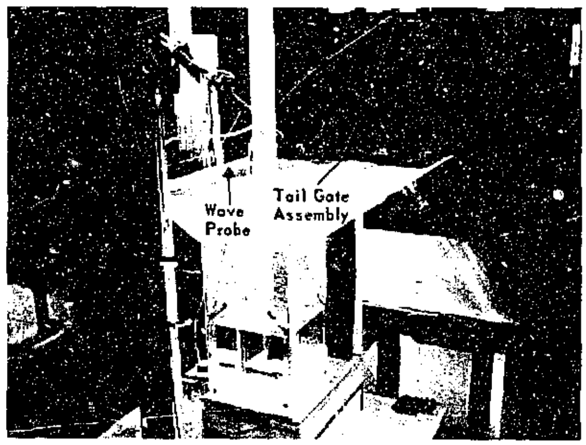


Figure 4. View of 9-inch model. Photo P801-D-73030

A 2-inch (5.08-cm) sleeve valve was constructed of plastic and used in the tests involving pressure distribution on the walls and floor of the well. Flow was supplied to the model through a fireline with available pressure up to 90 pounds per square inch (0.63kg/sq cm). A valve upstream of the model throttled the flow. A tail box with a 90° V-notch weir was used to measure the discharge. Head immediately upstream of the sleeve valve was measured with a mercury manometer. Wave runup on the side slopes of the downstream channel was measured with a capacitance wave probe and recorded on a strip chart recorder.

This model was used early in the investigation to determine the optimum values for the corner configuration dimensionless parameters.

Experimental Approach

The important hydraulic and geometric variables identified in the study were:

Variables Q, g, D, d, b, C, J, K, L, T, Z, α, H, a, Y

Dimensions $\frac{\ell^3}{t}, \frac{\ell}{t^2}, \ell, \ell, \ell, \ell, \ell, \ell, \ell, \ell, 0, 0, \ell, \ell, \ell$

where ℓ = length and t = time

A foldout summary sheet is included at the end of the appendix as an aid in identifying the variables.

It was desired to find a functional relationship between these variables and the wave height, h, in the downstream channel.

$$h = f_1 (Q, g, D, d, b, C, J, K, L, T, Z, \alpha, a, Y)$$

There are 15 variables and 2 dimensions. Using the Buckingham π - theorem, the variables may be arranged into 13 independent dimensionless groupings. The method used to determine the groupings of the variable is to select a certain number of the individual variables to be repeating variables. The number depends on the number of different dimensions used in describing the variables. These repeating variables should collectively contain all of the dimensions and appear in each grouping along with one of the other variables.

Since two dimensions are involved in this case, two repeating variables are selected. The variables g and b will be the repeating variables. The variable, g, has both dimensions, ℓ and t, and b is the basic well variable.

The 13 groupings follow:

$\pi_1 = g^x b^y Q$	$\pi_7 = L/b$
$\pi_2 = D/b$	$\pi_8 = T/b$
$\pi_3 = d/b$	$\pi_9 = Z$
$\pi_4 = C/b$	$\pi_{10} = \alpha$
$\pi_5 = J/b$	$\pi_{11} = h/b$
$\pi_6 = K/b$	$\pi_{12} = a/b$
	$\pi_{13} = Y/b$

The two repeating variables were used only in the first grouping since there are no other unique groups which can be formed using both variables. Since Z and α are dimensionless, they form independent groups.

To determine the exponents x, and y, in π_1:

$$\pi_1 = g^x b^y Q = (\ell t^{-2})^x (\ell)^y (\ell^3 t^{-1})$$

Since π_1 is to be dimensionless, the expondents of the dimensions ℓ and t are, in turn, set equal to zero.

Therefore:

for (ℓ) $\quad x + y + 3 = 0$

for (t) $\quad -2x - 1 = 0$

$$\therefore x = -\frac{1}{2}$$

and $\quad y = -\frac{5}{2}$

Therefore $\quad \pi_1 = \frac{Q}{\sqrt{gD^5}}$

and

$$f_2\left(\frac{Q}{\sqrt{gD^5}}, \frac{D}{b}, \frac{d}{b}, \frac{C}{b}, \frac{J}{b}, \frac{K}{b}, \frac{L}{b}, \frac{T}{b}, Z, \alpha, \frac{h}{b}, \frac{a}{b}, \frac{Y}{b}\right) = 0$$

It is convenient to:

1. Square $\pi_1 \rightarrow \frac{Q^2}{gD^5}$ (Figure 5)

2. Divide π_{12} by $\pi_2 \rightarrow \frac{a}{D}$ (defines % valve opening)

3. Divide π_{11} by $\pi_{13} \rightarrow \frac{h}{Y}$ (Figure 5)

Therefore:

$$f_3\left(\frac{Q^2}{gD^5}, \frac{D}{b}, \frac{d}{b}, \overbrace{\frac{C}{b}, \frac{J}{b}, \frac{K}{b}, \frac{L}{b}, \frac{T}{b}}^{\text{Well Corner Geometry}}, Z, \alpha, \frac{h}{Y}, \frac{a}{D}, \frac{Y}{b}\right) = 0$$

or

$$\frac{h}{Y} = f_1\left(\frac{Q^2}{gD^5}, \frac{n}{b}, Z, \alpha\right) \qquad (1)$$

where n = any of the length variables.

In the tests for optimization of the well geometry the valve opening was constant at 100 percent (defined as a/D = 0.5) and the water depth in the canal was maintained at a constant ratio of Y/b = 0.5.

The 9-inch (22.9-cm) model with a 2-inch (5.08-cm) valve was utilized to develop the optimization of the stilling well upon which the general design criteria are based. The D/b ratio for the tests was thus 0.22. Table 1 illustrates the values of each variable tested. Over 100 test runs were conducted with combinations of values for the above mentioned variables.

Wave Analysis

The wave runup, h, measured along the 1.5 to 1 side slope of the downstream channel was used for all tests as the criterion for the efficiency of energy dissipation of each well configuration. The amplitude of the wave runup was irregular; therefore, a statistical approach was adopted to effectively reduce data. The wave amplitude was assumed to follow a Normal distribution such that:

$$X_{95} = 1.645\,\sigma + \mu,$$

where X_{95} was the wave amplitude, h, along the side slope (Figure 1) which 95 out of 100 waves would not exceed, 1.645 is from statistical tables for Normal distributions at the 95 percent probability level, σ is the population standard deviation, and μ is the population mean. Since measurement of μ and σ is not possible, the sample mean $(\bar{x})$ and the sample standard deviation (s) of 40 observations were used. A computer program performed the computation for X_{95} with 40 wave amplitudes taken from the wave trace. For each test setup, three or more discharges and associated wave traces were obtained.

TEST RESULTS

Sizing the Vertical Stilling Well

In order to present the designer with a concise and accurate method of sizing the vertical stilling well, a graphical method of presentation was adopted. Equation (1) implies that the degree of energy dissipation, represented by the downstream water surface wave action, h/Y, is a function of the flow parameter, Q^2/gD^5, and several dimensionless parameters, n/b Z and α, representing various aspects of the stilling well geometry. The variables C, J, K, L, and T represent the dimensions for the well corner geometry (Figures 1 and 2). Previous investigations have attempted to express these variables as constant dimensionless parameters. Assuming these variables can be expressed in this manner, the remaining parameters are; Q^2/gD^5, h/Y, D/b, and d/b. Figure 5 illustrates the proposed relationship, h/Y = f(Q^2/gD^5, D/b) for d/b = constant. Individual graphs representing different values of d/b are presented in the General Design Criteria section of this report. The development of these graphs will follow the optimization of the dimensionless parameters.

The designer will be equipped to size the vertical stilling well once the graphs and optimization of the dimensionless parameters are established. The flow parameter, Q^2/gD^5, can be calculated upon selection of the design discharge, Q, and pipe diameter, D. Selection of the well depth-to-width ratio d/b will determine the proper graph to use. The d/b ratio will depend on the designers judgment, where deep excavation is relatively costly a smaller d/b ratio may be desired. Another aspect to be considered is the high-velocity jet leaving the valve. For high head installations, lower d/b ratios will provide a greater distance, and therefore more energy dissipation, between the valve outlet and the stilling well wall. In general a d/b ratio equal to 1.5 will give the best results.

As shown in Figure 5, the proper selection of the pipe diameter to well width value D/b, will depend on the desired value of h and the calculated value of Q^2/gD^5. Once the D/b value has been selected, the value for b and the other variables can be calculated, since the pipe diameter, D, is known.

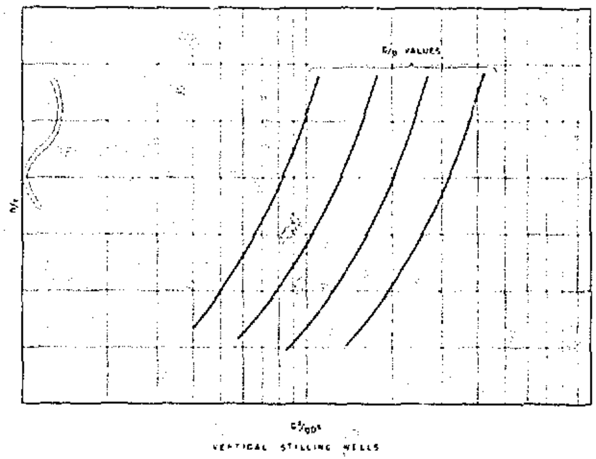


Figure 5. Concept of general design curves

Corner Fillet Design

In the development of a vertical stilling well design for Soap Lake Siphon[2], corner fillets similar to those shown in Figure 1 were tested and found to yield a very smooth water surface. The corner fillet design of the vertical stilling wells for Wanship Dam was similar to that developed for the Soap Lake Siphon stilling well. To provide adequate design criteria for the vertical stilling well the corner fillet measurements in the present study are expressed in dimensionless form applicable to a wide range of discharges.

Table II lists as dimensionless parameters the optimum fillet measurements developed by various investigators. As indicated in Table II, an approximate value of K/b equal to 0.415 was the consensus of the investigators. In plan, this yields an octagonal vertical water passage. There was considerable scatter among the values for J/b, C/b, and Z. As a result of this review, studies were undertaken on the 9-inch (22.9-cm) model to determine independently the optimum values for J/b, C/b, and Z.

Data collected for the corner fillet design are tabulated in the Appendix. The wave height parameter h/Y was established as the criterion to measure effective energy dissipation of the well geometry.

Table I

VALUES OF VARIABLES TESTED ON 9-INCH MODEL

Variable	Values tested—inches (cm)
Q	Variable
D	2 (5.08)
a	1/2, 1, 2 (1.27, 2.54, 5.08)
b	9 (22.86)
d	9, 13-1/2 (22.86, 34.29)
Y	1.5 (3.81)
a'	0, 1, 2 (0, 2.54, 5.08) (Figure 1)
D'	2-1/2, 3 (6.35, 7.62) (Figure 1)
C	0, 0.26, 0.80, 1.05, 1.42, 1.55, 1.80 (0, 0.66, 2.03, 2.67, 3.61, 3.94, 4.57)
J	0.5, 1.0, 1.5, 2.0, 4.0, 5.5 (1.27, 2.54, 3.81, 5.08, 10.16, 13.97)
K	3.75 (9.53)
L	2.5, 3.0, 3.3, 3.73, 5, 6.3 (6.35, 7.62, 8.38, 9.47, 12.70, 16.00)
T	0.30, 0.40, 0.48, 0.50, 0.525, 0.60 (0.76, 1.02, 1.22, 1.33, 1.52)
Z	0.70, 1.43 (1.78, 3.63)
α	30°, 45° 60°

Table II

OPTIMUM DIMENSIONLESS PARAMETERS DEVELOPED BY VARIOUS INVESTIGATIONS

Project	d/b	K/b	J/b	C/b	Z
Soap Lake	1.5	0.411	0.241	0.135	0.7
Wanship	1.5	0.411	0.250	0.250	0.7
*Work by Denson	1.0	0.417	0.445	0.021	1.4
	1.5	0.417	0.666	0.104	1.4
	2.0	0.417	0.890	0.188	1.4
*Work by Matchett	1.5	0.269-0.472	—	0.095	1.4
*Work by Wu	1.5	0.269-0.472	—	0.100	1.7
Work by author	1.0	0.417	0.190	0.100	1.4
	1.5	0.417	0.225	0.100	1.4

*Unpublished

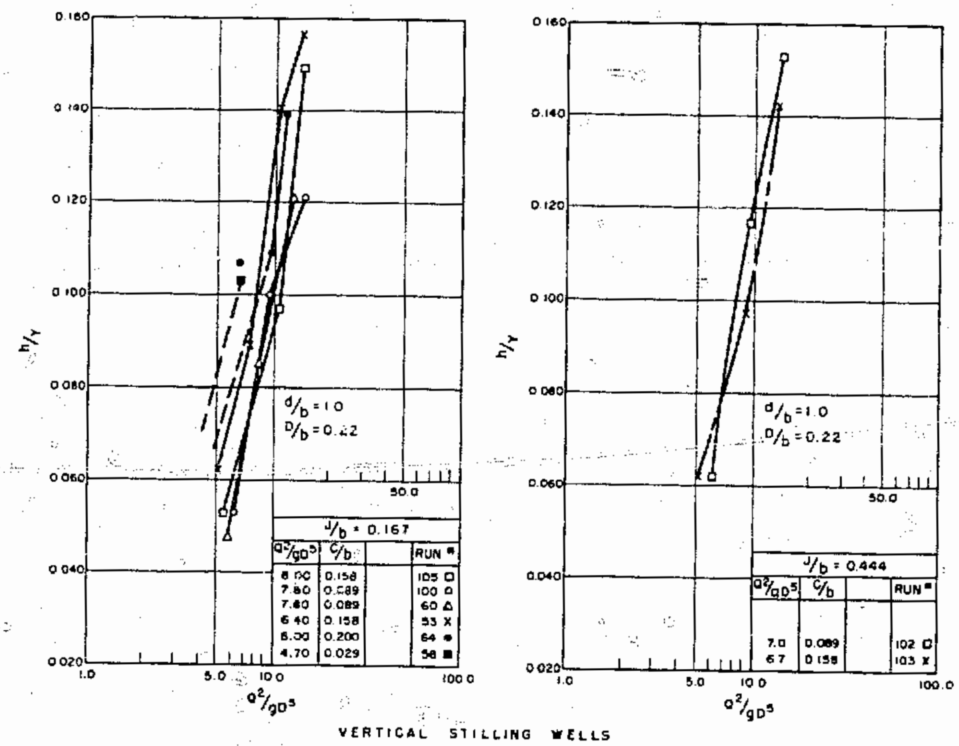


Figure 6a. h/Y vs. Q^2/gD^5 for variable C

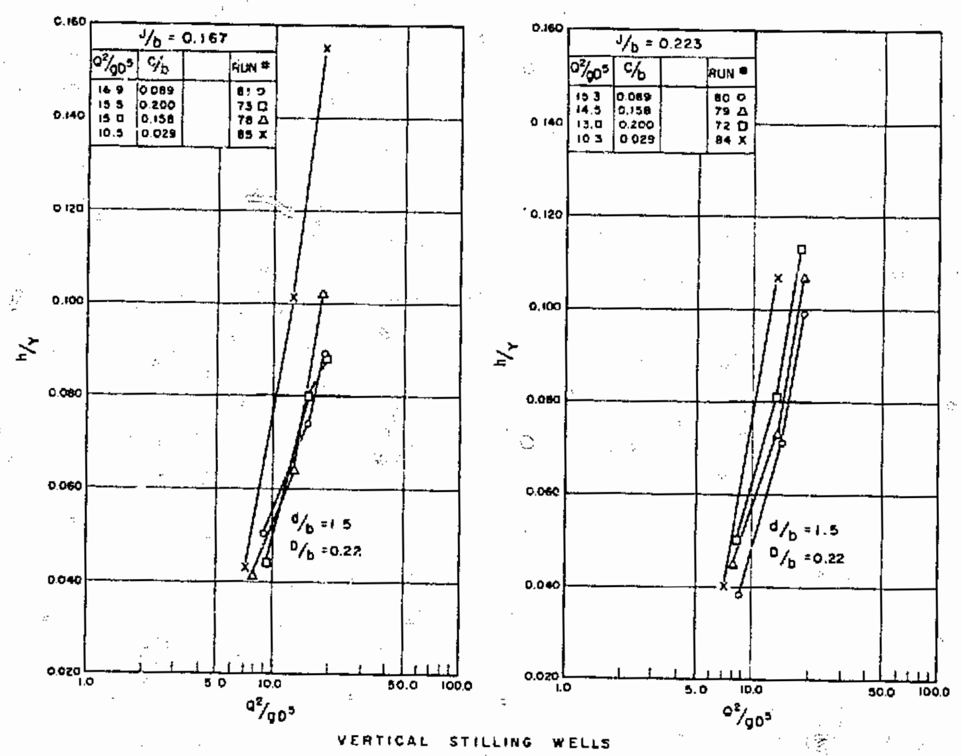


Figure 6b. h/Y vs. Q^2/gD^5 for variable C

Determination of the optimum fillet height ratio C/b—A series of tests was conducted, varying C, for several values of J/b. Figure 6a is a plot of the test results obtained for well depth d equal to well width b, or d/b = 1. Figure 6b is a plot of the test results conducted for d/b = 1.5. Data from this series of tests are tabulated on Data Sheets 2 and 3 in the Appendix.

A tailwater surface fluctuation of h/Y = 0.080 was selected as the standard on which to compare the efficiency of energy dissipation for various fillet height ratios, C/b. Figure 7 illustrates the optimization of the dimensionless parameter C/b using several plots representing different J/b values to maximize Q^2/gD^5 with respect to C/b, based on h/Y = 0.080 from Figures 6A and 6B. The various curves in Figure 7 indicate the following trend:

when d/b = 1.0, C/b = 0.100;
when d/b = 1.5, C/b = 0.100

It is therefore concluded that the variable C is directly proportional to the variable b, and that the dimensionless parameter C/b = 0.10 represents the optimum value.

Determination of the optimum fillet length ratio J/b—A series of tests was also conducted, varying J, for several values of C/b. Figure 8a is a plot of the test results conducted for d/b = 1.0 and Figure 8b for d/b = 1.5. Data from this series of tests are tabulated on Data Sheets 4, 5, and 6.

Figure 9 illustrates the optimization of the fillet length ratio, J/b, using several plots representing different values of C/b to maximize Q^2/gD^5 with respect to J/b based on h/Y = 0.080 from Figures 8a and 8b. The various curves of Figure 9 indicate the following trend:

when d/b = 1.0, J/b = 0.225;
when d/b = 1.5, J/b = 0.190

It is concluded that the variable J is also directly proportional to b, and that the dimensionless parameter J/b = 0.21 best describes the average optimum value.

Determination of the bottom slope, Z—The early vertical stilling wells such as Soap Lake and Wanship had a bottom slope on the corner fillet of 0.71 to 1.0. Later investigations in the laboratory showed that a 1.4 to 1.0 bottom slope on the corner fillet resulted in a much smoother water surface. Figure 10 illustrates the improved tailwater surface fluctuation h/Y with the 1.4 to 1.0 slope compared to the 0.71 to 1.0 slope (Data Sheet 6). The top slope of the corner fillet is not critical and can be in the range from horizontal to 1.4 to 1.0.

In order to observe the flow patterns present in the well, air was injected into the upstream pipe, after test data were recorded for each run. Photographs were taken through the sidewall with the air bubbles illuminated by light through 1/4-inch slits in the center of the otherwise darkened sidewalls. Photographs were also taken to show the flow pattern around the corner fillets or corner angles. Figure 11 best illustrates the flow pattern for the recommended corner fillet design.

Corner fillet work by Denson—In 1966, Keith H. Denson* completed a series of tests using the 3-foot (0.92-meter) vertical stilling well model. He established constant values for the dimensionless parameters C/d, J/d, and K/b, based on studies for well depth to width ratio, d/b = 1.5. He assumed the values for these parameters also would be constant for d/b = 1 and d/b = 2. Figure 12 illustrates the relationship between h/Y and Q^2/gD^5 for d/b = 1 and d/b = 1.5, using Denson's and the author's data for the 3-foot model where D/b = 0.22 (Data Sheet 7). The duplication of the data for d/b = 1.5 further adds to the validity of C/b = 0.100 since the value of C/b for Denson's work is very close to the author's (C/b = 0.104) for d/b = 1.5 (Table II).

However, data for d/b = 1.0 do not agree, Figure 12. The author's data indicate less wave height, h/Y, for a given value of Q^2/gD^5 than those data given by Denson's studies. Table II also indicates a considerable difference in the value of the fillet height ratio, C/b, for Denson's and the author's optimum value at d/b = 1.0 (0.021 vs 0.100).

The optimization curves for C/b and J/b in Figures 7 and 9 indicate that for values below their respective optimum value the curves fall off rapidly. For values above their respective optimum value the curves decrease much more slowly.

The fact that the fillet length ratio, J/b, for Denson and the author do not agree for d/b = 1.5 (Table II), although the design curves agree in Figure 12, is an indication of the relative unimportance of the value of J/b once above the optimum value of 0.210, Figure 9.

Denson established a series of curves for values of D/b = 0.33, 0.28, 0.22, and 0.17 on three graphs for d/b = 1.0, 1.5, and 2.0. These curves are shown in Figure 13.

*Mr. Keith H. Denson, Associate Professor of Civil Engineering, Mississippi State University, spent the summer of 1966 working in the Hydraulics Branch of the Bureau of Reclamation's Division of General Research.

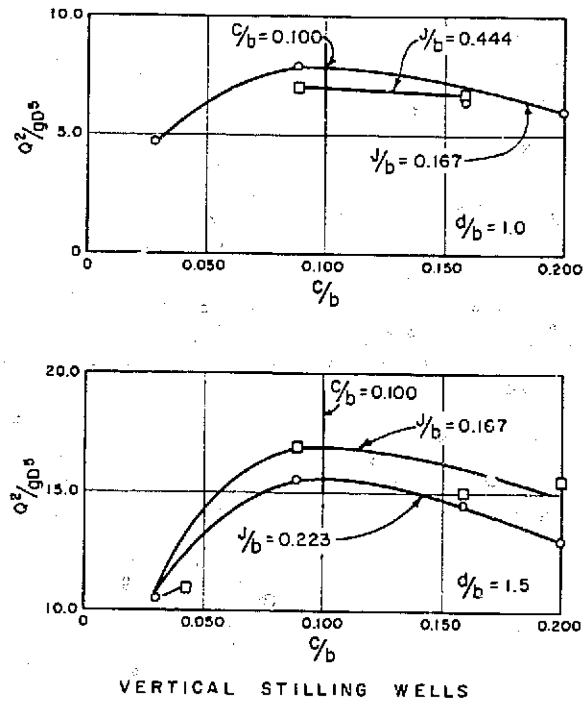


Figure 7. Optimization of C/b

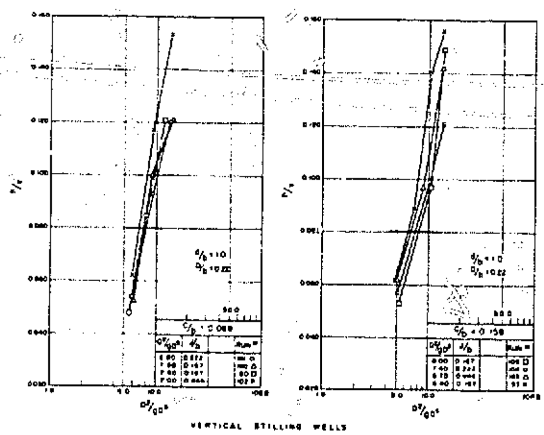


Figure 8a. h/Y vs. Q^2/gD^5 for variable J

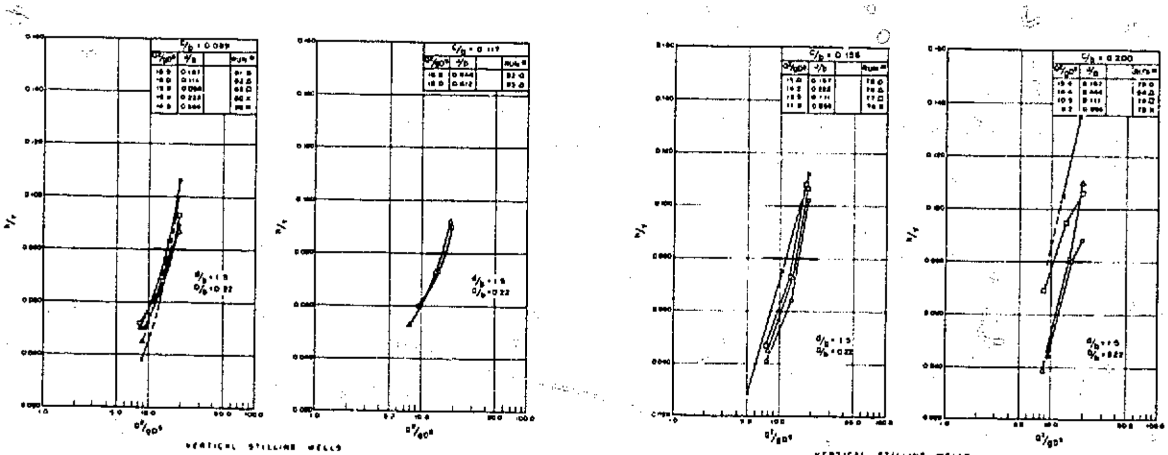
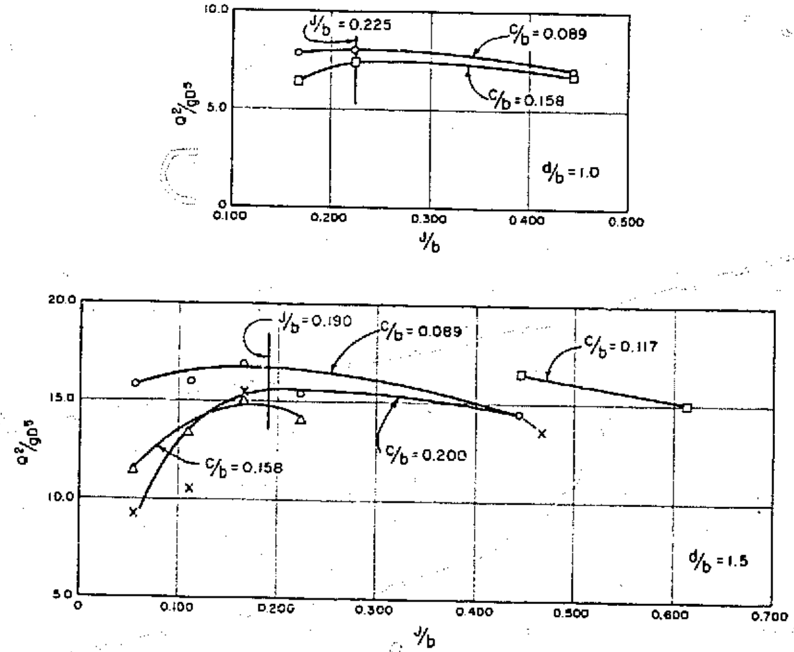
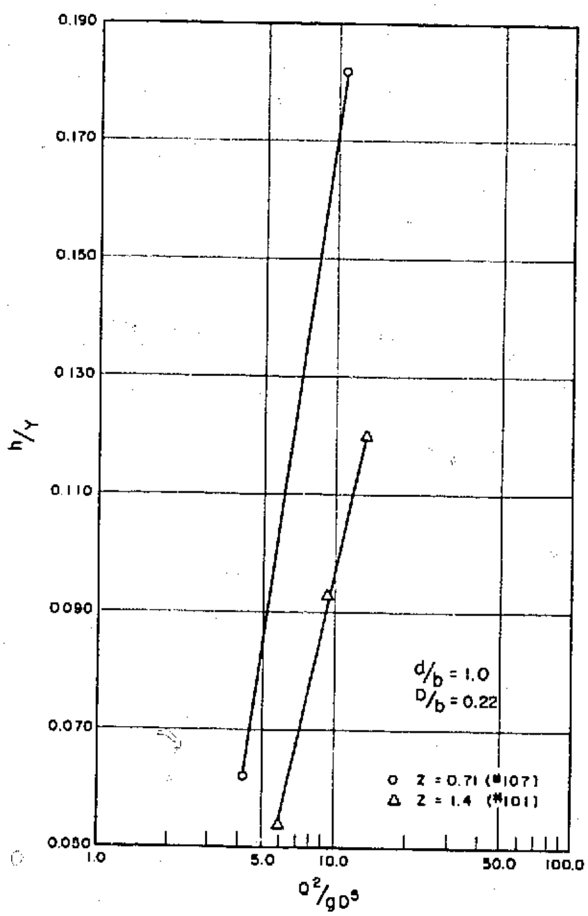


Figure 8b. h/Y vs. Q^2/gD^5 for variable J



VERTICAL STILLING WELLS

Figure 9. Optimization of J/b



VERTICAL STILLING WELLS

Figure 10. h/Y vs. Q^2/gD^5 for variable Z

a. Flow pattern in well bottom. View from side
P801-D-73025

b. Flow pattern around corner fillet. View from corner
P801-D-73026

Figure 11. Corner fillet design
C/b = 0.089, J/b = 0.167, K/b = 0.415, Z = 1.4

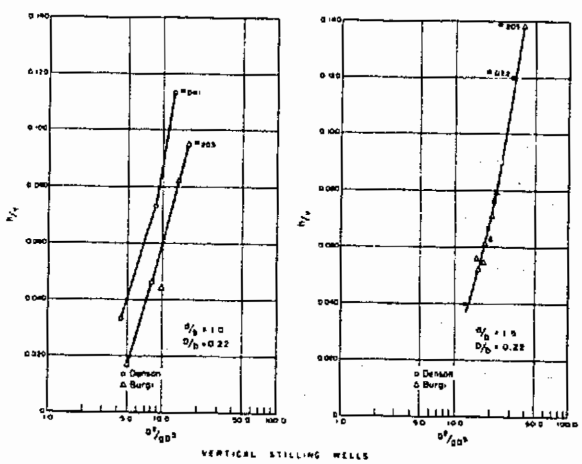


Figure 12. Optimum h/Y vs. Q^2/gD^5 3 foot model

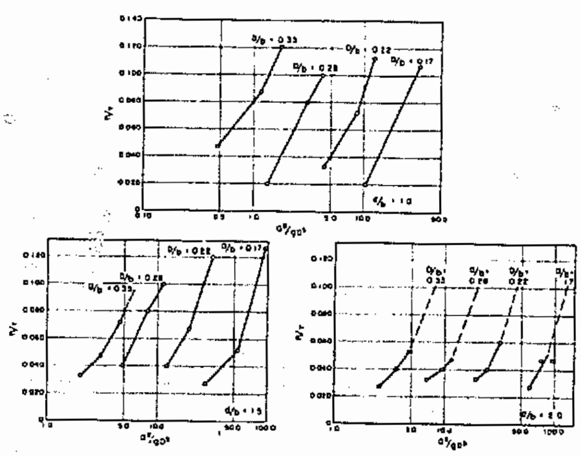


Figure 13. h/Y vs. Q^2/gD^5 (Work by Denson)

Since Figure 12 verified the agreement between Denson's and the author's data for d/b = 1.5 when D/b = 0.22, the curves of D/b = 0.33, 0.28, and 0.17 were accepted without further verification. Although Denson's work for d/b = 2.0 was not verified by the author, it was his opinion that these data should also be accepted and used for sizing the vertical stilling well. Since the optimization curves for C/b and J/b (Figures 7 and 9) decreased very slowly for values above the optimum and since Denson's C/b and J/b ratios for d/b = 2.0 both exceeded the optimum ratio, Denson's d/b = 2.0 curves were accepted for use in the General Design Criteria section. However, data for d/b = 1.0 were not accepted due to the disagreement in Figure 12.

Corner Angle Design

The 9-inch (22.9-cm) stilling well was also tested using *small angles*, which on the prototype scale would be ordinary angle iron and would result in a more economical stilling well. The optimum angle length, L, and angle width, T, were determined with respect to well width, b, Figure 2. The height of the angles above the well floor, C and angle, α, were also determined.

Determination of the optimum angle width ratio, T/b, and length ratio, L/b—To optimize the angle width radio, T/b, a series of tests was conducted, varying T, for several values of L/b. Data from these runs for d/b = 1.0 and d/b = 1.5 are presented on Data Sheet 8. As with the corner fillet tests, a tailwater surface fluctuation, h/Y = 0.080, was selected as the standard on which to compare the efficiency of energy dissipation for various T/b ratios. Figure 14a illustrates the relationship between h/Y and Q^2/gD^5 for d/b = 1.0. Figures 14b and 14c illustrate the same relationship for d/b = 1.5.

In a similar series of tests the angle length ratio, L/b, was optimized. Data from these tests are presented on Data Sheet 9. Figure 15 illustrates the relationship between h/Y and Q^2/gD^5 for d/b = 1.0 and d/b = 1.5. Figure 16 illustrates the optimization of the T/b and L/b parameters by maximizing the flow parameter Q^2/gD^5 with respect to T/b and L/b based on h/Y = 0.080 from Figures 14 and 15. The curves in Figure 16 which extend over a wide range of L/b and T/b values maximize the flow parameter, Q^2/gD^5, at

L/b = 0.333
and T/b = 0.053

Determination of the Angle, α— Tests were also conducted to optimize the angle, α, Figure 2. Data from three tests are presented on Data Sheet 9. Figure

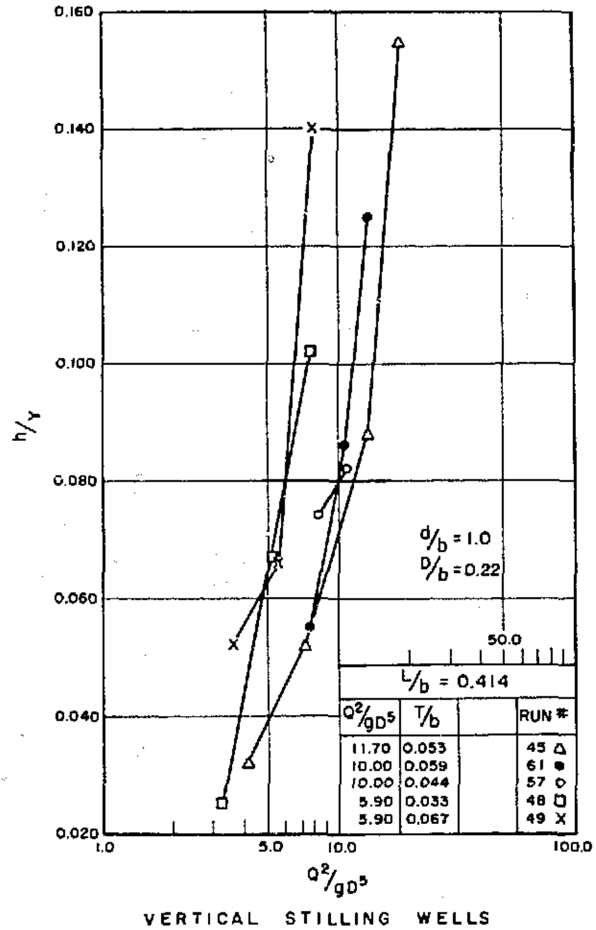


Figure 14a. h/Y vs. Q^2/gD^5 for variable T

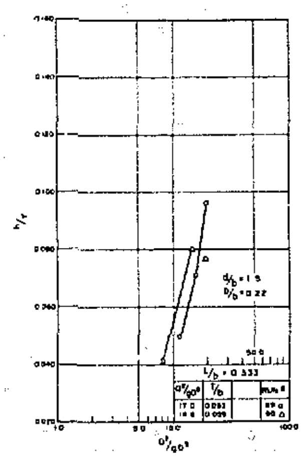


Figure 14b.

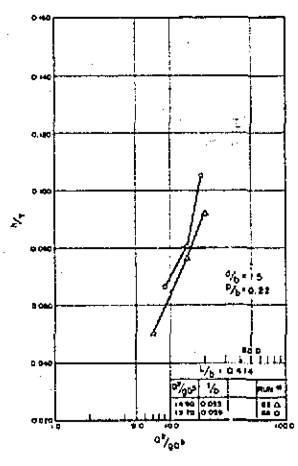


Figure 14c.

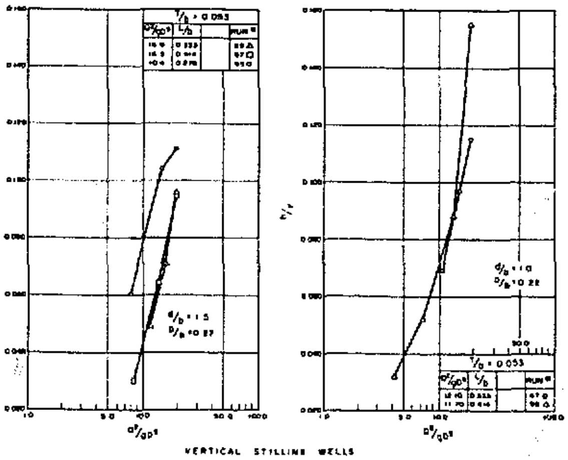


Figure 15. h/Y vs. Q^2/gD^5 for variable L

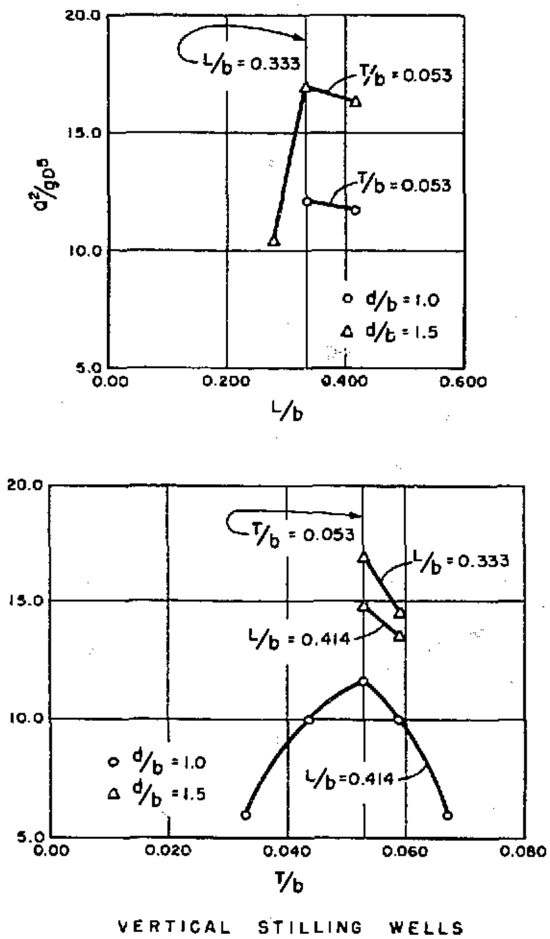


Figure 16. Optimization of T/b and L/b

17 illustrates the relation between h/Y and Q^2/gD^5 and indicates the optimum value of alpha to be 45°.

Determination of the variables a' and C—Four tests were conducted to determine the optimum values of pedestal height, a', and corner angle height, C, above the floor. Figure 18 illustrates these four tests. The flow parameter, Q^2/gD^5, is approximately the same for a' = 0 and a' = 1.0 inches (2.54 cm) but less for a' = 2.0 inches (5.08 cm) when h/Y = 0.080.

The pedestal does not improve the energy dissipation characteristics of the well. Figure 19 illustrates the flow pattern in the bottom of the well for a' equal to 0, 1 inch (2.54-cm) and 2 inches (5.08-cm).

In Figures 19B and 19C a high velocity roller is noted under the jet and bounded by the floor and pedestal walls. Any debris caught in the roller, including fine sediment, could produce a highly abrasive action against the concrete surfaces. The advantage of eliminating the pedestal, as shown in Figure 19A is evident.

Figure 20 illustrates the flow pattern with a' equal to 1.0 inch (2.54-cm) and pedestal diameter D' equal to 3.0 inches (7.62-cm). This flow pattern is very similar to that which occurs with Bureau of Reclamation stilling wells presently in use where the jet leaves the pedestal horizontally. Note the roller at the intercept of the sidewalls and floor.

The energy dissipation characteristics of the stilling well are not improved by the pedestal, Figure 18, and, since there is a potential for abrasion damage on the

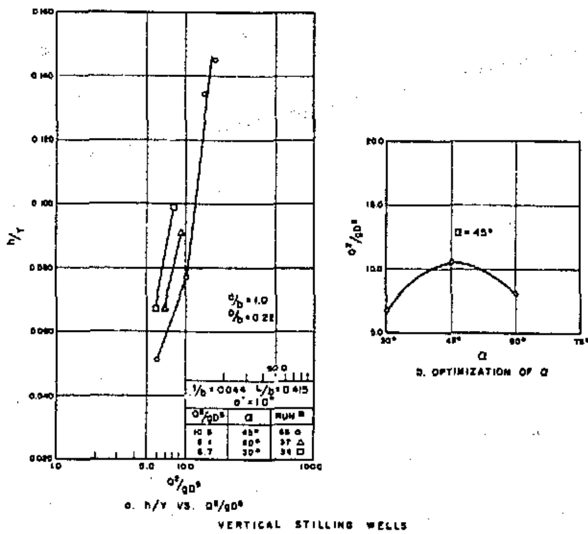


Figure 17. Optimization of α

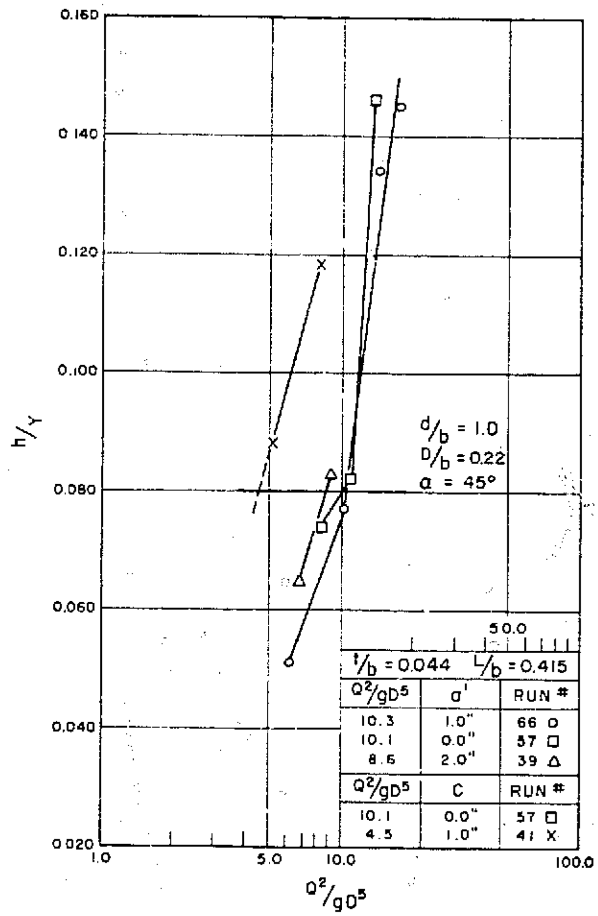


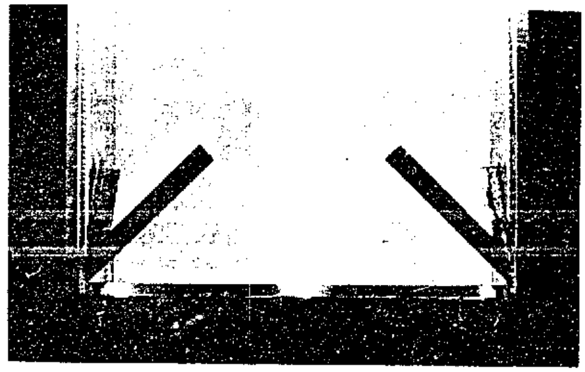
Figure 18. h/Y vs. Q^2/gD^5 for variables a' and C

boundaries of the well, it is recommended that the pedestal not be included in future designs.

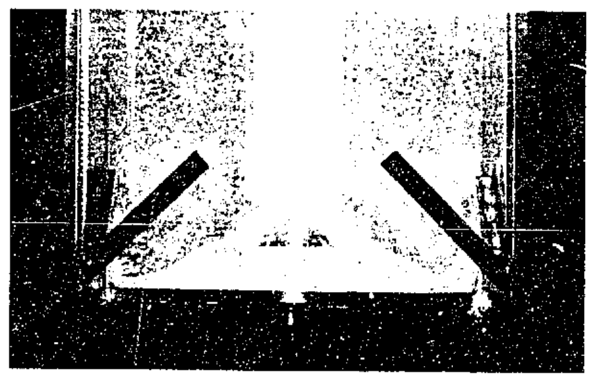
Raising the corner angles off the floor actually decreases the well efficiency with respect to wave action, Figure 18. Therefore, C = 0 was selected.

Figure 21 illustrates the energy dissipation characteristics of the vertical stilling well using angle irons in the corners, Run 67.

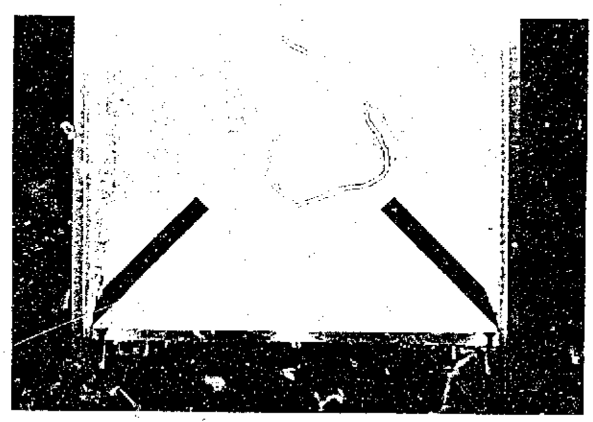
It is instructive to compare the corner fillet design (Figure 11) with the corner angle design (Figure 21). The turbulent roller action (dark area in lower portion of well) occurs lower in the well with the corner angles, resulting in a fairly uniform vertical flow in the upper half of the well (Figure 21b).



a. No pedestal, D' = 2-1/2 inches. Photo P801-D-73024



b. a' = 1 inch, D' = 2-1/2 inches. Photo P801-D-73027



c. a' = 2 inches, D' = 2-1/8 inches. Photo P801-D-73023

Figure 19. Effect of pedestal height on flow patterns

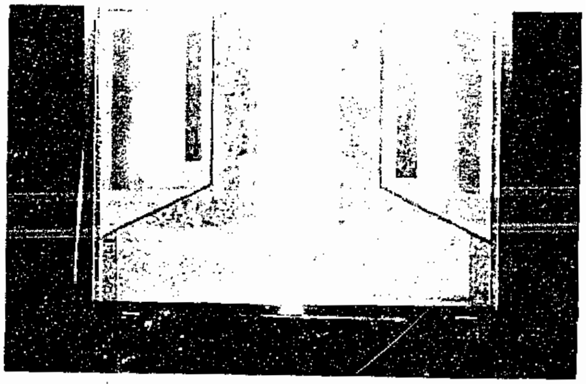
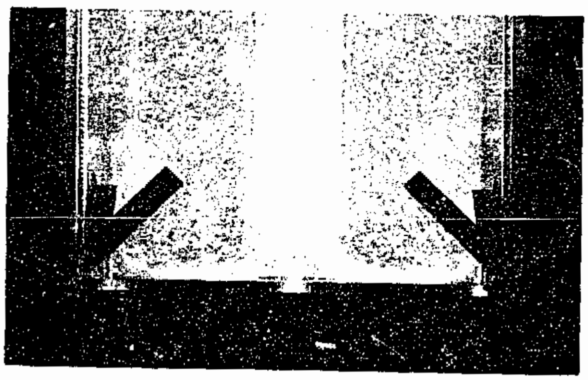
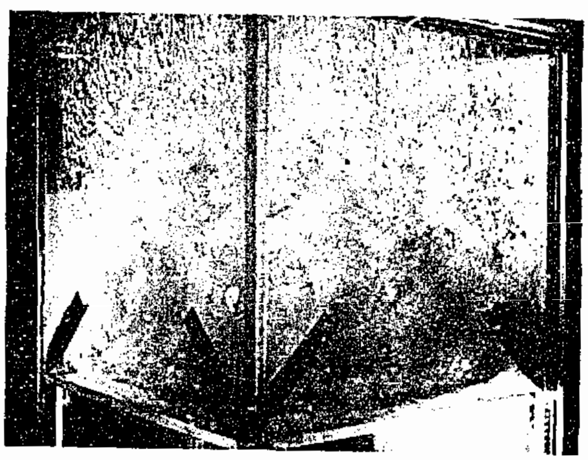


Figure 20. Flow pattern with wide pedestal
a' = 1" P801-D-73022



a. Flow pattern in well bottom. View from side
P801-D-73028

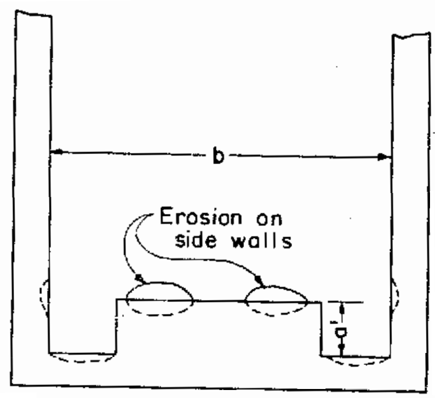


b. Flow pattern around corner angles. View from corner
P801-D-73029

Figure 21. Corner angle design
$T/b = 0.053$, $L/b = 0.333$, $\alpha = 45°$

Pressure Distribution

Several vertical stilling wells on Reclamation projects have experienced erosion of the concrete on the walls, floor, and pedestal. Various causes for the erosion have been proposed, including cavitation, foreign-abrasive materials in the well, sandblasting effect from silt in the flow, and impact of the high-velocity jet leaving the valve. Stilling well damage found in some field installations is diagrammed on Figure 22. The four sidewalls erode in a symmetrical pattern with two elliptical depressions on each sidewall. The depressions are at the level of the valve seat (top of pedestal) and on each side of the pipe and valve supports. The floor tends to erode between the pedestal and sidewalls as shown, and at times, actually undercuts the pedestal.



SECTION A-A

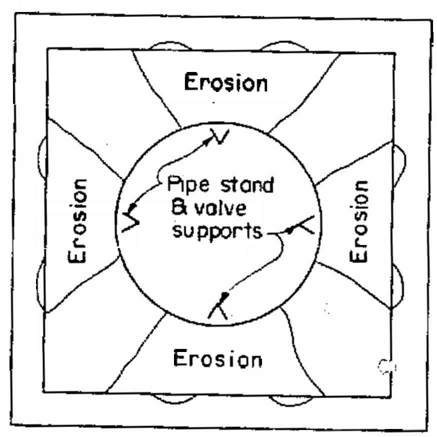


Figure 22. Typical stilling well erosion patterns

A test program was conducted to study pressure distributions in the erosion areas. The 9-inch (22.9-cm) plastic stilling well was equipped with 23 piezometers and the pedestal used on some of the tests had an additional 8 piezometers, as shown in Figure 23. Piezometers 1 through 23 were placed on the wall and floor of the stilling well. Piezometers 24 through 31 were placed on the pedestal wall and top. Data for these tests are summarized on Data Sheet 10. Pressures are minimum water manometer pressures when the average pressure is less than static well pressure and maximum water manometer pressures when the average pressure is above static well pressure. (Run No. 12 was the only run where a subatmospheric pressure was recorded). The series of tests related to pressure distribution in the stilling well was conducted using a 2-inch (5.08-cm) plastic sleeve valve constructed geometrically and dynamically similar to a 12-inch (30.5-cm) prototype valve.

Standard sleeve valve—The standard sleeve valve investigations consisted of studies involving a sleeve valve design similar to the conventional Bureau of Reclamation sleeve valve, where the flow leaving the valve spreads radially from the top of a pedestal. The head loss coefficient, K, for a/D = 1/2 was about 1.84 at maximum opening.

$K = \frac{1}{C_d^2} = \frac{2g\Delta h}{V^2}$, where Δh is the static head difference from the inlet of the valve elbow to the water surface in the well. V is the mean velocity based on the nominal pipe area.

Figures 24 and 25 illustrate the piezometric head on the walls, floor, and pedestal of the conventional well

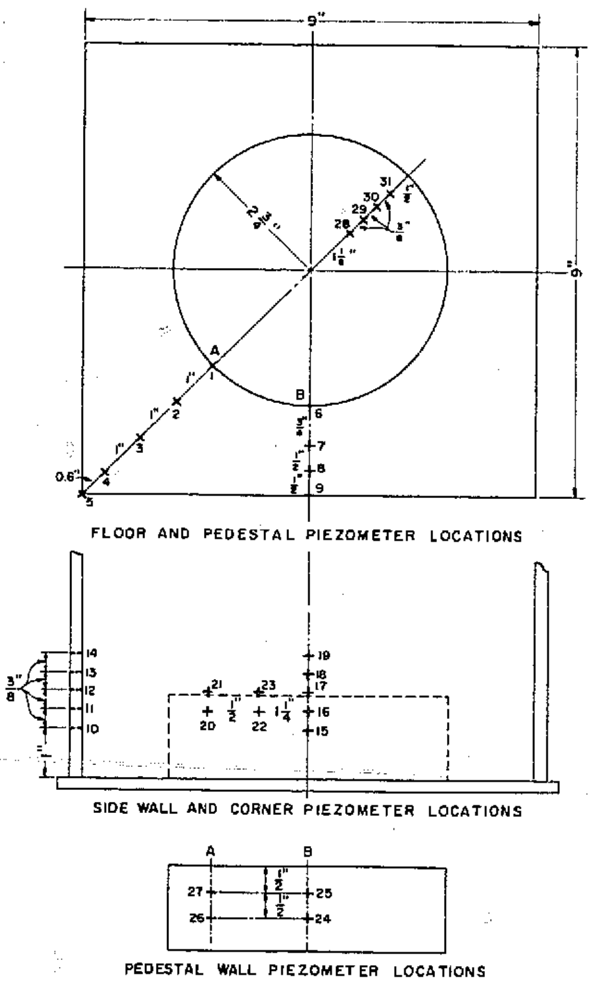


Figure 23. 9-inch Model piezometer locations

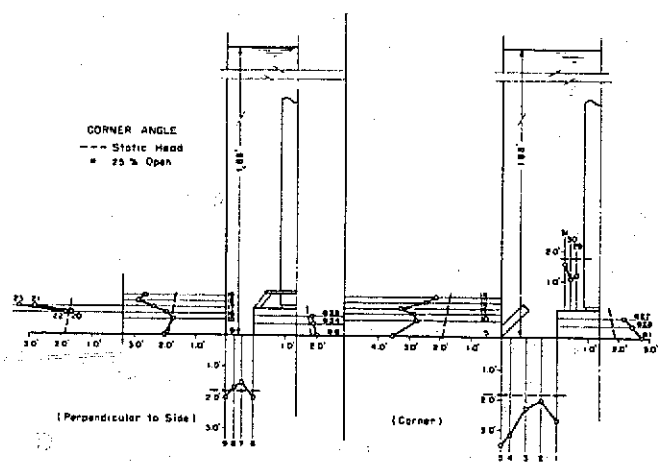


Figure 24. Stilling well pressure distribution run no. 2

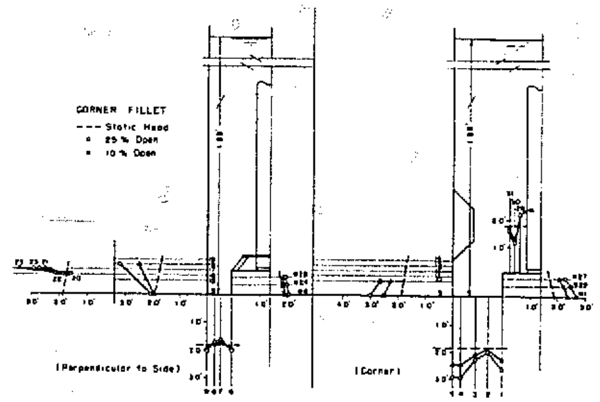


Figure 25. Stilling well pressure distribution run no. 1

with corner angles and corner fillets, respectively. For 25 percent open, the piezometric heads are the same except for the corner areas where the corner configuration affects the pressure. It is interesting to note that in the areas where erosion of the concrete has been found, namely, Piezometers 6 through 9 and 20 through 23, there is a tendency for pressures near and below static head. The pressure-gradients in the area of piezometers 20 through 23 indicate a zone of very unstable flow along the wall. Piezometers 29-30 on the pedestal are below static. This region is covered with steel in field installations. Although the aforementioned zones show trends toward low pressures, they are by no means in the subatmospheric range where damage as indicated in Figure 22 could be considered caused by cavitation.

Figure 26 shows a cavitation cloud in the jet leaving the standard model sleeve valve under extremely high head loss conditions. Vertical stilling wells presently in use have a stainless steel cap on the pedestal top to prevent cavitation damage to this surface. Note that the legs of the support structure are in the high-velocity jet which could generate cavitation directly behind them.

To compare the well pressures without a pedestal to those mentioned above, a false floor was added to the model to simulate removal of the pedestal and the standard sleeve valve was tested with the corner fillets and angles. Figures 27 and 28 illustrate the wall pressures with the radial jet on the well floor. Pressure measurements on the floor close to the valve are similar to those found on top of the pedestal (No. 29-31) in Figures 24 and 25. With the valve on the well floor, the impact pressures on the wall area near piezometers 20 through 23 are higher than with the valve on the pedestal. However, the pressure gradients in this area

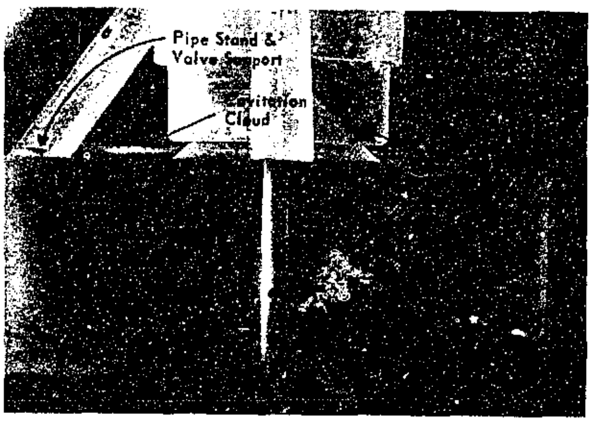


Figure 26. Typical cavitation cloud in jet of standard sleeve valve (2-inch model) P801-D-73031

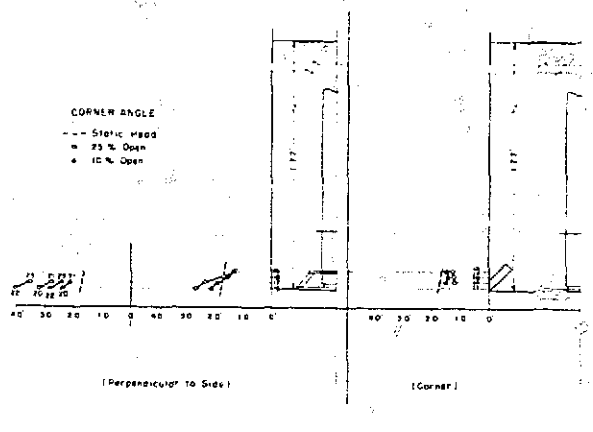


Figure 27. Stilling well pressure distribution run no. 4

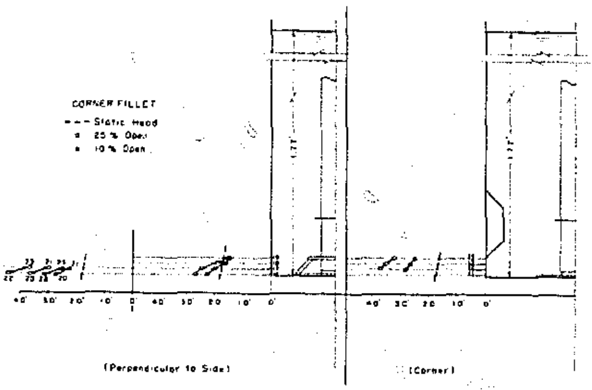


Figure 28. Stilling well pressure distribution run no. 3

are not as great with the valve on the floor. A possible area of concern may be in the corners of the well in back of the apex of the corner angles. The pressures in the corner (Figure 27) are not negative but there is a tendency for lower pressures in this area. If this were a problem at high head differentials, (in wells without steel lining), a triangular steel plate could be welded across the corner angles and extended above the maximum sleeve travel of the valve.

Although the pressure distribution tests did not pinpoint the cause of erosion, two areas for improvement were recognized by the author. The first area involved the present use of a pedestal in the stilling well. It is the author's opinion that the conventional sleeve valve should be placed on the floor of the stilling well to eliminate the roller under the jet and that the floor and possibly the sidewalls of the well should be steel lined to an elevation equal to 1.5D to protect the concrete from erosion. The second area involved the present use of the pipe stand and valve support structure. The legs of the structure placed in the high-velocity jet provide an excellent opportunity for a low-pressure zone to form immediately behind the legs, with the possibility for cavitation. It is recommended that another method be developed for supporting the pipe stand and valve, such that there would be no obstruction placed in the high-velocity jet leaving the valve.

Ported sleeve valve—Modifications by Miller[5], Winn and Johnson[6], and Johnson[7] to the original Bureau sleeve valve design have resulted in the use of the sleeve valve in stilling wells with differential heads up to 400 feet (122-meter). The basic change in design has been referred to as a ported valve or multijet discharge valve, Figure 29, where instead of a solid jet expanding radially, numerous small jets discharge through ports as the interior sleeve portion of the valve rises. The small ports provide a maximum jet surface area which shears against the water in the stilling well, creating small scale turbulence. Rouse[8] and Albertson, Dai, Jensen, and Rouse[9] discuss the characteristics of a submerged jet. The smaller the ports the greater the energy dissipation of the jet. Limitations on size of ports are

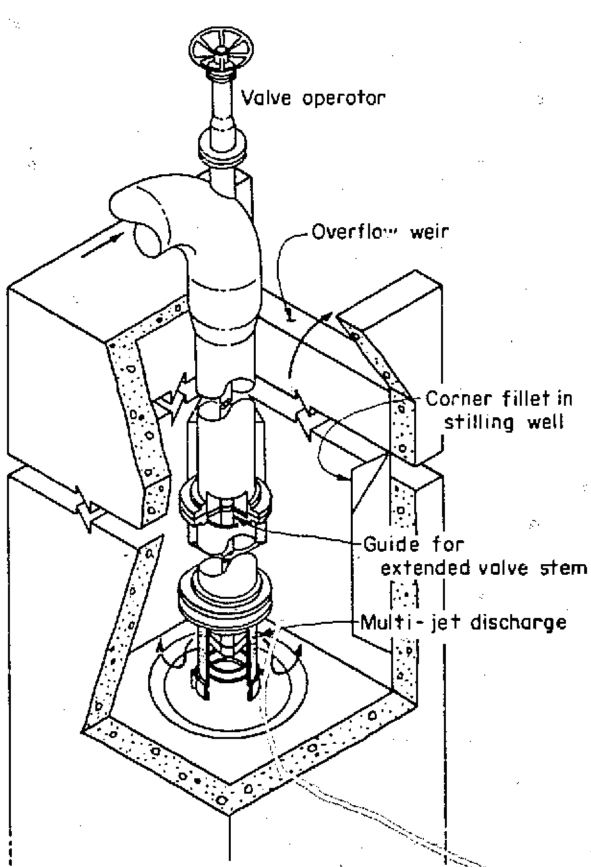


Figure 29. Multijet sleeve valve

based on desired valve flow capacity, stilling well size, and size of possible debris in the water.

In the past, water delivery systems developed by the Bureau of Reclamation have transported untreated water where debris would have presented a real problem with the multijet discharge valve. With the increased delivery of municipal and industrial water, some of which is treated, the multijet discharge valve appears to have real potential, especially in situations where throttling of high heads is necessary (above 150 feet).

In an effort to develop ports which could pass a certain size debris, studies were conducted to determine pressures on the walls and floor for various port configurations. The theory behind the multijet valve is the dissipation of the high-velocity jet by viscous shear between the jet and the surrounding tranquil fluid (Figure 30). The core of a single submerged jet is penetrated by the viscous shear until the center velocity is dissipated. An equation of the form, $V_X/V_O = K\sqrt{D_O/X}$, describes the jet core velocity, V_X, at distance, X, from the jet origin based on the jet velocity at the origin, V_O, and the diameter of the port, D_O. K is a constant based on the shape of the port. The core velocity, V_X, is thus proportional to the port diameter, D_O, distance from the origin, X, and port velocity, V_O.

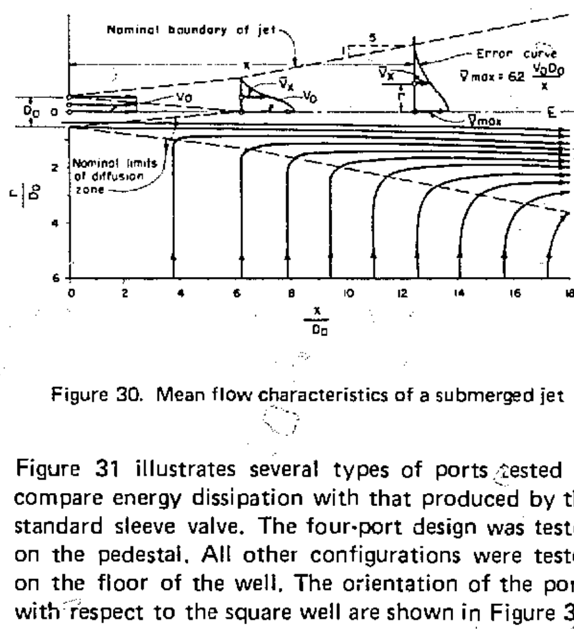


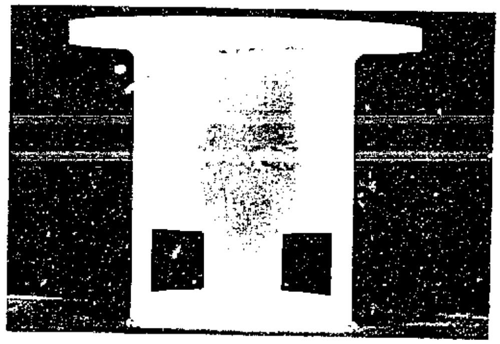
Figure 30. Mean flow characteristics of a submerged jet

Figure 31 illustrates several types of ports tested to compare energy dissipation with that produced by the standard sleeve valve. The four-port design was tested on the pedestal. All other configurations were tested on the floor of the well. The orientation of the ports with respect to the square well are shown in Figure 32. The sleeve travel was adjusted for each port configuration such that the head loss across the valve was the same for the discharge based on the standard sleeve valve tested earlier. Table III lists the various port

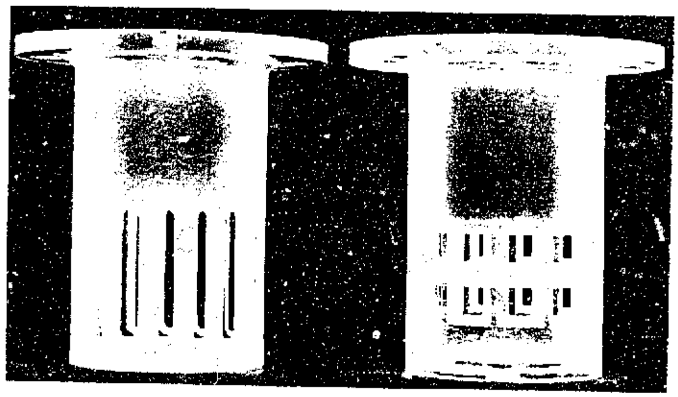
Table III

VARIOUS PORT CONFIGURATIONS TESTED

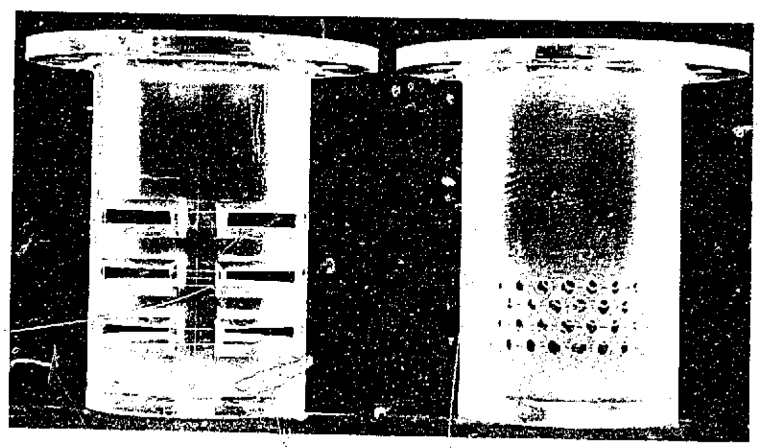
Run No.	Port configuration	Port size in (cm)	Distance of valve seat above floor in (cm)	Percent open	Model head loss ft (m)	Discharge cfs (m^3/s)	Total Port area in^2 (cm^2)
1	Standard sleeve valve	-	1-3/4 (4.44)	10	51.6 (15.48)	0.100 (0.0028)	-
1	Standard sleeve valve	-	1-3/4 (4.44)	25	41.0 (12.30)	0.210 (0.0059)	0.652 (4.21)
3	Standard sleeve valve	-	1/4 (0.64)	10	51.6 (15.48)	0.100 (0.0028)	-
3	Standard sleeve valve	-	1/4 (0.64)	25	41.0 (12.30)	0.210 (0.0059)	0.652 (4.21)
5	4 ports	0.88X0.79 (2.24X2.01)	2 (5.08)	10	51.6 (15.48)	0.100 (0.0028)	0.352 (2.27)
6	8 ports	0.59X0.71 (1.50X1.80)	0.9 (2.29)	25	41.0 (12.30)	0.210 (0.0059)	0.850 (5.48)
7	12 ports (per tier)	0.30X0.32 (0.76X0.81)	0.8 (2.03)	25	41.0 (12.30)	0.210 (0.0059)	0.906 (5.84)
8	4 slots (per tier)	1.18X0.16 (3.00X0.41)	0.8 (2.03)	25	41.0 (12.30)	0.210 (0.0059)	0.934 (6.03)
9	16 slots	0.14X1.16 (0.36X2.95)	0.8 (2.03)	25	41.0 (12.30)	0.210 (0.0059)	0.84 (5.42)
10	16 slots	0.14X1.16 (0.36X2.95)	0.38 (0.97)	25	41.0 (12.30)	0.210 (0.0059)	0.84 (5.42)
11	16 slots	0.14X1.16 (0.36X2.95)	1.13 (2.87)	25	41.0 (12.30)	0.210 (0.0059)	0.84 (5.42)
12	1/8-inch holes	1/8 dia (3.2 mm)	0.80 (2.03)	25	41.0 (12.30)	0.210 (0.0059)	0.517 (3.34)



a. 4 Ports (0.88" by 0.79") P801-D-73034



b. 16 Vertical Slots (0.14" by 1.16") and 12 ports (0.30" by 0.32") P801-D-7303L



c. 4 Horizontal slots (1.18" by 0.16") and 1/8" holes P801-D-73033

Figure 31. Valve port configurations tested

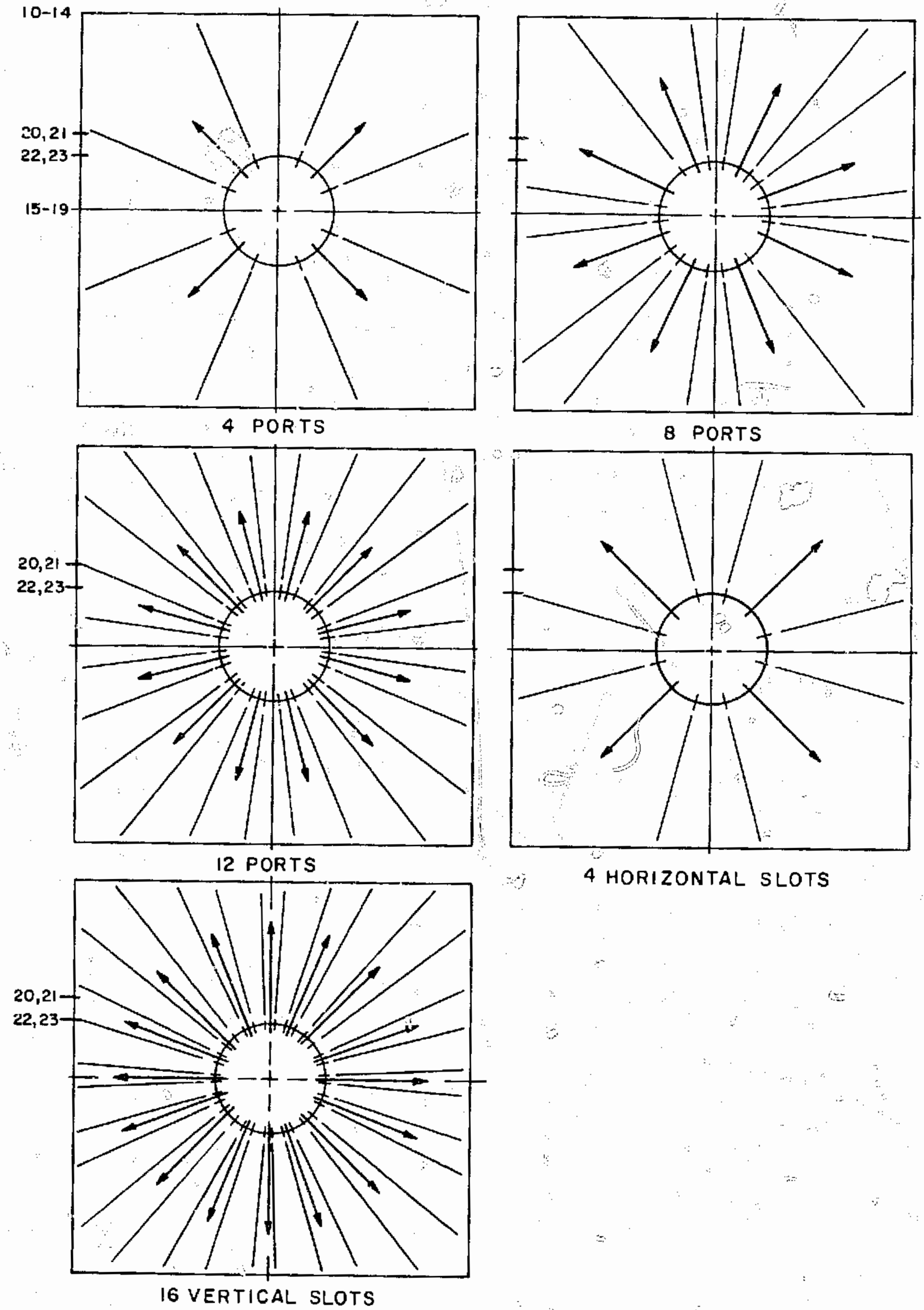


Figure 32. Orientation of valve ports in 9-inch stilling well

configurations along with corresponding head loss, discharge, and port areas for 10 and 25 percent openings of the standard sleeve valve.

In the tests to determine the flow characteristics of the ported sleeve valve, the 9-inch stilling well model with corner fillets was modified as shown in Figure 33. Piezometers 11 through 14 and 16 through 23 were utilized and three piezometers were placed in the false floor (Piezometers 32, 33, and 34). Data for these tests are given on Data Sheets, 10, 11, and 12. Water manometer pressures for the various port configurations tested are shown in Figures 34 through 41.

In general, the port configurations which yielded the lowest impact pressures on the wall were those which had a small dimension in at least one direction. The 4-, 8-, and 12-port designs created a jet too thick to diffuse in the short distance from the valve to the stilling well wall. The 16-vertical-slot configuration had slot widths which varied from 0.14 inch (0.36-cm) to 0.22 inch (0.56-cm), varying with the distance, X, from the valve to the stilling well wall (largest slots opposite

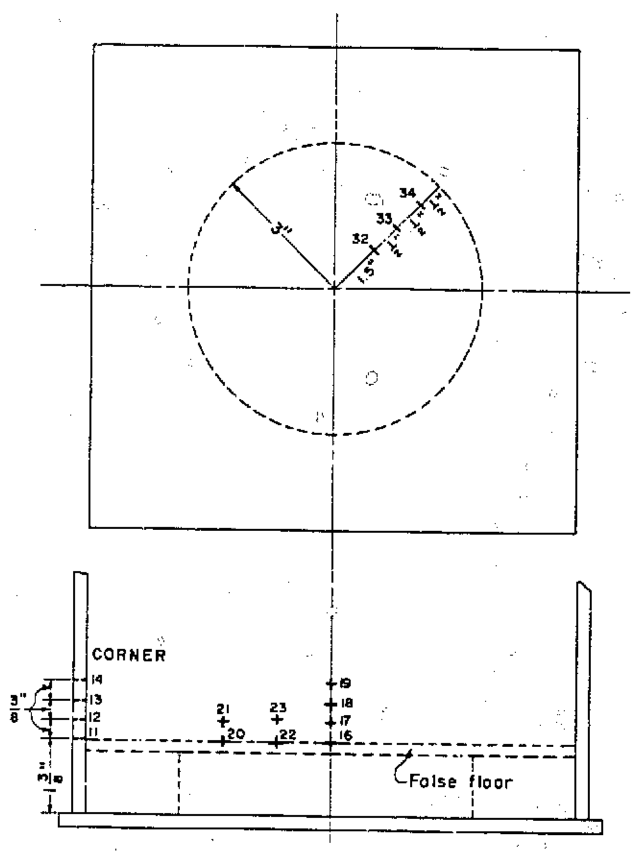


Figure 33. Piezometer locations for well without pedestal

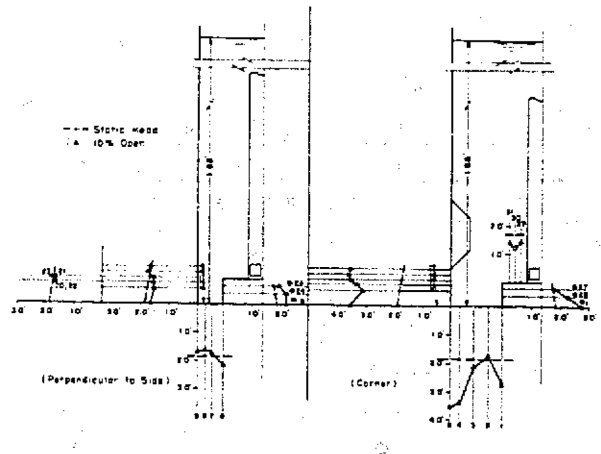


Figure 34. Stilling well pressure distribution run no. 5 – 4 ports

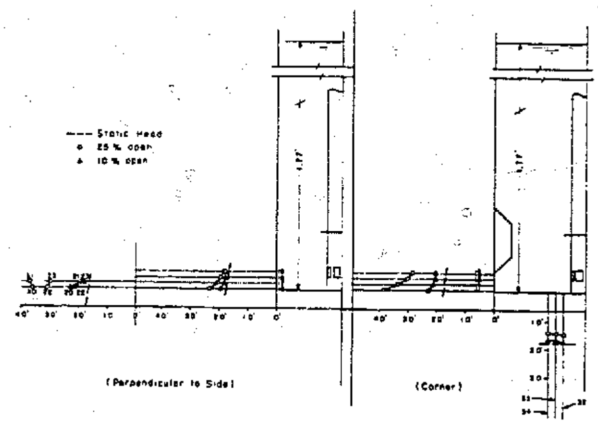


Figure 35. Stilling well pressure distribution run no. 6 – 8 ports

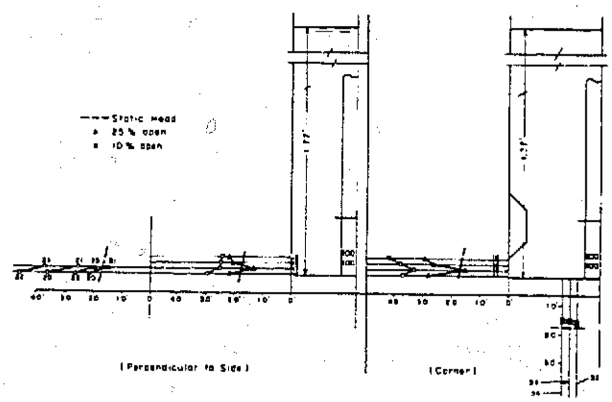


Figure 36. Stilling well pressure distribution run no. 7 – 12 ports

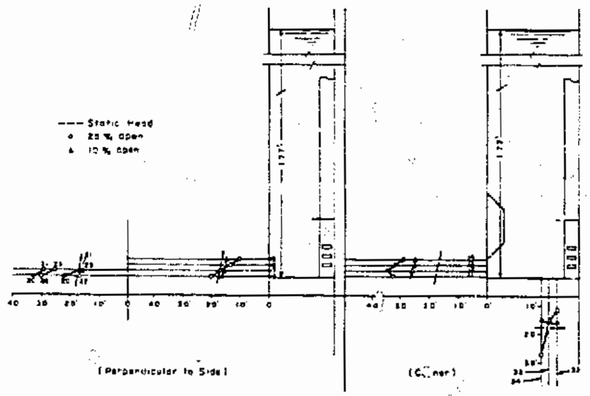


Figure 37. Stilling well pressure distribution run no. 8 – 4 slots

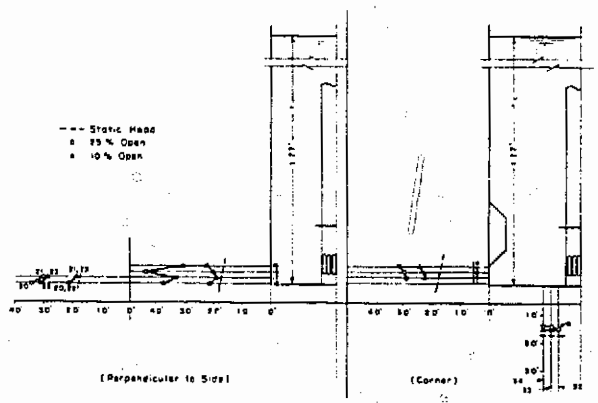


Figure 38. Stilling well pressure distribution run no. 9 – 16 slots

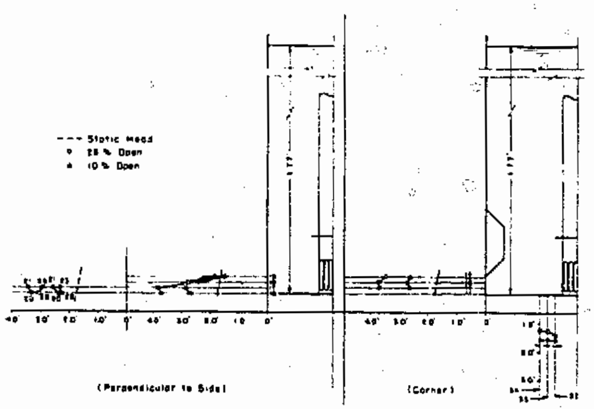


Figure 39. Stilling well pressure distribution run no. 10 – 16 slots

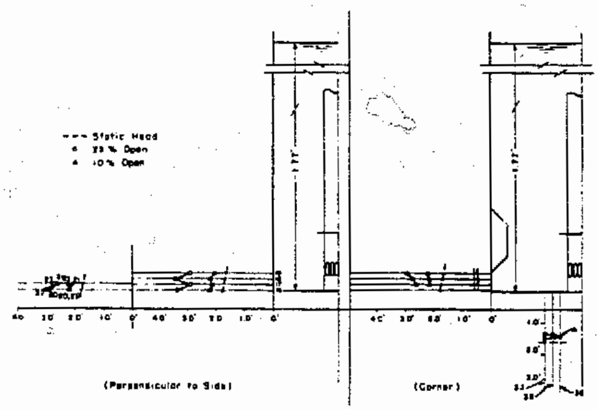


Figure 40. Stilling well pressure distribution run no. 11 – 16 slots

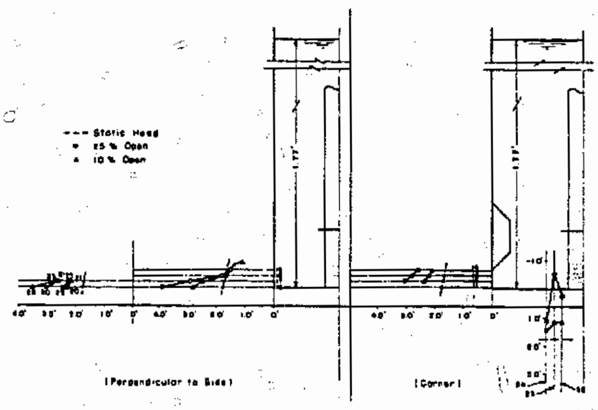


Figure 41. Stilling well pressure distribution run no. 12 – 1/8" holes

the corners). Improved pressure distribution on the well sidewall was achieved by raising the vertical slots higher off the stilling well floor. The fairly even pressure distribution on the walls and in the corner of the stilling well indicate good flow distribution by the 16-vertical slot multijet valve.

A port configuration using 1/8-inch (0.32-cm) diameter holes was also tested. Although the well wall pressure distribution was more even than that for the standard valve, a negative pressure was observed on the well floor near the valve at Piezometer 33, Figure 41. It appears that this low-pressure zone could be corrected by raising the ports higher off the floor. The Metropolitan Water District of Southern California experienced a similar situation with a 12-inch test valve[7]. These preliminary tests indicate that more extensive tests are needed to relate stilling well pressures to port size, flow velocity, height of ports above floor, and distance from wall before the multijet valve can be confidently used in stilling wells.

DISCUSSION OF RESULTS

Conformance Between the Models

During the testing program on the 9-inch (22.9-cm) model, it was noted that the tailgate assembly of the model channel reflected the surface wave back upstream to the capacitance probe. When tested later for verification on the 3-foot (0.915-meter) model, the wave height variable, h/Y, for a given value of Q^2/gD^5 was consistently higher for the 9-inch (22.9-cm) model than that observed in the 3-foot (0.915-meter) model for both the corner fillet and corner angle configurations.

Figure 42 describes this difference. Runs 101 and 203, 80 and 205, 67 and 200, and 69 and 204 represent corresponding tests in the 9-inch (22.9-cm) and 3-foot (0.915-meter) models for the two corner configurations and well depth to width ratios, d/b = 1.0 and 1.5 (Data Sheet 1). Because of this error, date from the 9-inch (22.9-cm) model investigation were used only to optimize the stilling well dimensionless parameters; C/b, J/b, K/b, L/b, and T/b. The 3-foot (0.915-meter) model data were used to describe the design curves presented in the General Design Criteria section.

General Design Criteria

The results of the tests on the 9-inch (22.9-cm) and 3-foot (0.915-meter) stilling well models by the author, plus the work completed by Denson, provide the basis on which to establish general design criteria.

The design criteria apply to vertical stilling wells, with a standard sleeve valve placed on the floor, (without a pedestal) with maximum sleeve travel equal to one-half the pipe diameter, a/D = 1/2 and the ratio of tailwater depth to well width, Y/b = 0.5. The standard sleeve valve is defined as an unported sleeve-type valve with an internal control stem passing through the valve elbow. Data are presented graphically for the corner fillet and corner angle designs. The corner angle configuration has not been field tested but the model studies indicate a smoother tailwater surface than that produced by the corner fillet, and it is a more economical design.

Figures 43, 44, and 45 present the relationship

$$h/Y = f\,(Q^2/gD^5,\ D/b)$$

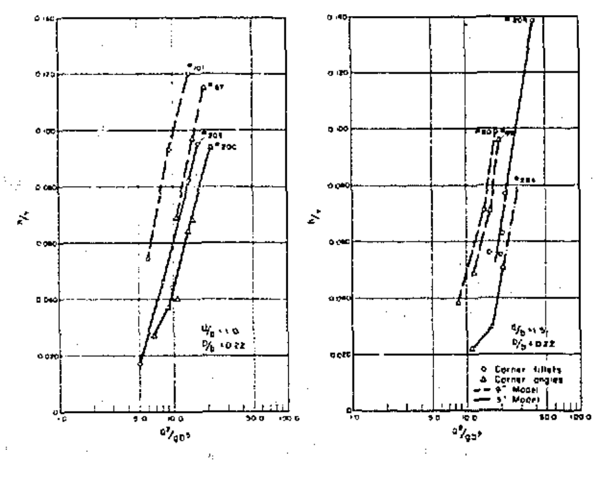


Figure 42. Model verification curve

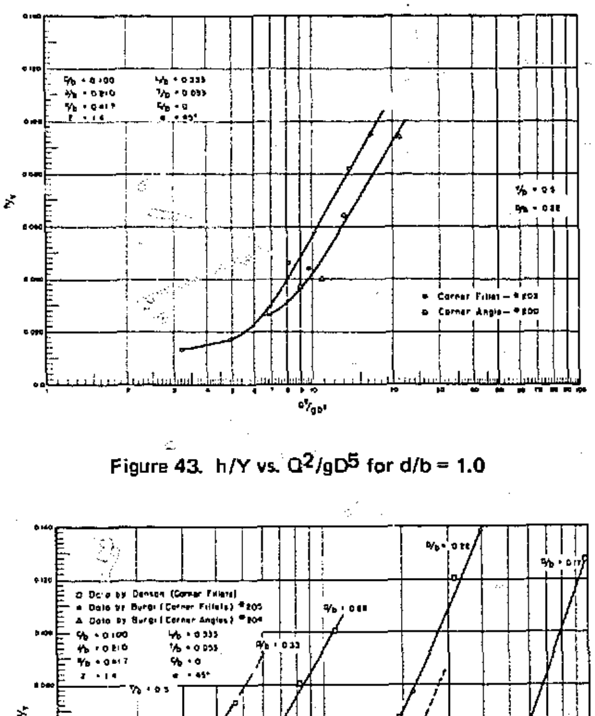


Figure 43. h/Y vs. Q^2/gD^5 for d/b = 1.0

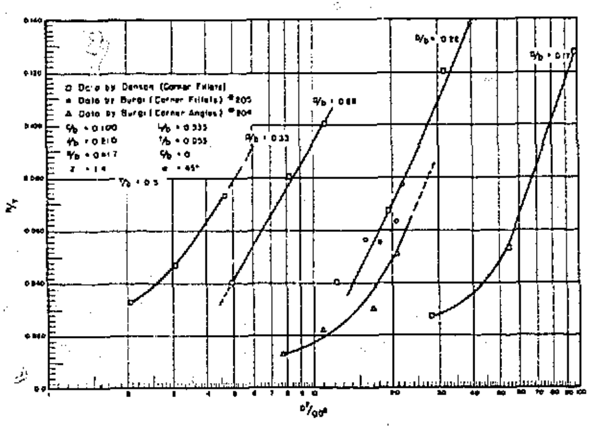


Figure 44. h/Y vs. Q^2/gD^5 for d/b = 1.5

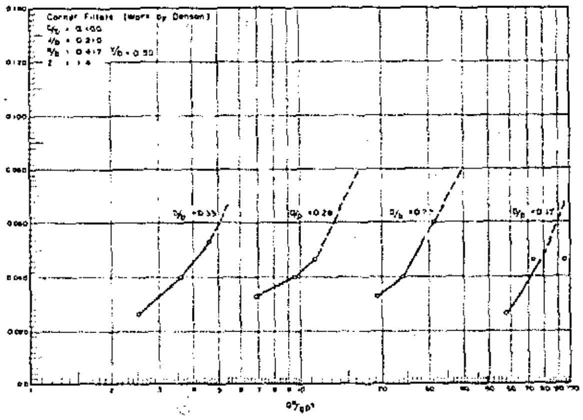


Figure 45. h/Y vs. Q^2/gD^5 for d/b = 2.0

for d/b = 1.0, 1.5, and 2.0 as described earlier in Figure 5. The dimensionless parameters C/b, J/b, K/b, L/b, and T/b have also been determined. Figure 43 shows the results of the authors work for d/b = 1.0. Figure 44 shows the results of Denson's and the author's work for d/b = 1.5 and Figure 45 shows the results of Denson's work for d/b = 2.0. The optimum values for the dimensionless parameters are recorded on each figure. Figures 43 and 44 also show the corner angle curve for D/b = 0.22.

The values for the design discharge, Q, and the pipe diameter, D, will generally be known by the designer. For cases where the well is to be designed so as to produce a specific wave height, h, it would be more appropriate to express the dimensionless wave parameter in terms of the pipe diameter, D, rather than the tailwater depth, Y, since the value of the former is known. Therefore, the data used to plot Figures 44 and 45 were rearranged and used to generate families of curves (h/D) in Figures 46 and 47. These two figures will simplify the design approach for the vertical stilling well.

The dashed lines in Figure 46 are the estimated h/D curves for the corner angle configuration when d/b = 1.5. There are no data for the corner angle configuration at d/b = 2.0. Therefore if a depth to width ratio, d/b = 2.0, is selected and it is desired to use the corner angle, the well should be designed using the corner fillet curves in Figure 47. However, this will result in an actual wave height, h, somewhat less than if the corner fillet were used. The step by step procedure for designing a vertical stilling well will be illustrated in the Design Examples.

The general design criteria would not be complete without some mention of the effect of head differential across the valve. In the past, well size has been based on water surface roughness, h/Y, as presented in this report. With the trend toward higher head differentials across the sleeve valve, whether standard or ported, the need arises for a research effort in the area of determining allowable jet velocities at the concrete wall of the stilling well. This question can be circumvented by lining the lower area of the well with steel plate.

There is some evidence that the present design of the standard sleeve valve may result in damage to the stilling well and/or valve under high-head (above 150 feet) conditions. During testing of a similar 12-inch (30.48-cm) standard sleeve valve, Winn and Johnson[6] detected cavitation noise and vibration above 100 feet (30.48-meter) of head differential across the valve.

Table IV is a tabulation of standard sleeve valves installed by the Bureau of Reclamation. Damage to the stilling well walls and floor, and breakage of the control stem have been reported on some of these installations. However, there is no positive correlation between the damage and head differential across the valve.

Design Examples

Design Example No. 1

Design a stilling well for a sleeve-type valve discharging a maximum flow of 220 cfs (6.23 m^3/sec) with a total head, H_T, at the valve of 250 feet (76.2-meter). The flow discharges into a trapezoidal canal with 1.5 to 1 side slopes and it is desired to have a wave height, h, less than 3 inches (7.62-cm) one well width, b, from the well.

(1)

$$H_T = \frac{V^2}{2g} + \Delta H$$

where:

$\frac{V^2}{2g}$ = pipe velocity head, ft.

ΔH = Pressure head loss measured from the valve inlet flange immediately upstream of the elbow to the downstream canal water surface, ft.

Table IV

TABULATION OF STANDARD SLEEVE VALVES INSTALLED BY THE BUREAU OF RECLAMATION

Structure	Date installed	Size in.	Maximum Static head ft.	Discharge ft^3/sec	Well size Width ft.	Well size Depth ft.	Type of service	Damage
Wanship Dam	1955	16	120	17	6	8.25	Irrigation	No damage
		16	150	17	6	8.25	Irrigation	Sleeve valve pitting, well erosion
Fort Cobb Dam	1959	24	110	21	9	21	Municipal and industrial	No damage
Agate Dam	1966	24	84	78	10	16	Irrigation	Well erosion
Mason Dam	1967	12	170	-	6	17	Outlet Works	No damage
Mann Creek Dam	1967	12	140	14	6	8	Irrigation	Control stem broke, well erosion
		24	74	18	9	9	Irrigation	No damage
Contra Loma Dam(2)	1967	24	100	-	10	15	Outlet works	No damage
Stampede Dam	1967	12	250	36	6	13	Outlet works	No report
Starvation Dam(2)	1968	12	150	-	6	12	Outlet works	No report
Pleasant Valley Pumping Plant	1968	24	200	-	-	-	Drain	No report
Sinlahekin Creek	1969	12	400	70	6.67	13.5	Inlet to storage reservoir	Control stem broke, well erosion

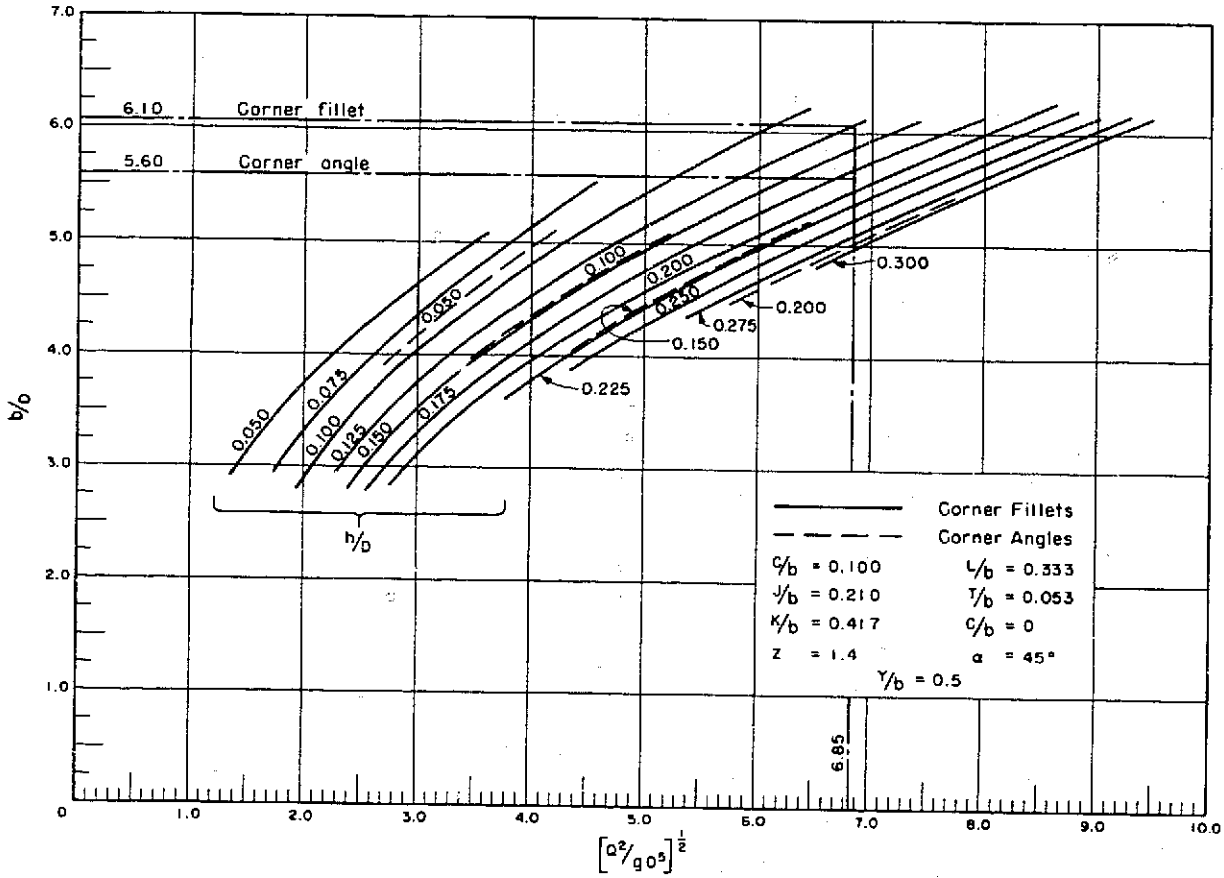


Figure 46. Design curve of b/D vs. $\left[\frac{Q^2}{gD^5}\right]^{1/2}$ for d/b = 1.5

Figure 48 illustrates the head loss coefficient, $K = \frac{2g\Delta H}{V^2}$, for the 2 inch (5.08-cm) model sleeve valve tested in this study. Therefore for a valve 100 percent open K = 1.84 or:

$$H_T = \frac{V^2}{2g} + 1.84\frac{V^2}{2g} = 2.84\frac{V^2}{2g}$$

$$\frac{V^2}{2g} = \frac{H_T}{2.84} = \frac{250}{2.84} = 88.0 \text{ ft}$$

and V = 75.3 ft/sec

Since Q = VA

$$A = \frac{Q}{V} = \frac{220.0}{75.3} = 2.92 \text{ ft}^2$$

and $D = \left[\frac{4}{\pi}(A)\right]^{1/2} = 1.93$ ft

use a 2.00 foot I.D. valve.

(2) The design curves (Figures 46 and 47) for sizing the stilling well are based on 100 percent valve opening. To determine well width, b, calculate the flow parameter:

$$\left[\frac{Q^2}{gD^5}\right]^{1/2} = \left[\frac{(220)^2}{(32.2)\,(2)^5}\right]^{1/2} = 6.85$$

and the ratio of wave height to valve diameter, h/D:

h/D = 3/24 = 0.125

Let the well depth, d, equal 1.5 times the well width, b, (d/b = 1.5). In some instances a more economical

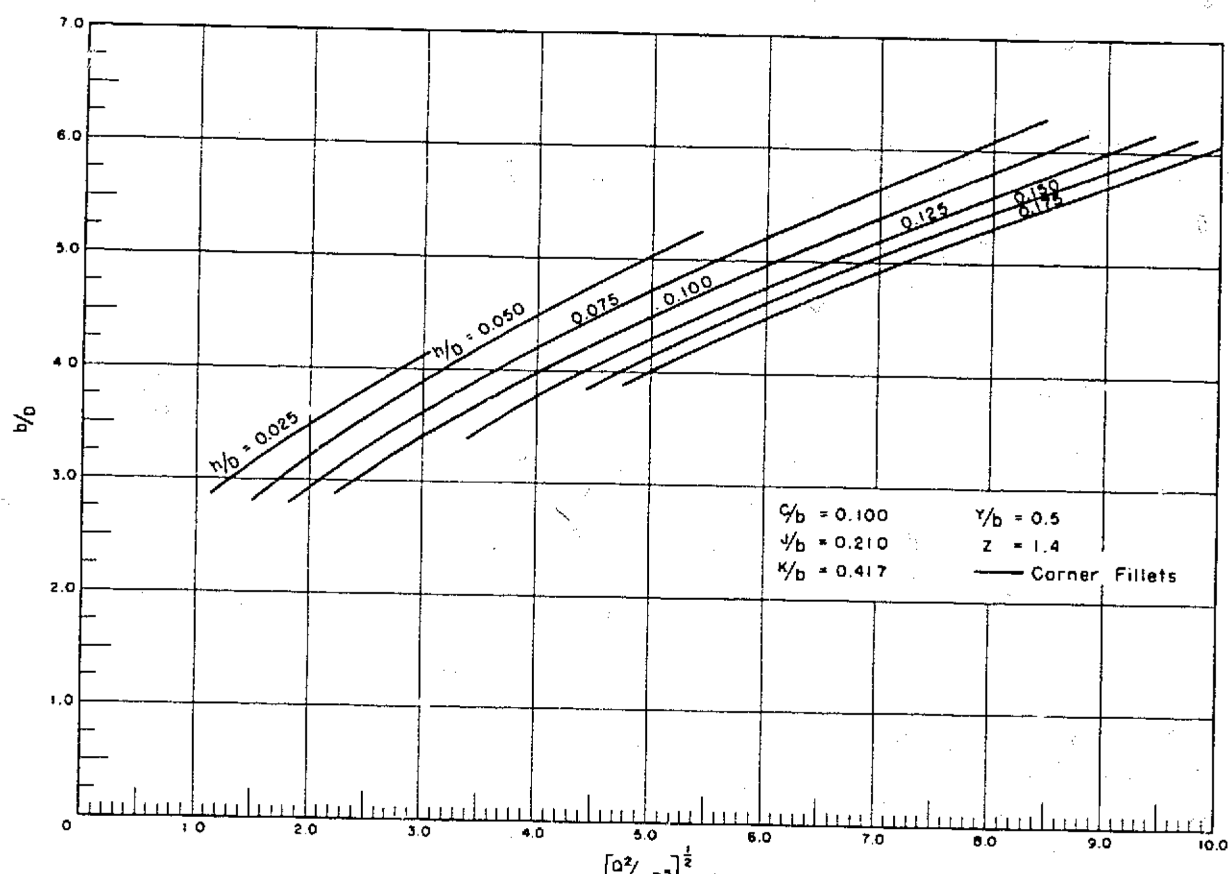


Figure 47. Design curve of b/D vs. $\left[\frac{Q^2}{gD^5}\right]^{½}$ for d/b = 2.0

design might be d/b = 1.0 or 2.0. However, in general, d/b = 1.5 will be the appropriate choice.

(3) From Figure 46 (d/b = 1.5) for

$$\left[\frac{Q^2}{gD^5}\right]^{½} = 6.85 \text{ and } \frac{h}{D} = 0.125$$

b/D = 6.1 (corner fillets)
b/D = 5.6 (corner angles)

Select the corner angles as the more economical design.

Therefore:

b = 11.20 feet (3.41 meter)
and d = 16.80 feet (5.12 meter)

(4) From the established parameters of the corner angle design:

T/b = 0.053	T = 0.59 feet (180 mm)
	use 7″ x 4″ corner angles where T = 7″
L/b = 0.333	L = 3.75 feet (1.14 meter)
C/b = 0	C = 0
α = 45°	

(5) Line the floor of the stilling well with ½-inch (12.7-mm) stainless steel and the walls to a height of 1.5D = 3.00 feet (0.91 meter) with ½-inch (12.7-mm) carbon steel. Weld the 7-by 4-inch corner angles to the steel liner (Figure 49).

Example No. 2

Design a stilling well for a sleeve-type valve under the

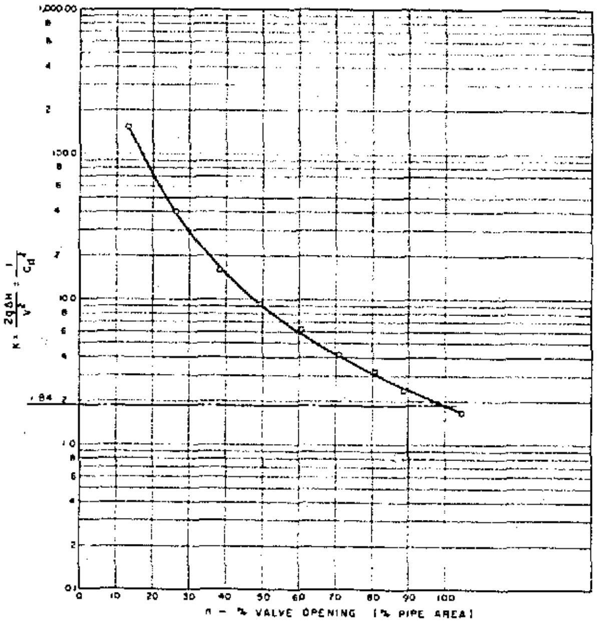


Figure 48. Head loss coefficient, K, for standard sleeve valve (2-inch model)

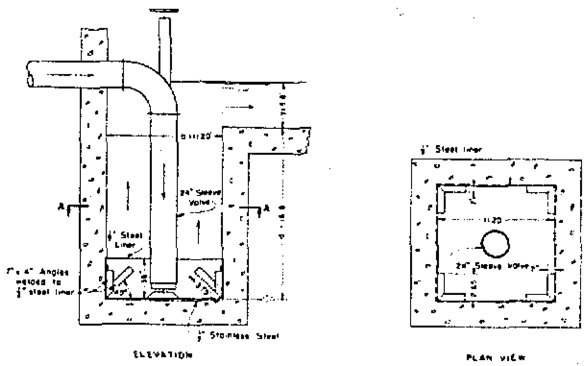


Figure 49. Design example

conditions listed in Example No. 1, but with a total head, H_T, at the valve of 30 feet (9.14 meter).

$$H_T = \frac{V^2}{2g} + \Delta H$$

$$\text{or } H_T = \frac{V^2}{2g} + 1.84\,\frac{V^2}{2g} = 2.84\,\frac{V^2}{2g}$$

$$\text{Therefore } \frac{V^2}{2g} = \frac{30}{2.84} = 10.56 \text{ ft.}$$

and V = 26.08 ft/sec

Since Q = VA

$$A = \frac{Q}{V} = \frac{220.0}{26.08} = 8.44 \text{ ft}^2$$

$$\text{and} \quad D = \left[\frac{4}{\pi}(A)\right]^{1/2} = 3.28 \text{ ft.}$$

(2) To determine well width, b, calculate the flow parameter:

$$\left[\frac{Q^2}{gD^5}\right]^{1/2} = \left[\frac{(220)^2}{32.2\,(3.33)^5}\right]^{1/2} = 1.92$$

and the ratio of wave height to valve diameter, h/D:

$$\frac{h}{D} = \frac{3}{40} = 0.075$$

Select d/b = 1.5

(3) From Figure 46 (d/b = 1.5) for

$$\left[\frac{Q^2}{gD^5}\right]^{1/2} = 1.92 \text{ and } \frac{h}{D} = 0.075$$

b/d = 3.25 (corner fillet)

let b/d = 3.00 (corner angle)

Select the corner angles as the more economical design. Using b/D = 3.00 actually yields h/D = 0.05 instead of 0.075. However, the design curves were not tested below b/D = 3.0.

Therefore:

b = 10.00 feet (3.05 meter)
d = 15.00 feet (4.57 meter)

(4) From the established parameters of the corner angle design:

T/b = 0.053	T = 0.53 feet (162 mm)
	use 6″ x 4″ corner angles where T = 6″
L/b = 0.333	L = 3.33 feet (1.01 meter)
C/b = 0	
$\alpha = 45°$	

(5) Line the floor of the stilling well with ½-inch (12.7-mm) stainless steel and the walls to a height of 1.5(D) = 5.00 feet (1.52 meter) with ½-inch (12.7-mm) carbon steel. Weld the 6- by 4-inch corner angles to the steel liner.

Example No. 3

Design a stilling well for a sleeve-type valve under the combined conditions of Examples No. 1 and 2. It is required to insure a design discharge, Q = 220 cfs (6.23 m^3/sec), for a total head at the valve which may vary from 30 feet (9.14 meter) to 250 feet (76.2 meter) depending on the upstream reservoir water surface elevation.

To insure delivery of 220 cfs (6.23 m^3/s) when the total head at the valve is only 30 feet (9.14 meter) the larger valve of example No. 2, D = 40 inches (101.6 cm), should be used. When the total head is 250 feet (76.2 meter) the valve will be throttled to give a maximum discharge of 220 cfs (6.23 m^3/s). However, the well should be sized based on the larger total head H_T = 250 feet (76.2 meter) of Example No. 1. Therefore, the well size will be identical to Example No. 1 even though the valve diameter, D = 3.33 feet (1.01 cm).

b = 11.2 feet (3.41 meter)
d = 16.8 feet (5.12 meter)
T = 7" (178 mm) use 7"x4" angle
L = 3.73 feet (1.14)
C = 0
and $\alpha = 45^\circ$

The steel liner height should be based on the larger valve diameter D = 3.33 feet (1.11 meter) or 1.5D = 5.00 feet (1.52 meter).

Amount of throttling:

Since $H_T = \frac{V^2}{2g} + \Delta H$

and $\frac{V^2}{2g} = 9.87$ ft

Therefore $\Delta H = 250.00 - 9.87 = 240.13$

$$K = \frac{2g\Delta H}{V^2} = \frac{240.13}{9.87} = 24.4$$

From Figure 48, the valve will be 32 percent open for a discharge, Q = 220 cfs (6.23 m^3/s) and a total head of 250 feet (76.2 meter) and 100 percent open for a total head of 30 feet (9.14 meter) and a discharge, Q = 220 cfs (6.23 m^3/s).

This design approach is based on the downstream channel depth, Y, equal to one half the well width, b. In Design Example No. 1, Y = ½(b) = 5.60 feet (1.71 meter). If the channel has a depth greater or less than Y, the well depth, d, should be adjusted to maintain a total submergence, Y+d, of 22.4 feet (6.83 meter) to assure a wave height, h = 3.0 inches (76 mm) or less.

For example, if the channel depth is only 4.5 feet (1.37 meter) instead of 5.60 feet (1.71 meter), the well depth, d, must be increased 1.10 feet (0.34 meter) to produce the calculated wave height, h, based on Y = ½ b.

Judgment must be used in designing stilling wells that discharge into channels or canals with side slopes or depths different from those used in the development tests. In most cases, minor adjustments of the well depth can be made without affecting the efficiency of the stilling well as an energy dissipator or the predicted wave heights in the downstream channel.

Limitations:

(a) In reference to Design Example No. 1 where V = 75.3 ft/sec, Miller[5] and Johnson[7] recommend a maximum valve velocity of 40 ft/sec (12.19 m/s) for sleeve valves with an internal operating stem. This limitation can be circumvented by placing the operating stem(s) outside the valve body. Recent sleeve valve designs by the Bureau of Reclamation have used this approach.

(b) In reference to Design Example No. 3 where the valve is oversized to meet the condition of design discharge, Q = 220 cfs (6.23 m^3/s) at minimum total head, H_T = 30 feet (9.14 meter), caution must be used when the total head, H_T, exceeds 30 feet (9.14 meter). When the design discharge is delivered at total heads greater than 30 feet (9.14 meter), the valve must be correspondingly throttled in the range from 100 to 32 percent as H_T increases from 30 feet (9.14 meter) to 250 feet (76.2 meter) to assure that the design discharge is not exceeded.

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APPENDIX

The material contained in the appendix includes h/Y versus Q^2/gD^5 data for studies on the 9-inch (22.9-cm) and 3-foot (0.915-meter) vertical stilling well models and stilling well pressure data for the walls, floor, and pedestal of the 9-inch stilling well model.

Runs below 200 were tested on the 9-inch (22.9-cm) stilling well model. Runs 200 and higher were tested on the 3-foot (0.915 meter) stilling well model. Runs D22 and D41 (Data Sheet 7) are from work by Denson.

Data Sheet 1 — Tests dealing with 9-inch model verification

Data Sheets 2-9 — Tests dealing with optimization of stilling well geometry

Data Sheets 10-12 — Tests dealing with well piezometric pressure data (Runs 1-4 — standard sleeve valve, Runs 5-12 — ported sleeve valve).

Data Sheet 1

Run No.	101	203	67	230	80	205	69	204
D/b	0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.22
d/b	1.0	1.0	1.0	1.0	1.5	1.5	1.5	1.5
a/D	1/2	1/2	1/2	1/2	1/2	1/2	1/2	1/2
Corner fillet								
K/b	0.417	0.417			0.417	0.417		
J/b	0.222	0.222			0.223	0.223		
C/b	0.089	0.089			0.089	0.089		
Z	1.43	1.43			1.43	1.43		
Corner angle								
T/b			0.053	0.055			0.053	0.055
L/b			0.333	0.333			0.333	0.333
α			45°	45°			45°	45°
h(ft)	0.045	0.142	0.043	0.055	0.037	0.084	0.036	0.020
h/Y	0.120	0.095	0.115	0.037	0.099	0.056	0.096	0.013
Q(cfs)	0.238	8.43	0.279	6.18	0.274	8.21	0.284	5.69
Q^2/gD^5	13.70	16.72	18.77	9.00	18.09	15.86	19.47	7.61
h_2	0.035	0.123	0.036	0.059	0.027	0.083	0.027	0.032
h_2/Y	0.093	0.082	0.097	0.040	0.071	0.055	0.071	0.022
Q	0.197	7.69	0.249	6.82	0.241	8.74	0.257	6.82
Q^2/gD^5	9.39	13.93	14.99	10.93	14.06	19.97	15.98	10.95
h_3	0.020	0.067	0.026	0.102	0.014	0.095	0.018	0.044
h_3/Y	0.054	0.044	0.069	0.068	0.038	0.063	0.049	0.030
Q	0.157	6.43	0.208	7.90	0.188	9.34	0.219	8.49
Q^2/gD^5	5.97	9.73	10.50	14.68	8.51	20.54	11.54	16.96
h_4		0.068		0.096		0.116		0.077
h_4/Y		0.046		0.064		0.077		0.051
Q		5.87		7.50		9.59		9.39
Q^2/gD^5		8.10		13.28		21.65		20.75
h_5		0.025		0.040		0.208		0.202
h_5/Y		0.017		0.027		0.138		0.135
Q		4.58		5.34		12.98		12.63
Q^2/gD^5		4.94		6.71		39.66		37.55

Data Sheet 2

Run No.	53	56	60	64	100	102	103	105
a	1	1	1	1	1	1	1	1
d′	8.88	8.88	8.88	8.88	8.88	8.88	8.88	8.88
C	1.42	0.26	0.80	1.80	0.80	0.80	1.42	1.42
J	1.50	1.50	1.50	1.50	1.50	4.0	4.0	1.50
d/b	1	1	1	1	1	1	1	1
D/b	0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.22
a/D	1/2	1/2	1/2	1/2	1/2	1/2	1/2	1/2
C/b	0.158	0.029	0.089	0.200	0.089	0.089	0.158	0.158
J/b	0.167	0.167	0.167	0.167	0.167	0.167	0.167	0.167
h_1	0.058	0.082	0.045	0.052	0.046	0.057	0.053	0.056
h/Y	0.156	0.219	0.121	0.139	0.121	0.153	0.142	0.149
Q	0.240	0.231	0.226	0.217	0.243	0.241	0.234	0.238
Q^2/gD^5	13.88	12.84	12.34	11.39	14.25	14.06	13.18	13.70
h_2	0.052		0.032	0.041	0.038	0.044	0.036	0.037
h/Y	0.140		0.085	0.109	0.100	0.117	0.097	0.097
Q	0.207		0.184	0.199	0.196	0.199	0.192	0.207
Q^2/gD^5	10.35		8.15	9.53	9.26	9.53	8.88	10.35
h_3	0.033	0.039	0.018	0.040	0.020	0.023	0.023	0.020
h/Y	0.089	0.103	0.048	0.107	0.053	0.062	0.062	0.053
Q	0.175	0.164	0.152	0.163	0.160	0.158	0.145	0.148
Q^2/gD^5	7.36	6.53	5.61	6.44	6.15	6.06	5.10	5.27
h_4	0.023							
h/Y	0.062							
Q	0.144							
Q^2/gD^5	5.02							

Data Sheet 3

Run No.	73	78	81	85	72	79	80	84
a	1	1	1	1	1	1	1	1
d′	13.375	13.375	13.375	13.375	13.375	13.375	13.375	13.375
C	1.80	1.42	0.80	0.26	1.80	1.42	0.80	0.26
J	1.50	1.50	1.50	1.50	2.00	2.00	2.00	2.00
d/b	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
D/b	0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.22
a/D	1/2	1/2	1/2	1/2	1/2	1/2	1/2	1/2
C/b	0.200	0.158	0.089	0.029	0.200	0.158	0.089	0.029
J/b	0.167	0.167	0.167	0.167	0.223	0.223	0.223	0.223
h_1	0.033	0.038	0.033	0.058	0.042	0.040	0.037	
h/Y	0.088	0.102	0.089	0.155	0.113	0.107	0.099	
Q	0.282	0.279	0.280	0.280	0.272	0.277	0.274	
Q^2/gD^5	19.23	18.77	19.00	19.00	17.87	18.54	18.09	
h_2	0.030	0.024	0.028	0.038	0.030	0.027	0.027	0.040
h/Y	0.080	0.064	0.074	0.101	0.081	0.073	0.071	0.107
Q	0.252	0.232	0.251	0.231	0.234	0.237	0.241	0.235
Q^2/gD^5	15.38	13.00	15.187	12.84	13.18	13.53	14.06	13.35
h_3	0.017	0.015	0.019	0.016	0.19	0.017	0.014	0.015
h/Y	0.044	0.041	0.050	0.043	0.050	0.045	0.038	0.040
Q	0.197	0.180	0.194	0.173	0.186	0.181	0.188	0.172
Q^2/gD^5	9.39	7.80	9.13	7.25	8.39	7.92	8.51	7.15

Data Sheet 4

Run No.	60	100	101	102	53	105	104	103
a	1	1	1	1	1	1	1	1
d'	8.875	8.875	8.875	8.875	8.875	8.875	8.875	8.875
C	0.80	0.80	0.80	0.80	1.42	1.42	1.42	1.42
J	1.5	1.50	2.0	4.0	1.5	1.5	2.0	4.0
d/b	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
D/b	0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.22
a/D	1/2	1/2	1/2	1/2	1/2	1/2	1/2	1/2
C/b	0.089	0.089	0.089	0.089	0.158	0.158	0.158	0.158
J/b	0.167	0.167	0.222	0.444	0.167	0.167	0.222	0.444
h_1	0.045	0.046	0.045	0.057	0.058	0.056	0.046	0.053
h/Y	0.121	0.121	0.120	0.153	0.156	0.149	0.121	0.142
Q	0.226	0.243	0.238	0.241	0.240	0.238	0.238	0.234
Q^2/gD^5	12.34	14.25	13.70	14.06	13.88	13.70	13.70	13.18
h_2		0.038	0.035	0.044	0.052	0.037	0.037	0.036
h/Y		0.100	0.093	0.117	0.140	0.097	0.099	0.097
Q		0.196	0.197	0.199	0.207	0.207	0.204	0.192
Q^2/gD^5		9.26	9.39	9.53	10.35	10.35	10.07	8.88
h_3	0.032	0.020	0.020	0.023	0.033	0.020	0.021	0.023
h/Y	0.085	0.053	0.054	0.062	0.089	0.053	0.057	0.062
Q	0.184	0.160	0.157	0.158	0.175	0.148	0.147	0.145
Q^2/gD^5	8.15	6.15	5.97	6.06	7.36	5.27	5.19	5.10
h_4					0.023			
h/Y					0.062			
Q					0.144			
Q^2/gD^5					5.02			

Data Sheet 5

Run No.	80	81	82	83	92	93	98
a	1	1	1	1	1	1	1
d′	13.38	13.38	13.38	13.38	13.38	13.38	13.38
C	0.80	0.80	0.80	0.80	1.05	1.05	0.80
J	2.00	1.50	1.00	0.50	4.00	5.50	4.00
d/b	1.5	1.5	1.5	1.5	1.5	1.5	1.5
D/b	0.22	0.22	0.22	0.22	0.22	0.22	0.22
a/D	1/2	1/2	1/2	1/2	1/2	1/2	1/2
C/b	0.089	0.089	0.089	0.089	0.117	0.117	0.089
J/b	0.222	0.167	0.111	0.056	0.444	0.612	0.444
h_1	0.037	0.033	0.032	0.035	0.034	0.034	0.040
h/Y	0.099	0.089	0.087	0.093	0.090	0.092	0.106
Q	0.274	0.280	0.280	0.280	0.282	0.279	0.282
Q^2/gD^5	18.09	19.0	19.0	19.0	19.23	18.77	19.23
h_2	0.027	0.028	0.028	0.025	0.027	0.027	0.031
h/Y	0.071	0.074	0.076	0.068	0.073	0.073	0.083
Q	0.241	0.251	0.243	0.234	0.248	0.237	0.251
Q^2/gD^5	14.06	15.19	14.25	13.18	14.80	13.53	15.19
h_3	0.014	0.019	0.017	0.020	0.023	0.020	0.019
h/Y	0.038	0.050	0.045	0.052	0.060	0.053	0.050
Q	0.188	0.194	0.189	0.184	0.197	0.180	0.186
Q^2/gD^5	8.51	9.13	8.63	8.15	9.39	7.80	8.39

Data Sheet 6

Run No.	73	74	75	76	77	78	79	94	101	107
a	1	1	1	1	1	1	1	1	1	1
d'	13.38	13.38	13.38	13.38	13.38	13.38	13.38	13.38	8.88	8.88
C	1.80	1.80	1.80	1.42	1.42	1.42	1.42	1.80	0.81	0.81
J	1.50	1.00	0.50	0.50	1.00	1.50	2.00	1.50	2.00	2.25
d/b	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.0	1.0
D/b	0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.22
Z									1.43	0.70
a/D	1/2	1/2	1/2	1/2	1/2	1/2	1/2	1/2	1/2	1/2
C/b	0.200	0.200	0.200	0.158	0.158	0.158	0.158	0.200	0.90	0.90
J/b	0.167	0.111	0.056	0.056	0.111	0.167	0.222	0.167	0.250	0.222
h_1	0.033	0.040	0.051	0.042	0.041	0.038	0.040	0.033	0.045	0.068
h/Y	0.088	0.106	0.135	0.112	0.108	0.102	0.107	0.088	0.120	0.182
Q	0.282	0.282	0.275	0.279	0.270	0.279	0.277	0.282	0.238	0.213
Q^2/gD^5	19.23	19.23	18.32	18.77	17.65	18.77	18.54	19.23	13.70	10.93
h_2	0.030	0.036	0.039	0.028	0.027	0.024	0.027	0.030	0.035	0.023
h/Y	0.080	0.095	0.105	0.075	0.073	0.064	0.073	0.080	0.093	0.062
Q	0.252	0.238	0.231	0.211	0.229	0.232	0.237	0.252	0.197	0.132
Q^2/gD^5	15.38	13.70	12.84	10.79	12.67	13.00	13.53	15.38	9.39	4.21
h_3	0.017	0.026		0.011	0.018	0.015	0.017	0.017	0.020	
h/Y	0.044	0.069		0.029	0.047	0.041	0.045	0.044	0.054	
Q	0.197	0.188		0.145	0.176	0.180	0.181	0.197	0.157	
Q^2/gD^5	9.39	8.51		5.10	7.47	7.80	7.92	9.39	5.97	

Data Sheet 7

Run. No.	200	203	204	205	205	D22	D41
D/b	0.22	0.22	0.22	0.22	Data		
d/b	1.0	1.0	1.5	1.5	taken	1.5	1.0
a/D	1/2	1/2	1/2	1/2	at one		
					well		
Corner fillet					width		
					down-		
K/b		0.417		0.417	stream		
J/b		0.223		0.223	from		
C/b		0.089		0.089	well.		
Z		1.43		1.43			
Corner angle							
T/b	0.055		0.055				
L/b	0.333		0.333				
α	45°		45°				
h_1	0.055	0.143	0.020	0.084	0.078	0.18	0.17
h/Y	0.037	0.095	0.013	0.056	0.052	0.120	0.113
Q	6.18	8.43	5.69	8.21		11.55	7.27
Q^2/gD^5	9.00	16.72	7.61	15.86		31.37	12.47
h_2	0.059	0.123	0.032	0.083	0.091	0.10	0.11
h_2/Y	0.040	0.082	0.022	0.055	0.061	0.067	0.073
Q	6.82	7.69	6.82	8.74		9.031	6.10
Q^2/gD^5	10.93	13.93	10.95	17.97		19.19	8.78
h_3	0.102	0.067	0.044	0.095	0.106	0.06	0.05
h_3/Y	0.068	0.044	0.030	0.063	0.071	0.040	0.033
Q	7.90	6.43	8.49	9.34		7.23	4.30
Q^2/gD^5	14.68	9.73	16.96	20.54		12.28	4.36
h_4	0.096	0.068	0.077	0.0116	0.118		
h_4/Y	0.064	0.046	0.051	0.077	0.079		
Q	7.50	5.87	9.39	9.59			
Q^2/gD^5	13.28	8.10	20.75	21.65			
h_5	0.040	0.025	0.202	0.208			
h_5/Y	0.027	0.017	0.135	0.138			
Q	5.34	4.58	12.63	12.98			
Q^2/gD^5	6.71	4.94	37.55	39.66			

Data Sheet 8

Run No.	45	48	49	57	61	69	88	89	90
a	1	1	1	1	1	1	1	1	1
d′	8.88	8.88	8.88	8.88	8.88	13.38	13.38	13.38	13.38
T	0.48	0.30	0.60	0.40	0.525	0.048	0.525	0.480	0.525
L	3.73	3.73	3.73	3.73	3.73	3.00	3.73	3.73	3.00
α	45°	45°	45°	45°	45°	45°	45°	45°	45°
d/b	1.0	1.0	1.0	1.0	1.0	1.5	1.5	1.5	1.5
b/D	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5
T/b	0.053	0.033	0.067	0.044	0.049	0.053	0.059	0.053	0.059
L/b	0.414	0.414	0.414	0.414	0.414	0.333	0.414	0.414	0.333
h_1	0.058	0.038	0.052	0.031	0.047	0.036	0.039	0.035	0.029
h/Y	0.155	0.102	0.140	0.082	0.125	0.096	0.105	0.092	0.077
Q	0.279	0.177	0.181	0.213	0.237	0.284	0.275	0.284	0.280
Q^2/gD^5	18.77	7.58	7.92	10.93	13.54	19.47	18.32	19.47	19.00
h_2	0.033	0.025	0.025	0.028	0.032	0.027	0.030	0.028	0.030
h/Y	0.088	0.067	0.066	0.074	0.086	0.071	0.080	0.076	0.080
Q	0.235	0.147	0.151	0.182	0.210	0.257	0.238	0.235	0.246
Q^2/gD^5	13.35	5.19	5.52	8.03	10.64	15.98	13.70	13.35	14.62
h_3	0.020	0.009	0.020		0.021	0.018	0.025	0.019	0.015
h/Y	0.052	0.025	0.052		0.055	0.049	0.066	0.050	0.041
Q	0.171	0.118	0.121		0.176	0.219	0.190	0.169	0.184
Q^2/gD^5	7.04	3.38	3.56		7.47	11.54	8.75	6.94	8.15
h_4	0.012								
h/Y	0.032								
Q	0.130								
Q^2/gD^5	4.07								

Data Sheet 9

Run No.	67	99	95	97	69	34	37	66	39	41	57
a	1	1	1	1	1	1	1	1	1	1	1
d′	8.88	8.88	13.38	13.38	13.38	7.88	7.88	7.88	7.00	8.88	8.88
T	0.48	0.48	0.48	0.48	0.48	0.40	0.40	0.40	0.40	0.40	0.40
L	3.00	3.73	2.50	3.73	3.00	3.73	3.73	3.73	3.73	3.73	3.73
α	45°	45°	45°	45°	45°	30°	60°	45°	45°	1″45°	45°
d/b	1.5	1.5	1.5	1.5	1.5	1.0	1.0	1.0	1.0	1.0	1.0
b/D	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5
T/b	0.053	0.053	0.053	0.053	0.053	0.044	0.044	0.044	0.044	0.044	0.044
L/b	0.333	0.414	0.278	0.414	0.333	0.415	0.415	0.415	0.415	0.415	0.415
h_1	0.043	0.058	0.042	0.036	0.036	0.037	0.034	0.055	0.031	0.044	0.055
h/Y	0.115	0.155	0.111	0.095	0.096	0.099	0.091	0.145	0.083	0.118	0.146
Q	0.279	0.279	0.282	0.284	0.284	0.184	0.197	0.265	0.193	0.182	0.238
Q^2/gD^5	18.77	18.77	19.23	19.46	19.47	8.15	9.39	17.01	9.01	8.03	13.70
h_2	0.036	0.033	0.039	0.024	0.027	0.025	0.025	0.050	0.023	0.033	0.031
h/Y	0.097	0.088	0.104	0.064	0.071	0.067	0.067	0.134	0.063	0.088	0.082
Q	0.249	0.235	0.248	0.238	0.257	0.156	0.168	0.241	0.166	0.147	0.213
Q^2/gD^5	14.99	13.35	14.80	13.70	15.98	5.87	6.83	14.06	6.63	5.19	10.93
h_3	0.026	0.020	0.022	0.011	0.188			0.029			0.028
h/y	0.069	0.052	0.060	0.030	0.041			0.077			0.074
Q	0.208	0.171	0.180	0.186	0.219			0.206			0.182
Q^2/gD^5	10.50	7.04	7.80	8.39	11.54			10.21			8.03
h_4		0.012						0.019			
h/y		0.032						0.051			
Q		0.130						0.160			
Q^2/gD^5		4.07						6.15			

Data Sheet 10

Piezometric Pressures (feet of water)

Run No.	1	1	2	3	3	4	4	5	6	6
Percent open	10	25	25	10	25	10	25	10	10	25
Valve seat above floor (inch)	1-3/4	1-3/4	1-3/4	1/4	1/4	1/4	1/4	2	0.9	0.9
Corner configurations	Fillets	Fillets	Angles	Fillets	Fillets	Angles	Angles	Fillets	Fillets	Fillets
Piezometer No.										
1	2.35	2.70	2.76					2.80		
2	1.99	2.09	2.01					1.78		
3	2.13	2.33	2.27					2.14		
4	2.52	3.00	3.24					3.42		
5	2.51	2.99	3.50					3.58		
6	2.07	2.05						2.18		
7	1.79	1.65	1.65					1.77		
8	1.82	1.78	1.75					1.68		
9	1.99	2.04	2.00					1.70		
10	2.27	2.62	2.71					3.12		
11			2.80					3.32	2.30	3.88
12			3.26	2.84	3.75	1.51	1.23	3.55	2.14	3.38
13			2.43	2.68	3.53	1.47	1.24	3.61	2.07	3.04
14			2.10	2.50	3.24	1.51	1.30	3.58	2.06	2.88
15			1.72					1.57		
16			1.95	2.27	2.68	2.14	2.68	1.59	1.98	2.32
17			2.36	2.02	2.44	1.94	2.37	1.58	1.85	2.03
18	2.51	3.20	2.89	1.67	1.91	1.56	1.69	1.75	1.82	1.95
19			2.65	1.50	1.46	1.35	1.24	1.69	1.84	1.87
20	1.70	1.65	1.67	2.75	3.68	2.44	3.28	1.66	2.30	3.65
21	2.55	2.76	2.86	2.27	2.99	2.16	2.82	1.68	1.95	3.77
22	1.87	1.87	1.84	3.16	4.43	3.89	4.11	1.66	2.15	3.11
23	2.91	3.47	3.39	2.48	3.69	2.46	3.59	1.77	1.89	3.02
24	1.89	2.01	1.92					2.19		
25	1.87	1.96	1.90					1.91		
26	2.21	2.49	2.45					2.29		
27	2.05	2.26	2.18					1.80		
28										
29	2.13	2.12	1.18					1.43		
30	1.17	1.11	1.08					1.25		
31	1.63	1.53	1.55					1.43		
32									1.75	1.46
33									1.69	1.41
34									1.68	1.39

Data Sheet 11

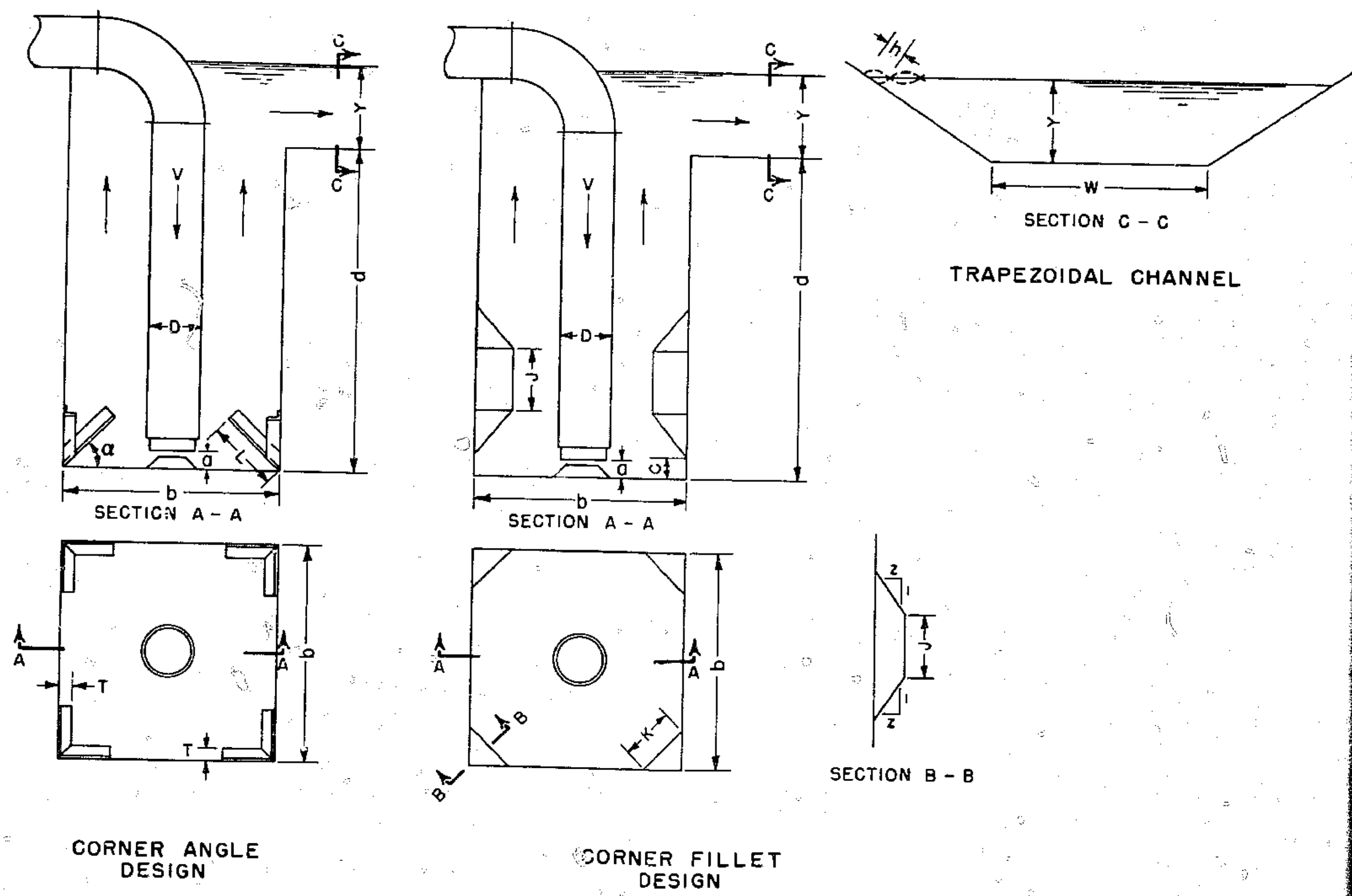
Piezometric Pressures (feet of water)

Run No.	7	7	8	8	9	9	10	10	11	11
Percent open	10	25	10	25	10	25	10	25	10	25
Valve seat above floor (inch)	0.80	0.80	0.80	0.80	0.80	0.80	0.38	0.38	1.13	1.13
Corner configurations	Fillet	Fillet	Fillet	Fillet	Fillet	Fillet	Fillet	Fillet	Fillet	Fillet
Piezometer No.										
11	2.81	3.75	2.64	3.29						
12	1.53	3.32	2.62	3.44	2.23	2.88	2.66	3.75	2.19	2.66
13	2.67	3.83	2.54	3.19	2.24	2.96	2.73	3.77	2.19	2.80
14	2.95	4.23	2.54	2.91	2.43	3.18	2.67	3.50	2.23	2.98
15										
16	2.18	2.95	1.68	2.03	2.15	3.78	2.73	3.74	2.23	3.38
17	1.29	2.50	1.57	1.70	1.92	3.34	2.89	3.84	2.17	2.90
18	2.06	2.47	1.52	1.36	2.02	4.42	2.81	2.44	2.23	3.47
19	2.16	2.40	1.49	1.03	2.28	3.10	1.88	1.52	2.08	2.97
20	2.18	3.66	2.21	3.33	2.13	3.46	2.38	3.35	2.24	2.91
21	1.49	2.57	1.63	2.97	1.89	3.01	2.59	3.48	2.13	2.66
22	2.68	4.64	1.73	3.01	2.13	3.18	2.30	3.11	2.33	2.98
23	1.96	3.77	1.57	2.57	1.89	2.89	2.39	2.96	2.28	2.74
32	1.58	1.57	1.60	1.14	1.53	1.52	1.59	1.41	1.59	1.58
33	1.55	1.52	1.56	1.50	1.53	1.46	1.59	1.26	1.57	1.49
34	1.52	1.50	1.49	2.70	1.54	1.41	1.56	1.23	1.62	1.49

Data Sheet 12

Piezometric Pressures (feet of water)

Run No.	12	12
Percent open	10	25
Valve seat above floor (inch)	0.86	0.86
Corner configuration	Fillet	Fillet
Piezometer No.		
12	2.40	3.09
13	2.27	2.82
14	2.16	2.64
15		
16	2.85	3.93
17	2.54	2.95
18	1.74	1.87
19	1.52	1.53
20	2.34	3.10
21	2.19	2.63
22	2.49	3.57
23	2.24	2.68
32	1.19	0.27
33	1.19	-0.53
34	1.44	1.14



SUMMARY OF STILLING WELL CHARACTERISTICS

7-1750 (3-71)
Bureau of Reclamation

CONVERSION FACTORS—BRITISH TO METRIC UNITS OF MEASUREMENT

The following conversion factors adopted by the Bureau of Reclamation are those published by the American Society for Testing and Materials (ASTM Metric Practice Guide, E 380-68) except that additional factors (*) commonly used in the Bureau have been added. Further discussion of definitions of quantities and units is given in the ASTM Metric Practice Guide.

The metric units and conversion factors adopted by the ASTM are based on the "International System of Units" (designated SI for Systeme International d'Unites), fixed by the International Committee for Weights and Measures; this system is also known as the Giorgi or MKSA (meter-kilogram (mass)-second-ampere) system. This system has been adopted by the International Organization for Standardization in ISO Recommendation R-31.

The metric technical unit of force is the kilogram-force; this is the force which, when applied to a body having a mass of 1 kg, gives it an acceleration of 9.80665 m/sec/sec, the standard acceleration of free fall toward the earth's center for sea level at 45 deg latitude. The metric unit of force in SI units is the newton (N), which is defined as that force which, when applied to a body having a mass of 1 kg, gives it an acceleration of 1 m/sec/sec. These units must be distinguished from the (inconstant) local weight of a body having a mass of 1 kg, that is, the weight of a body is that force with which a body is attracted to the earth and is equal to the mass of a body multiplied by the acceleration due to gravity. However, because it is general practice to use "pound" rather than the technically correct term "pound-force," the term "kilogram" (or derived mass unit) has been used in this guide instead of "kilogram-force" in expressing the conversion factors for forces. The newton unit of force will find increasing use, and is essential in SI units.

Where approximate or nominal English units are used to express a value or range of values, the converted metric units in parentheses are also approximate or nominal. Where precise English units are used, the converted metric units are expressed as equally significant values.

Table I

QUANTITIES AND UNITS OF SPACE

Multiply	By	To obtain
LENGTH		
Mil	25.4 (exactly)	Micron
Inches	25.4 (exactly)	Millimeters
Inches	2.54 (exactly)*	Centimeters
Feet	30.48 (exactly)	Centimeters
Feet	0.3048 (exactly)*	Meters
Feet	0.0003048 (exactly)*	Kilometers
Yards	0.9144 (exactly)	Meters
Miles (statute)	1,609.344 (exactly)*	Meters
Miles	1.609344 (exactly)	Kilometers
AREA		
Square inches	6.4516 (exactly)	Square centimeters
Square feet	*929.03	Square centimeters
Square feet	0.092903	Square meters
Square yards	0.836127	Square meters
Acres	*0.40469	Hectares
Acres	*4,046.9	Square meters
Acres	*0.0040469	Square kilometers
Square miles	2.58999	Square kilometers
VOLUME		
Cubic inches	16.3871	Cubic centimeters
Cubic feet	0.0283168	Cubic meters
Cubic yards	0.764555	Cubic meters
CAPACITY		
Fluid ounces (U.S.)	29.5737	Cubic centimeters
Fluid ounces (U.S.)	29.5729	Milliliters
Liquid pints (U.S.)	0.473179	Cubic decimeters
Liquid pints (U.S.)	0.473166	Liters
Quarts (U.S.)	*946.358	Cubic centimeters
Quarts (U.S.)	*0.946331	Liters
Gallons (U.S.)	*3,785.43	Cubic centimeters
Gallons (U.S.)	3.78543	Cubic decimeters
Gallons (U.S.)	3.78533	Liters
Gallons (U.S.)	*0.00378543	Cubic meters
Gallons (U.K.)	4.54609	Cubic decimeters
Gallons (U.K.)	4.54596	Liters
Cubic [illegible]	28.3160	Liters
Cubic yards	*764.55	Liters
Acre-feet	*1,233.5	Cubic meters
Acre-feet	*1,233,500	Liters

Table II

QUANTITIES AND UNITS OF MECHANICS

Multiply	By	To obtain
	MASS	
Grains (1/7,000 lb)	64.79891 (exactly)	Milligrams
Troy ounces (480 grains)	31.1035	Grams
Ounces (avdp)	28.3495	Grams
Pounds (avdp)	0.45359237 (exactly)	Kilograms
Short tons (2,000 lb)	907.185	Kilograms
Short tons (2,000 lb)	0.907185	Metric tons
Long tons (2,240 lb)	1,016.05	Kilograms
	FORCE/AREA	
Pounds per square inch	0.070307	Kilograms per square centimeter
Pounds per square inch	0.689476	Newtons per square centimeter
Pounds per square foot	4.88243	Kilograms per square meter
Pounds per square foot	47.8803	Newtons per square meter
	MASS/VOLUME (DENSITY)	
Ounces per cubic inch	1.72999	Grams per cubic centimeter
Pounds per cubic foot	16.0185	Kilograms per cubic meter
Pounds per cubic foot	0.0160185	Grams per cubic centimeter
Tons (long) per cubic yard	1.32894	Grams per cubic centimeter
	MASS/CAPACITY	
Ounces per gallon (U.S.)	7.4893	Grams per liter
Ounces per gallon (U.K.)	6.2362	Grams per liter
Pounds per gallon (U.S.)	119.829	Grams per liter
Pounds per gallon (U.K.)	99.779	Grams per liter
	BENDING MOMENT OR TORQUE	
Inch-pounds	0.011521	Meter-kilograms
Inch-pounds	1.12985×10^{6}	Centimeter-dynes
Foot-pounds	0.138255	Meter-kilograms
Foot-pounds	1.35582×10^{7}	Centimeter-dynes
Foot-pounds per inch	5.4431	Centimeter-kilograms per centimeter
Ounce-inches	72.008	Gram-centimeters
	VELOCITY	
Feet per second	30.48 (exactly)	Centimeters per second
Feet per second	0.3048 (exactly)*	Meters per second
Feet per year	*0.965873×10^{-6}	Centimeters per second
Miles per hour	1.609344 (exactly)	Kilometers per hour
Miles per hour	0.44704 (exactly)	Meters per second
	ACCELERATION*	
Feet per second^2	*0.3048	Meters per second^2
	FLOW	
Cubic feet per second (second-feet)	*0.028317	Cubic meters per second
Cubic feet per minute	0.4719	Liters per second
Gallons (U.S.) per minute	0.06309	Liters per second
	FORCE*	
Pounds	*0.453592	Kilograms
Pounds	*4.4482	Newtons
Pounds	*4.4482×10^{5}	Dynes

Table II—Continued

Multiply	By	To obtain
	WORK AND ENERGY*	
British thermal units (Btu)	*0.252	Kilogram calories
British thermal units (Btu)	1,055.06	Joules
Btu per pound	2.326 (exactly)	Joules per gram
Foot-pounds	*1.35582	Joules
	POWER	
Horsepower	745.700	Watts
Btu per hour	0.293071	Watts
Foot-pounds per second	1.35582	Watts
	HEAT TRANSFER	
Btu in./hr ft^2 degree F (k, thermal conductivity)	1.442	Milliwatts/cm degree C
Btu in./hr ft^2 degree F (k, thermal conductivity)	0.1240	Kg cal/hr m degree C
Btu ft/hr ft^2 degree F	*1.4880	Kg cal m/hr m^2 degree C
Btu/hr ft^2 degree F (C, thermal conductance)	0.568	Milliwatts/cm^2 degree C
Btu/hr ft^2 degree F (C, thermal conductance)	4.882	Kg cal/hr m^2 degree C
Degree F hr ft^2/Btu (R, thermal resistance)	1.761	Degree C cm^2/milliwatt
Btu/lb degree F (c, heat capacity)	4.1868	J/g degree C
Btu/lb degree F	*1.000	Cal/gram degree C
Ft^2/hr (thermal diffusivity)	0.2581	Cm^2/sec
Ft^2/hr (thermal diffusivity)	*0.09290	M^2/hr
	WATER VAPOR TRANSMISSION	
Grains/hr ft^2 (water vapor) transmission)	16.7	Grams/24 hr m^2
Perms (permeance)	0.659	Metric perms
Perm-inches (permeability)	1.67	Metric perm-centimeters

Table III

OTHER QUANTITIES AND UNITS

Multiply	By	To obtain
Cubic feet per square foot per day (seepage)	*304.8	Liters per square meter per day
Pound-seconds per square foot (viscosity)	*4.8824	Kilogram second per square meter
Square feet per second (viscosity)	*0.092903	Square meters per second
Fahrenheit degrees (change)*	5/9 exactly	Celsius or Kelvin degrees (change)*
Volts per mil	0.03937	Kilovolts per millimeter
Lumens per square foot (foot-candles)	10.764	Lumens per square meter
Ohm-circular mils per foot	0.001662	Ohm-square millimeters per meter
Millicuries per cubic foot	*35.3147	Millicuries per cubic meter
Milliamps per square foot	*10.7639	Milliamps per square meter
Gallons per square yard	*4.527219	Liters per square meter
Pounds per inch	*0.17858	Kilograms per centimeter

GPO 835-188

ABSTRACT

Vertical stilling wells are economical and ideally suited to dissipate high energy pipe flow. Model studies established general design criteria for vertical stilling wells using a standard sleeve valve. Dimensionless parameters based on design discharge, Q, and valve diameter, D, were established to aid the designer in determining optimum well size for a specific need. Over 100 tests were conducted with 2 laboratory models to determine stilling well geometry. The wave runup measured along the side slope of the downstream channel was used for all tests as the criterion for the efficiency of energy dissipation of each well configuration. Generally, a well depth-to-width ratio of 1.5 will give the best results. The corner angle configuration yields a smoother tailwater surface than the corner fillet and is a more economical design. Pressure distribution tests have not pinpointed the cause of possible concrete erosion in the stilling well but possibly such erosion may be alleviated or completely eliminated by placing the standard sleeve valve on the floor and by removing the pedestal and the pipe stand sleeve supports. A graphical method of presentation aids the designer in sizing a vertical stilling well. Three design examples are included. Has 9 references.

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REC-ERC-73-3
Burgi, P H
HYDRAULIC MODEL STUDIES OF VERTICAL STILLING WELLS
Bur Reclam Rep REC-ERC-73-3, Div Gen Res, Feb 1973. Bureau of Reclamation, Denver, 44 p, 49 fig, 4 tab, 9 ref, append

DESCRIPTORS—/ hydraulic models/ cavitation/ *energy dissipation/ test procedures/ *energy dissipators/ *sleeve valves/ *stilling wells/ hydraulic structures/ hydraulic design/ design criteria/ cavitation control/ high head/ outlets/ pressure distribution
IDENTIFIERS—/ ported sleeve valve/ vertical stilling wells

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