PAP-458

HYDRAULIC DESIGN OF VERTICAL STILLING WELLS

BY

PHILLIP H. BURGI

PAP-458

JOURNAL OF THE
HYDRAULICS DIVISION

Hydraulic Design of Vertical Stilling Wells[a]

By Philip H. Burgi,[1] A. M. ASCE

Introduction

Vertical stilling wells are ideally suited for dissipation of high energy pipe flow. The pipe enters the stilling well along the vertical axis with a control valve attached to the terminus of the pipe (Fig. 1). The high velocity jet which leaves the valve seat in a radial-horizontal pattern converges in the corners of the square well. The convergence of the radial flow results in very intense vertical flow in the corners. Corner deflectors direct this vertical flow from the lower corners into the center of the well, creating a roller action that adds to the turbulence and energy dissipation. The flow rises vertically in the well where it is stilled and discharged with a smooth water surface into a channel or chamber.

Recognizing the value of the vertical stilling well, the U.S. Bureau of Reclamation (USBR) established a research program to develop general design criteria. This paper reviews the laboratory work to date and presents guidelines to aid the designer in determining optimum well geometry for his specific need.

Previous Investigations

As early as 1950, the USBR Hydraulic Laboratory studied designs of the vertical stilling well (2,6). 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.

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

Note.—Discussion open until December 1, 1975. To extend the closing date one month, a written request must be filed with the Editor of Technical Publications, ASCE. This paper is part of the copyrighted Journal of the Hydraulics Division, Proceedings of the American Society of Civil Engineers, Vol. 101, No. HY7, July, 1975. Manuscript was submitted for review for possible publication on October 7, 1974.

[a] Presented at the August 16–18, 1972, ASCE Hydraulics Division Specialty Conference, held at Ithaca College, Ithaca, N.Y.

[1] Hydraulic Engr., Div. of General Research, U.S. Bureau of Reclamation, Denver, Colo.

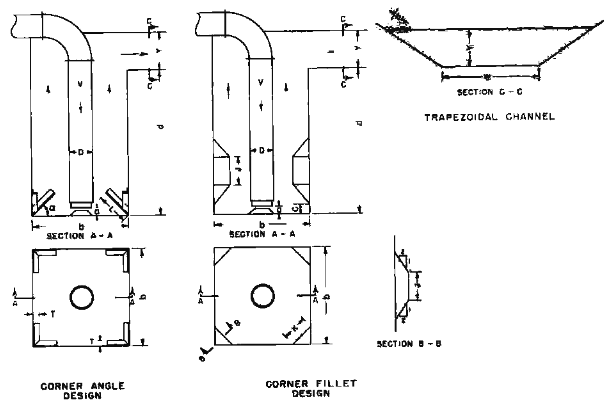


FIG. 1.—Summary of Stilling Well Characteristics

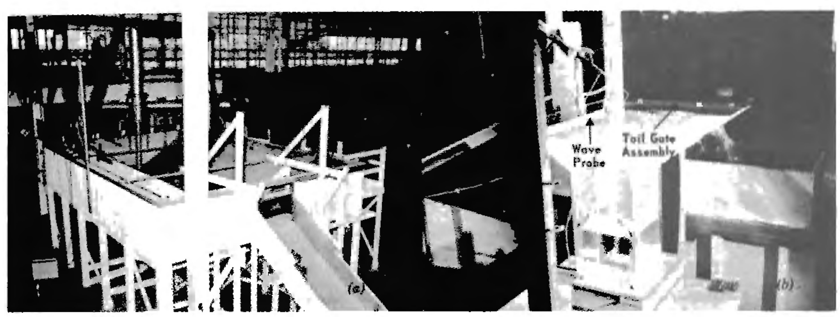


FIG. 2.—View of: (a) 3-ft (0.9-m) Model; (b) 9-in. (230-m) Model

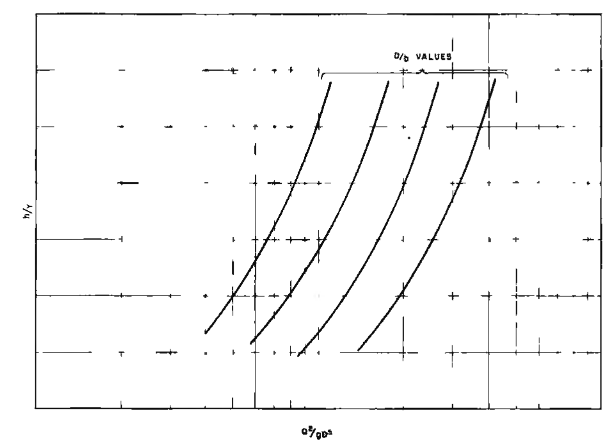


FIG. 3.—Concept of General Design Curves

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, vertical circular wall, baffle wall, and corner fillets. The configuration yielding the most satisfactory water surface was the corner fillet design in a square well. The octagonal wall also produced a satisfactory water surface but the corner fillets and square well offered a simpler design.

The idea of using a circular stilling well was also investigated in the laboratory. The data from the studies indicated 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 control valve was developed by the USBR 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 Colgate and reported by Falvey (3) 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 and placed it in competition with other high-head energy dissipators. The success of the vertical stilling well prompted the USBR to initiate a research program to develop general design criteria covering a wide range of heads and discharges. Between 1962–1970, studies were performed to optimize the design of the vertical stilling well. Although unpublished, the work was significant in developing the generalized design criteria published by the USBR in 1972 (1).

Investigation

Physical Description of 3-ft Model.—A 3-ft (0.9-m) square model constructed for the previous studies was utilized for some of the tests reported herein [Fig. 2(*a*)]. The model stilling well, constructed of wood, was 3 ft by 3 ft (0.9 m by 0.9 m) in plan with a maximum available depth of 6 ft (1.8 m). Various diameter downspouts ranging from 6 in.–12 in. (150 mm–300 mm) were tested in this model. The distance between the bottom of the downspout and the stilling well floor could be varied.

The downstream portion of the model consisted of a trapezoidal channel with 1.5:1 sideslopes. The bottom width of the channel was 3 ft (0.9 m).

Physical Description of 9-in. Model.—A 9-in. (230-mm) square plexiglass model [Fig. 2(*b*)] was constructed to a 1:4 scale of the large model and used for the majority of the tests by the writer. 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. Wave runup on the side slopes of the downstream channel was measured with a capacitance wave probe and recorded on a strip chart recorder.

A 2-in. (50-mm) sleeve valve was constructed of plastic and used in the tests involving pressure distribution on the walls and floor of the well. This model was used early in the investigation to determine the optimum value for the corner configuration dimensionless parameters.

Experimental Approach.—The important hydraulic and geometric variables identified in the study were Q,g, D, b, d, h, Y, a, C, J, K, L, T, Z, and α (Fig. 1). One goal of the study was to find a functional relationship between these variables, defined in Appendix II, and the wave action in the downstream channel. The variables are Q, g, D, b, d, h, Y, a, C, J, K, L, and T and the dimensions are l^3/t, l/t^2, l, l, l, l, l, l, l, l, l, l, l, in which l = length; t = time; h/Y = the downstream wave dimensionless parameter; and $a/D = 0.5$ as the dimensionless parameter for the maximum valve opening. The well width, b, was chosen as the repeating length variable.

By inspection:

$$f\left(\frac{Q^2}{gD^5}, \frac{D}{b}, \frac{d}{b}, \frac{C}{b}, \frac{J}{b}, \frac{K}{b}, \frac{L}{b}, \frac{T}{b}, \frac{h}{Y}, \frac{a}{D}\right) = 0 \quad \text{(1)}$$

$$\text{Therefore} \quad \frac{h}{Y} = f\left(\frac{Q^2}{gD^5}, \frac{n}{b}\right) \quad \text{(2)}$$

in which n = any of the length variables. The tests for optimization of the well geometry presented in the following pages were conducted for a valve opening of 100% where $a/D = 0.5$. The 9-in. (230-mm) model with the 2-in. (50-mm) sleeve 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 set at $D/b = 2/9 = 0.22$. Over 100 tests were conducted with combinations of values for the other variables. The wave runup, h, measured along the 1.5:1 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 the data. The wave amplitude was assumed to follow a normal distribution and 40 observations were used for each test. Three or more discharges and associated wave traces were obtained for each test setup.

Results

Sizing 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. Eq. 2 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, representing various aspects of the stilling well geometry. The variables C, J, K, L, and T represent the dimensions for the well corner geometry. Previous investigations have attempted to express these variables as dimensionless constants. Assuming these variables can be expressed as dimensionless constants, the remaining parameters are: $Q^2/(gD^5)$, h/Y, D/b, and d/b. Fig. 3 shows the proposed relationship: $h/y = f[Q^2/(gD^5), D/b]$ for d/b = constant.

The flow parameter, $Q^2/(gD^5)$, can be calculated upon selection of the design discharge, Q, and valve diameter, D. The d/b ratio will depend on the designer's 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 best results.

As shown in Fig. 3, the proper selection of the D/b value will depend on the desired value of h/Y 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.

Corner Fillet Design.—In the development of a vertical stilling well design for Soap Lake Siphon, (2) corner fillets similar to those shown in Fig. 1 were

TABLE 1.—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[a]	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[a]	1.5	0.269-0.472	—	0.095	1.4
Work by Wu[a]	1.5	0.269-0.472	—	0.100	1.7
Work by writer	1.0	0.417	0.190	0.100	1.4
	1.5	0.417	0.225	0.100	1.4

[a]Unpublished.

tested and found to yield a very smooth water surface. The corner fillet design of the vertical stilling wells for Wanship Dam (3) was similar to that developed for the Soap Lake Siphon stilling well. Table 1 lists as dimensionless parameters the optimum fillet measurements developed by various investigators.

In reviewing the development work, considerable scatter was noted among the various investigations for the values of J/b, C/b, and Z. As a result of this review, studies were undertaken on the 9-in. (230-mm) model to determine independently the optimum values for J/b, C/b, and Z. The criterion used to measure the efficiency of energy dissipation was the wave height parameter, h/Y, along the 1.5:1 side slope of the downstream channel.

A tailwater surface fluctuation of $h/Y = 0.080$ was selected as the standard on which to compare the efficiency of energy dissipation for the various well parameters.

A series of tests was conducted, varing C for several values of J/b. Fig. 4 is a plot of the test results conducted for $d/b = 1.5$. A series of tests was also conducted for $d/b = 1.0$.

Fig. 5 shows 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 Fig. 4. The various curves in the figure indicate the following trend: when d/b = 1.0, C/b = 0.100; and when d/b = 1.5, C/b = 0.100. The conclusion is, therefore, that the variable, C, is

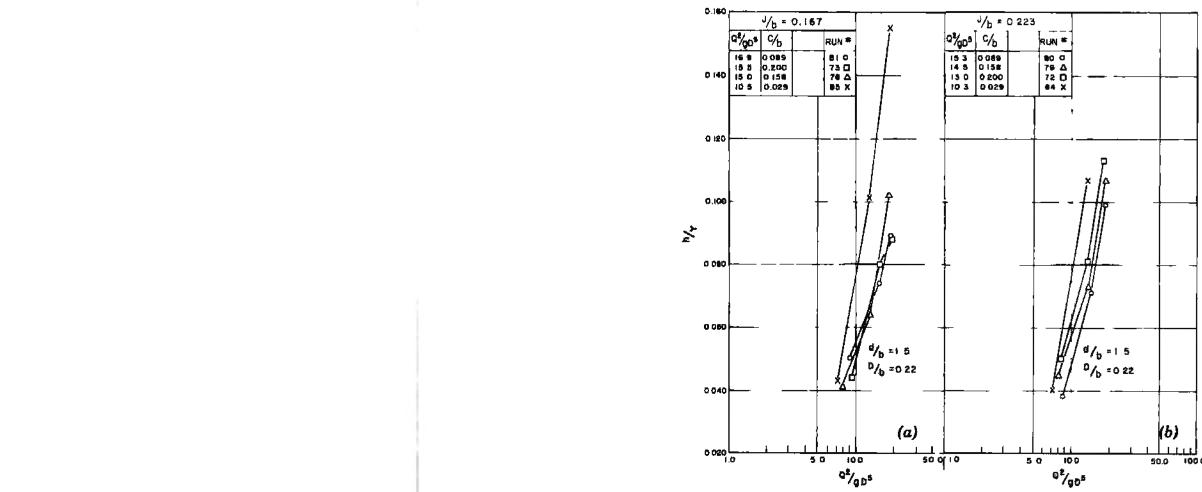


FIG. 4.—h/Y Versus $Q^2/(gD^5)$ for Variable C

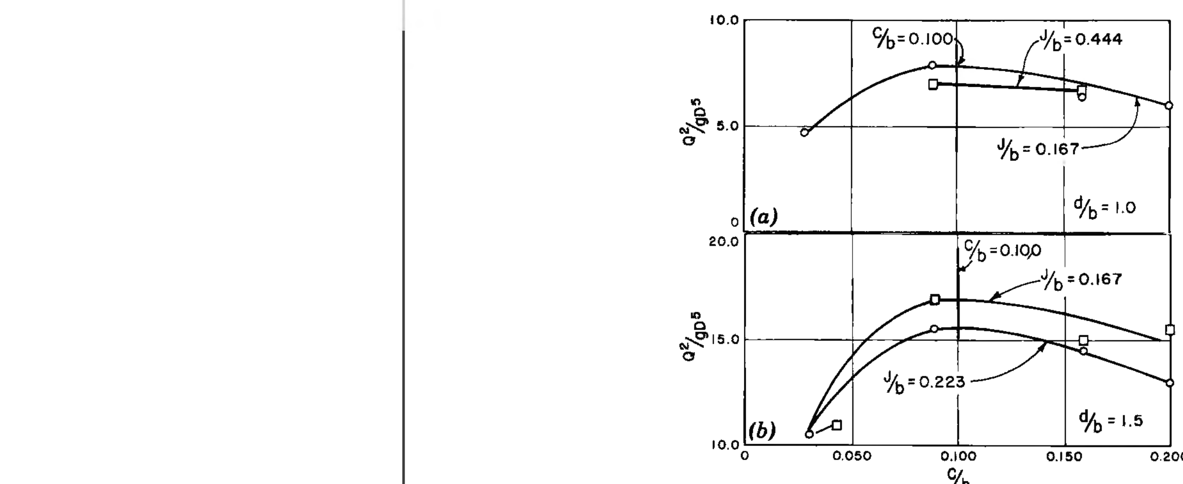


FIG. 5.—Optimization of C/b

proportional to the variable, b, and that the dimensionless parameter, C/b = 0.10, represents the optimum value.

The same laboratory approach was utilized to optimize the fillet length, J, and bottom slope, Z.

In 1966, Denson completed a series of tests using the 3-ft (0.9-m) vertical stilling well model in the USBR Hydraulic Laboratory. Constant values were established for the dimensionless parameters C/d, J/d, and K/b, based on studies for a well depth to width ratio, $d/b = 1.5$. He assumed that the values for these parameters would also be constant for $d/b = 1$ and $d/b = 2$. Denson's tests established a series of curves for values of $D/b = 0.33$, 0.28, 0.22, and

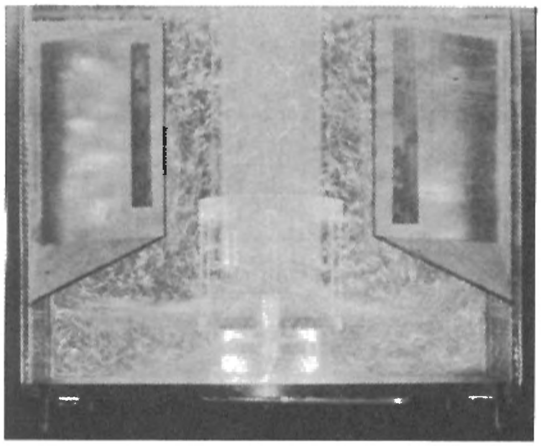
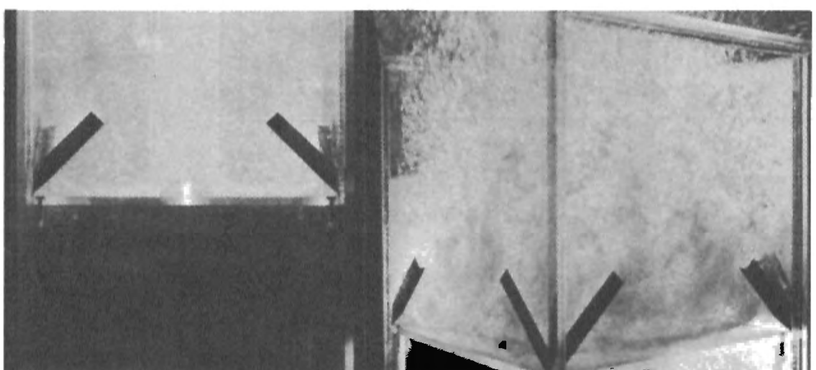


FIG. 6.—Flow Pattern with Wide Pedestal



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

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

FIG. 7.—Corner Angle Design: $T/b = 0.053$; $L/b = 0.333$; **and** $\alpha = 45°$

0.17 on three graphs for $d/b = 1.0$, 1.5, and 2.0. The writer has included Denson's results for $d/b = 1.5$ and 2.0 in the General Design Criteria section of the paper.

Corner Angle Design.—The 9-in. (230-mm) stilling well was also tested using small corner angles (Fig. 1), 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. The height of the angles above the well floor, C, and angle α, were also determined. Values of L/b and T/b maximize the flow parameter, $Q^2/(gD^5)$,

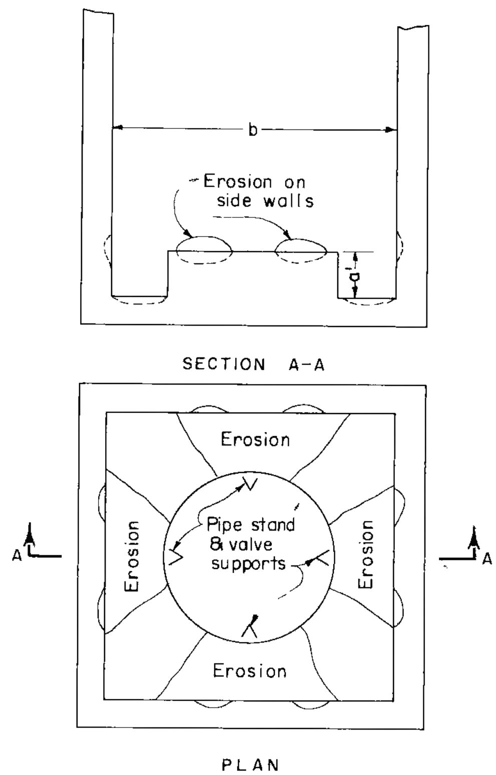


FIG. 8.—Typical Stilling Well Erosion Patterns

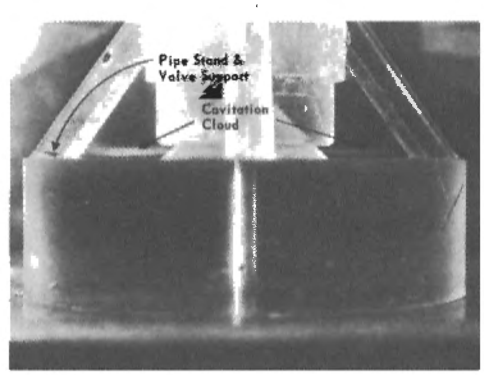


FIG. 9.—Typical Cavitation Cloud in Jet of Standard Sleeve Value [2-in. (50-mm)] Model

for a given wave height $h/Y = 0.80$ at: $L/b = 0.333$; and $T/b = 0.053$, with the optimum value of $\alpha = 45°$.

Four tests were conducted to determine the optimum values of pedestal height, a', and corner angle height, C, above the floor. A high velocity roller was noted under the jet, bounded by the floor and pedestal walls when the valve was placed on a pedestal. Any debris caught in the roller, including fine sediment, could produce a highly abrasive action against the concrete surfaces. Figure 6 shows the flow pattern with a' equal to 1.0 in. (25.4 mm) and the pedestal diameter D' equal to 3.0 in. (80 mm). This flow pattern is very similar to that which occurs with the USBR stilling wells presently in use where the jet leaves the pedestal horizontally. Note the roller at the intercept of the sidewalls and floor. In order to observe the flow patterns present in the well, air was injected into the upstream pipe after the test data were recorded for each run. Photographs were taken through the sidewall with the air bubbles illuminated by light through 1/4-in. (6.3-mm) slits in the center of the otherwise darkened sidewalls. The energy dissipation characteristics of the stilling well are not improved by the pedestal and since there is potential for abrasion damage on the 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. Therefore, $C = 0$ was selested. Fig. 7 shows the flow pattern for the recommended corner angle design.

Well Erosion.—Several vertical stilling wells on USBR 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 in Fig. 8. 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. A test program was conducted in the 9-in. (230-mm) plastic stilling well to study pressure distributions in the eroded areas.

Though the pressure distribution tests did not pinpoint the cause of erosion, two areas for improvement were recognized. The first area involves the present use of a pedestal in the stilling well. The conventional sleeve valve should be placed on the floor of the stilling well to eliminate the roller under the jet and the floor and possibly the sidewalls of the well should be steel-lined to a height equal to $1.5D$ to eliminate concrete erosion. The second area involves 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 develop immediately behind the legs, with the possibility for cavitation. Another method of support should be developed for the pipe stand and valve such that there would be no obstruction placed in the high-velocity jet leaving the valve.

Figure 9 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.

General Design Criteria.—The results of the tests on the 9-in. (230-mm) and 3-ft (0.9-m) stilling well models by the writer, plus the work completed by Denson, provide the basis on which the general design criteria were established.

The design criteria apply to vertical stilling wells, with a standard sleeve valve and a maximum sleeve travel equal to one-half the valve diameter, D, $a/D = 1/2$. 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.

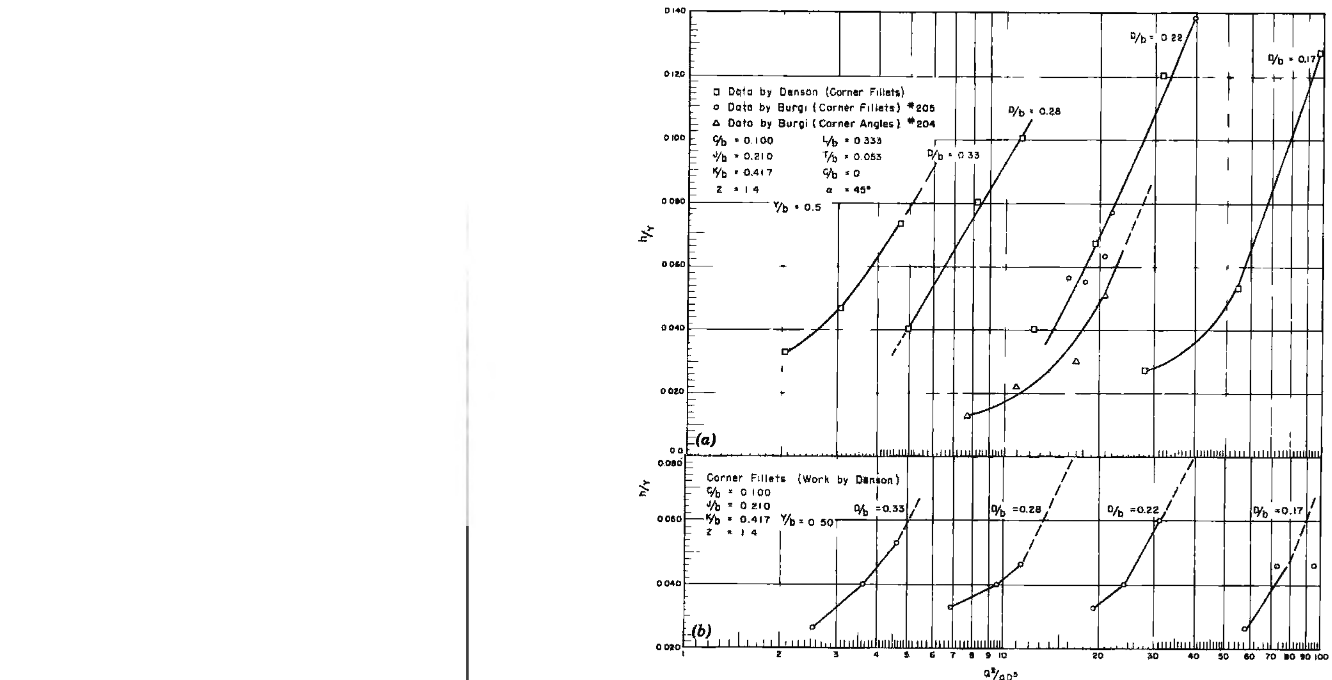


FIG. 10.—h/Y **Versus** $Q^2/(gD^5)$: **(*a*) For** $d/b = 1.5$; **(*b*) For** $d/b = 2.0$

Figs. 10(a) and 10(b) present the relationship, $h/Y = f[Q^2/(gD^5), D/b]$, for $d/b = 1.5$ and 2.0 as described earlier in Fig. 3. The dimensionless constants, C/b, J/b, K/b, L/b, and T/b, have also been determined. Fig. 10(a) shows the results of Denson's and the writer's work for $d/b = 1.5$ and Fig. 10(b) shows the results of Denson's work for $d/b = 2.0$. The optimum values for the dimensionless constants are recorded on the figures. For those curves representing values of D/b where the corner angle configuration is not shown, use of the corner fillet D/b curve is recommended. The step by step procedure for designing the vertical stilling well will be illustrated in a design example. As expected, the smaller the pipe diameter to well width ratio, D/b, the smoother the water surface for a given value of the flow parameter, $Q^2/(gD^5)$. The

h/Y values of 0.033 and 0.067 were arbitrarily chosen to define smooth and moderately rough water surfaces in the well.

The values for the design discharge, Q, and the valve 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 valve diameter, D, rather than the tailwater depth, Y, since the value of the former is known. Therefore,

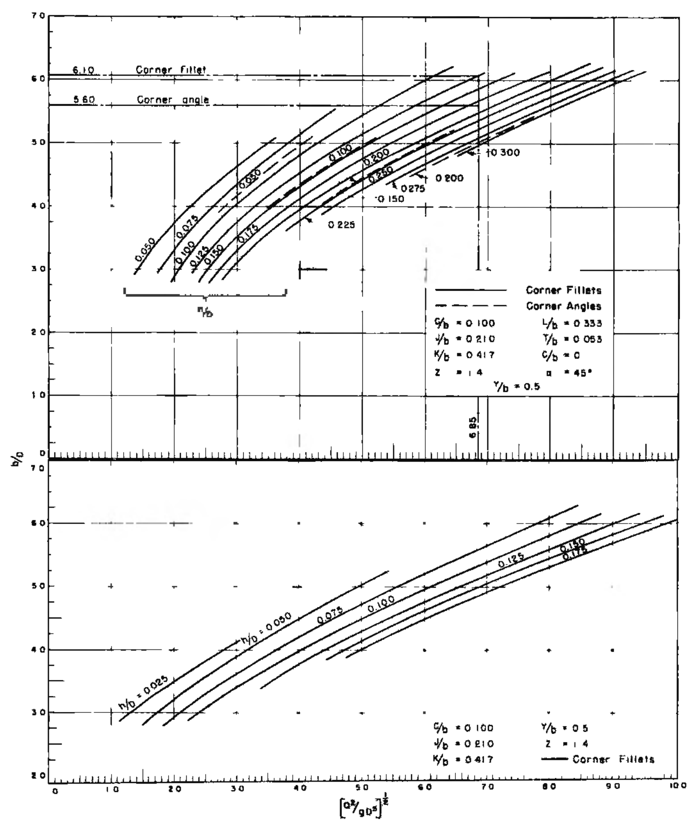


FIG. 11.—Design Curve of b/D Versus $[Q^2/(gD^5)]^{1/2}$: (*a*) For $d/b = 1.5$; (*b*) For $d/b = 2.0$

the data used to plot Fig. 10(*a*) and 10(*b*) were rearranged and used to generate families of curves h/D in Fig. 11(*a*) and 11(*b*). These two figures will simplify the design approach for the vertical stilling well.

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 herein. With the trend toward higher pressure differentials across the sleeve valve, the need arises for a research effort in the area of determining allowable jet velocities at the concrete wall of the stilling well. However, this question can be circum-

TABLE 2.—Tabulation of Standard Sleeve

Structure (1)	Date installed (2)	Size, in inches (3)	Maximum Static head, in feet (4)
Wanship Dam	1955	16	120
		16	150
Fort Cobb Dam	1959	24	110
Agate Dam	1966	24	84
Mason Dam	1967	12	170
Mann Creek Dam	1967	12	140
		24	74
Contra Loma Dam (2)	1967	24	100
Stampede Dam	1967	12	250
Starvation Dam (2)	1968	12	150
Pleasant Valley Pumping Plant	1968	24	200
Sinlahekin Creek	1969	12	400

Note: 1 in. = 25.4 mm; 1 ft = 0.305; 1 cu ft/sec = 0.028 m^3/s.

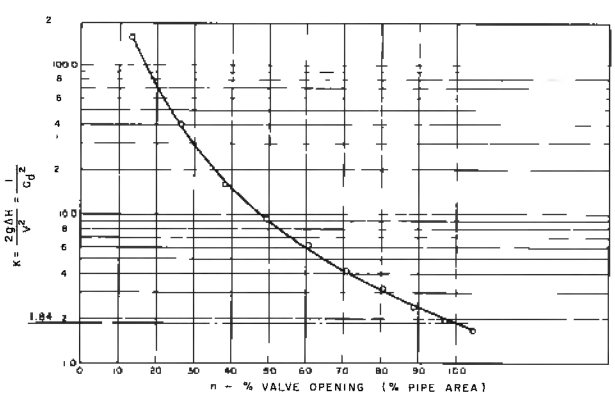


FIG. 12.—Head Loss Coefficient K for Standard Sleeve Value [2-in. (50-mm)] Model

vented by lining the lower area of the well with steel plate.

The present design of the standard sleeve valve may result in damage to the stilling well or valve under high-head [above 150 ft (50 m)] conditions, or both. During testing of a similar 12-in. (305-mm) standard sleeve valve, Winn and Johnson (7) detected cavitation noise and vibration above 100 ft (30 m) of head differential across the valve.

Table 2 lists standard sleeve valves installed by the USBR. Damage to the

Valves Installed by Bureau of Reclamation

Discharge, in cubic feet per second (5)	Well Size		Type of service (8)	Damage (9)
	Width, in feet (6)	Depth, in feet (7)		
17	6	8.25	Irrigation	No damage
17	6	8.25	Irrigation	Sleeve valve pitting, well erosion
21	9	21	Municipal and industrial	No damage
78	10	16	Irrigation	Well erosion
—	6	17	Outlet Works	No damage
14	6	8	Irrigation	Control stem broke, well erosion
18	9	9	Irrigation	No damage
—	10	15	Outlet works	No damage
36	6	13	Outlet works	No report
—	6	12	Outlet works	No report
—	—	—	Drain	No report
70	6.67	13.5	Inlet to storage reservoir	Control stem broke, well erosion

stilling well walls and floor and breakage of the sleeve valve control shaft have been reported on some of these installations. However, there is no positive correlation between the damage and head differential across the valve.

Design Example.—Design a stilling well for a sleeve-type valve discharging a maximum flow of 220 cfs (6.2 m^3/s) with a total head, H_T, at the valve of 250 ft (76 m). 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 in. (8.0 mm) one well width, b, from the well.

1. Use

$$H_T = \frac{V^2}{2g} + \Delta H \quad (3)$$

in which $V^2/(2g)$ = pipe velocity head, in feet; and ΔH = pressure head loss measured from the valve inlet flange immediately upstream of the elbow to the downstream canal water surface, in feet. Fig. 12 shows the head loss coefficient, $k = 2g\, \Delta H/V^2$, for the 2-in. (50-mm) model sleeve valve tested in this study. For a valve 100% open $K = 1.84$ and

$$H_T = \frac{V^2}{2g} + 1.84\frac{V^2}{2g} = 2.84\frac{V^2}{2g} \quad (4)$$

Therefore $$\frac{V^2}{2g} = \frac{H_T}{2.84} = \frac{250}{2.84} = 88 \text{ ft (30 m)} \quad (5)$$

and $V = 75.3$ fps (23 m/s) . . . . (6)

Since $Q = VA$

$$A = \frac{Q}{V} = \frac{220}{75.3} = 2.92 \text{ sq ft } (0.27 \text{ m}^2) \quad \ldots \quad (7)$$

$$\text{and} \quad D = \left[\left(\frac{4}{\pi}\right)A\right]^{1/2} = 1.93 \text{ ft } (0.59) \quad \ldots \quad (8)$$

use a 2.0-ft (0.61-m) I.D. valve.

2. The design curves [Fig. 11(a) and 11(b)] for sizing the stilling well are based on 100% valve opening. To determine well width, b, calculate the flow parameter:

$$\left[\frac{Q^2}{gD^5}\right]^{1/2} = \left[\frac{(220)^2}{(32.2)(2)^5}\right]^{1/2} = 6.85 \quad \ldots \quad (9)$$

and the desired ratio of wave height to valve diameter, $h/D = 3/24 = 0.125$. Let the well depth, d, equal 1.5 times the well width, b ($d/b = 1.5$). In some instances a more economical design might be $d/b = 1.0$ or 2.0. However, in general, $d/b = 1.5$ will be the appropriate choice.

3. From Fig. 11(a) ($d/b = 1.5$) for $[Q^2/(gD^5)]^{1/2} = 6.85$ and $h/D = 0.125$, $b/D = 6.1$ (corner fillets), $b/D = 5.6$ (corner angles). Select the angle as the more economical design. Therefore: $b = 11.20$ ft (3.41 m); and $d = 16.80$ ft (5.12 m).

4. From the established parameters of the corner angle design: $T/b = 0.053$; $T = 0.59$ ft (0.18 m); use 7-in. (180-mm) by 4-in. (100-mm) corner angles where $T = 7$ in. (180 mm); $L/b = 0.33$; $L = 3.75$ ft (1.14 m); $C/b = 0$; $C = 0$; and $\alpha = 45°$.

5. Line the floor of the stilling well with 1/2-in. (12.7 mm) stainless steel and the walls to a height of $1.5D = 3.00$ ft (0.9 m) with 1/2-in. (12.7 mm) carbon steel. Weld the corner angles to the steel liner.

This design approach is based on the downstream channel depth, Y, equal to one-half the well width, b. In the design example, $y = 5.6$ ft (1.71 m). If the channel has a depth greater or less than $Y = b/2$, the well depth, d, should be adjusted to maintain a total submergence, $Y + d$, of 22.4 ft (6.8 m) to assure a wave height, $h = 3.0$ in. (80 mm) or less.

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 height in the downstream channel.

Miller (5) and Johnson (4) recommend a maximum valve velocity of 40 fps (12.2 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. A recent sleeve valve design by the USBR used this approach.

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. Optimum values for the dimensionless parameters of the corner fillet and corner angle configurations are as follows:

Corner Fillet	Corner Angle
$C/b = 0.100$	$T/b = 0.053$
$J/b = 0.210$	$L/b = 0.333$
$K/b = 0.417$	$\alpha = 45°$
$Z = 1.4$	$C/b = 0$

The well dimensions are defined in Fig. 1.

3. The corner angle configuration yields a smoother tailwater surface than the corner fillet configuration. The corner angle configuration should also result in a more economical design.

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

5. 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 and floor with stainless clad steel plate. Studies indicate that protection of the floor and wall height to 1.5 D (valve diameter) above the valve seat may be required.

Acknowledgments

The writer is indebted to several members of the USBR Hydraulics Branch for their assistance during the course of the study. Earlier studies by Keith H. Denson, Wen Hsiung Huang, Chian Min Wu, and D. L. Matchett provided the groundwork for the subject study.

Appendix I.—References

1. Burgi, P. H., "Hydraulic Model Studies of Vertical Stilling Wells," *REC-ERC-73-3,* U.S. Bureau of Reclamation, Denver, Colo., Feb., 1973.
2. Colgate, D., "Hydraulic Model Studies of the Stilling Well for the Blow-Off Structure, Soap Lake (Inverted) Siphon—Columbia Basin Project," *Hydraulic Laboratory Report No. Hyd. 277,* U.S. Bureau of Reclamation, Denver, Colo., Apr., 1950.
3. Falvey, H. T., "Hydraulic Model Studies of the Wanship Dam Vertical Stilling Wells, Weber Basin Project, Utah," *Hydraulic Laboratory Report No. Hyd-481,* U.S. Bureau of Reclamation, Denver, Colo., Jan., 1962.
4. Johnson, D. E., "Sleeve Valves," presented at the Institute of Control of Flow in Closed Conduits, Colorado State University, Fort Collins, Colo., August 9–14, 1970.
5. Miller, E., "The Submerged Discharge Valve," *Glenfield Gazette, No. 229,* Feb., 1969.
6. Schuster, J. C., and Simmons, W. P., "Hydraulic Model Studies of the Masonville Siphon Turnout Structure-Horsetooth Feeder Canal-Colorado Big Thompson Project, Colorado," *Hydraulic Laboratory Report No. Hyd-277,* U.S. Bureau of Reclamation, Denver, Colo., Apr., 1950.
7. Winn, W. P., and Johnson, D. E., "Cavitation Parameters for Outlet Valves," *Journal of the Hydraulics Division,* ASCE, Vol. 96, No. HY12, Proc. Paper 7771, Dec., 1970, pp. 2519-2533.

Appendix II.—Notation

The following symbols are used in this paper:

A = cross-sectional pipe area;
a = vertical sleeve travel of valve (Fig. 1);
a' = pedestal height;
b = width of stilling well (Fig. 1);
C = vertical distance off well floor of corner angle or fillet (Fig. 1);
D = sleeve valve diameter;
D' = pedestal diameter;
d = depth of stilling well (Fig. 1);
f = function;
g = acceleration of gravity;
h = wave height measured along 1.5:1 channel slope (Fig. 1);
J = vertical height of corner fillet (Fig. 1);
K = width of corner fillet (Fig. 1);
k = head loss coefficient (design example);
L = length of corner angle (Fig. 1);
n = any length variable;
Q = valve discharge;
T = width of corner angle (Fig. 1);
V = valve velocity;
Y = water depth in downstream channel (Fig. 1);
Z = slope of corner fillet (Fig. 1);
α = angle of corner angle (Fig. 1); and
ΔH = pressure head loss from valve inlet to downstream canal water surface (see design example).

11451 HYDRAULIC DESIGN OF VERTICAL STILLING WELLS

KEY WORDS: Cavitation; **Design criteria; Energy dissipation; Hydraulic models; Hydraulics;** Hydraulic structures; Sleeve valves; **Stilling wells**

ABSTRACT: Vertical stilling wells are economical and ideally suited to dissipate high energy 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 two laboratory models to determine stilling well geometry. A graphical method of presentation aids the designer in sizing the vertical stilling well. A design example is included.

REFERENCE: Burgi, Philip H., "Hydraulic Design of Vertical Stilling Wells," *Journal of the Hydraulics Division,* ASCE, Vol. 101, No. HY7, **Proc. Paper 11451**, July, 1975, pp. 801-816