EVALUATION OF THREE ENERGY DISSIPATORS FOR STORM DRAIN OUTLETS

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Results of model tests of 3 commonly used energy dissipators for storm drain outlets are reported. The limiting discharges for various sized models of stilling wells, U. S. Bureau of Reclamation Type VI basins, and St. Anthony Falls stilling basins were determined. Charts were prepared for each type of energy dissipator and show the maximum recommended discharge that will result in good performance for given outlet diameters and structure widths in terms of the outlet diameter. With these charts and other known parameters, the designer can select the type of dissipator best suited to protect the outlet.

• RESEARCH previously conducted at the U. S. Army Engineer Waterways Experiment Station (WES) and reported by Bohan (1) gives generalized results for determining the extent of localized scour to be anticipated in cohesionless soils downstream from storm drain outlets. Also presented in this report are results for determining the size and extent of stone required to provide a stable horizontal blanket of riprap with top elevation the same as the outlet invert as a means of preventing localized scour. With these results the designer can estimate the expected scour and then decide on the degree of protective works that will be required. A scour hole with an appropriate cutoff wall might be permissible; riprap placed on a stable horizontal blanket may be adequate; a compromise of depth of scour and riprap may be desirable; or an energy dissipator may be required.

A field performance study that permitted observation of drainage and erosion control facilities at several Army and Air Force installations throughout the United States has been conducted by WES during the past few years. One of the results of this study was the indication that there is an urgent need for practical guidance in the selection and design of energy dissipators for drainage facilities.

Several energy dissipators have been developed for use at storm drain outlets. The research reported here was initiated as an effort to evaluate the applicability and limitations of three of the most commonly used energy dissipators: a stilling well, the U. S. Bureau of Reclamation (USBR) Type VI basin, and the St. Anthony Falls (SAF) stilling basin.

MODELS AND TEST PROCEDURES

A 1:5-scale model of a 48-in. diameter pipe outlet was used to study the various energy dissipators in a 16-ft wide, 5.5-ft deep, and 40-ft long test flume (Fig. 1). The trapezoidal channel downstream from the energy dissipators was molded in sand with side slopes of 1 on 3, and the area immediately downstream from the basin outlet was protected with riprap. A filter cloth was placed between the sand and riprap to prevent slumping of the riprap blanket. Models of the 3 energy dissipators are shown in Figure 2.

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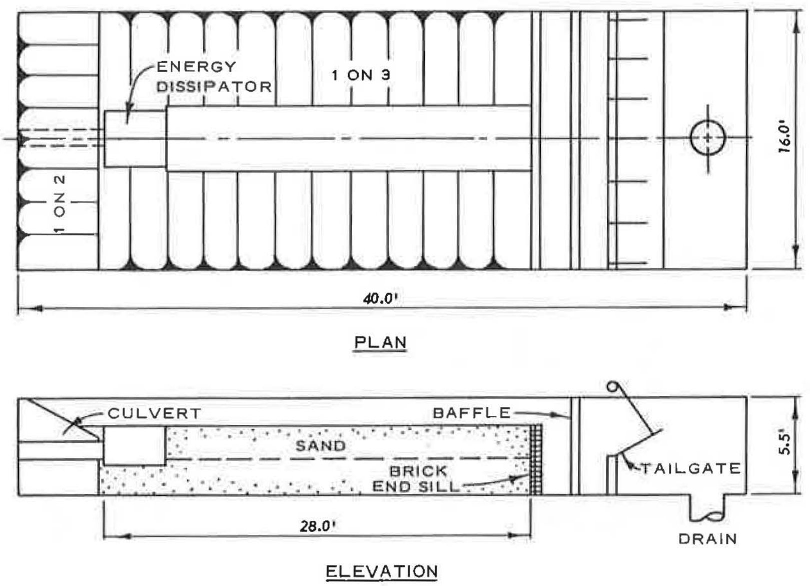


Figure 1. Experimental facilities.

Water used in the operation of the models was supplied by pumps, and discharges were measured by means of calibrated venturi meters. Steel rails set to grade along the sides of the flume provided a reference plane for measuring devices. Water surface elevations were measured by means of point gages, and velocities were measured with a pitot tube. Tailwater elevations were regulated by a gate at the downstream end of the flume.

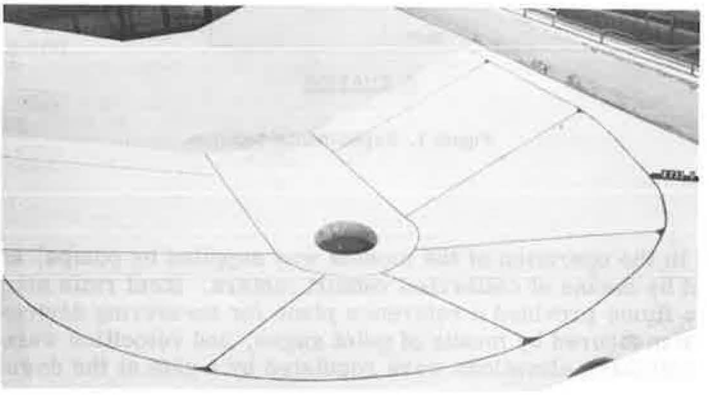
Before each series of tests was begun, the channel downstream of the energy dissipator was molded to the trapezoidal shape and flooded slowly in order to prevent erosion of the stream bed. The procedure used to determine the maximum or limiting discharge with a particular energy dissipator was to set a low discharge, observe the flow conditions with various tailwater depths, and then increase the discharge and repeat until the flow conditions were considered unacceptable. The highest discharge that was considered satisfactory was reset and allowed to run for a given period of time to determine whether the riprap downstream from the dissipator was sufficiently large to prevent failure. Also, in some tests, velocity and wave height measurements were made and sand scour patterns were recorded. If wave heights, velocities, or scour or all of these downstream from the riprap were excessive with this flow, the discharge was reduced and the procedure repeated until the flow was considered acceptable. Photographs of flow conditions, both satisfactory and unsatisfactory, were made with each design.

The general design practice that has developed in recent years relative to highway culverts results in the conclusion that most of these structures convey discharges 4 or 5 times the diameter of the culvert raised to the $^5/_2$ power. The magnitude of this quasi-dimensionless parameter will vary depending on the particular site or structure, but it is a useful descriptive parameter for classifying the relative design capacity of such structures. It is also related to the Froude number of flow commonly used in open-channel hydraulics. For example, the Froude number of full-pipe flow at the outlet of a circular pipe is unity for a $Q/D_o^{5/2}$ ratio of 4.5. Thus, the main objective of this study was to determine the limiting $Q/D_o^{5/2}$ ratio for various sizes of each of the stilling devices investigated.

STILLING WELL

The stilling well consists of a vertical section of circular pipe affixed to the outlet end of a storm drain outfall. Components of a typical stilling well are shown in Figure 3. In order to be effective, the top of the well must be located at the elevation of the invert of a stable natural drainage basin or artificial channel. The area adjacent to the top of the well, including the side slopes and outfall ditch, is usually protected by riprap or paving.

Energy dissipation is accomplished by the expansion of flow that occurs in the well, the impact of the fluid on the base and wall of the stilling well opposite the pipe outlet, and the change in momentum resulting from redirection of the flow. Important advantages of an energy dissipator of this type are that energy loss is accomplished without the necessity for maintaining a specified tailwater depth in the vicinity of the outlet and that construction is simpler and less expensive because the concrete formwork necessary for a conventional basin is eliminated.



stilling well

USBR Type VI basin

SAF stilling basin

Figure 2. Models of stilling well, USBR Type VI, and SAF stilling basin.

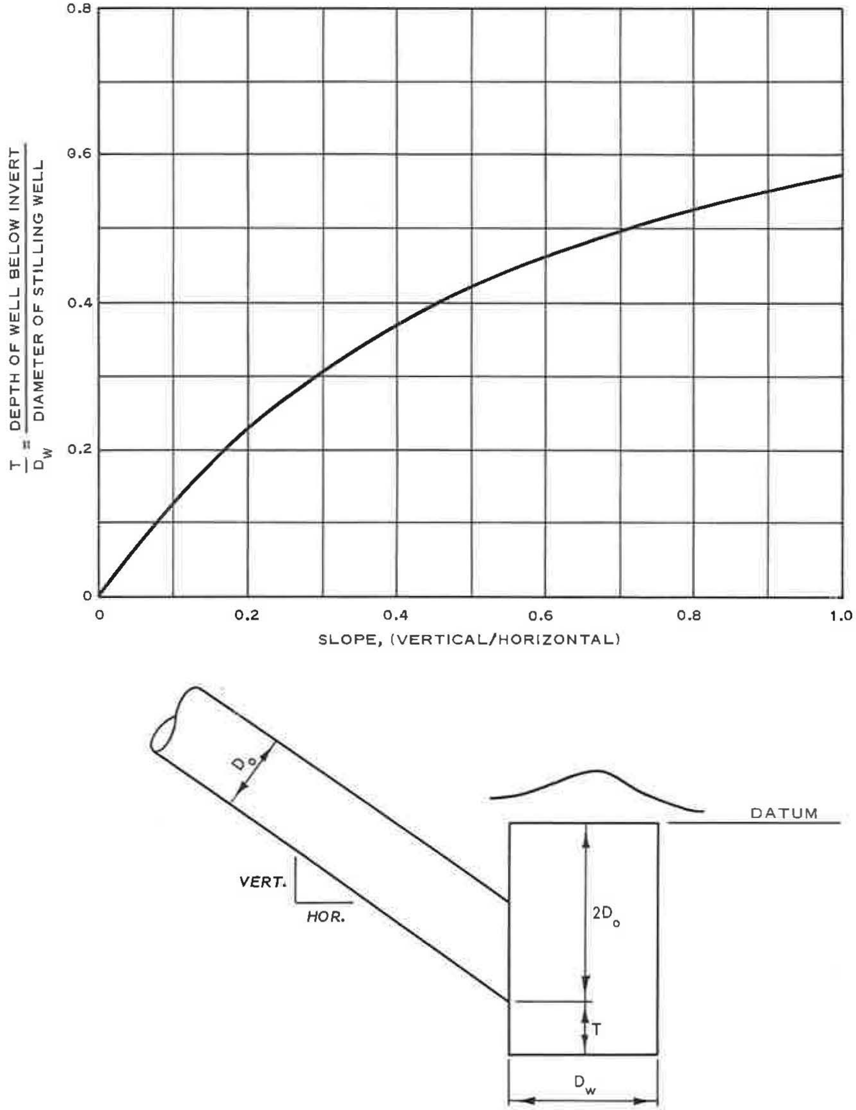
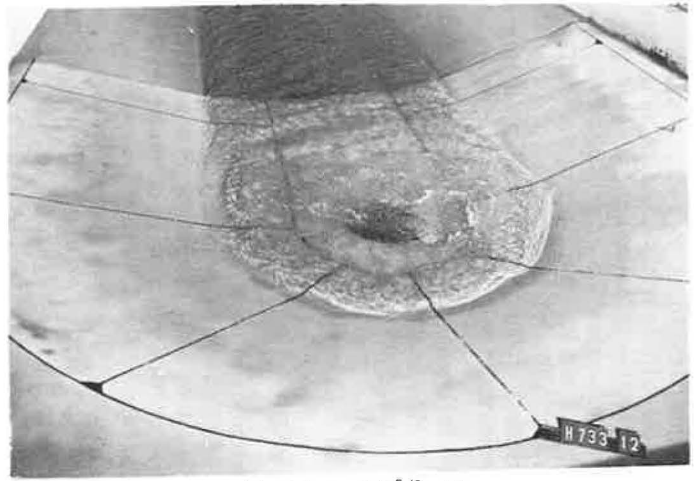
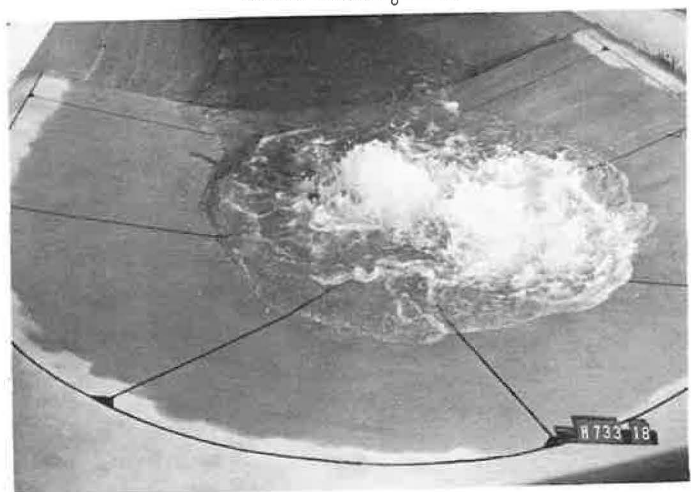


Figure 3. Stilling well.



(a) satisfactory, $Q/D_o^{5/2} = 3.5$



(b) unsatisfactory, $Q/D_o^{5/2} = 10$

Figure 4. Flow conditions with stilling well.

The stilling wells tested in this study were designed according to recommendations reported by Grace (2) from tests conducted on 9 model stilling wells. The recommended height of stilling well above the invert of the incoming pipe is 2 times the diameter of the incoming pipe, D_o. The recommended depth of well below the invert of the incoming pipe is dependent on the slope of the incoming pipe and the diameter of the stilling well, D_w, and can be determined from the plot shown in Figure 3.

Flow conditions, both satisfactory and unsatisfactory, that resulted with a stilling well diameter twice that of the incoming pipe are shown in Figure 4. The subject model investigations indicated that satisfactory performance could be maintained for $Q/D_o^{5/2}$ ratios as large as 2.0, 3.5, 5.0, and 10.0 respectively and stilling wells with diameters 1, 2, 3, and 5 times that of the incoming storm drain. These ratios were used to calculate the relations among actual storm drain diameter, well diameter, and maximum discharge recommended for selection and design of stilling wells (Fig. 5).

USBR TYPE VI BASIN

The Bureau of Reclamation impact-energy dissipator is an effective stilling device even with deficient tailwater. Dissipation is accomplished by the impact of the incoming jet on the vertical hanging baffle and by eddies that are formed by changing the direction of the jet after it strikes the baffle. Best hydraulic action is obtained when the tailwater elevation approaches, but does not exceed, a level halfway up the height of the baffle. Excessive tailwater, on the other hand, will cause some flow to pass over the top of the baffle. This should be avoided if possible. With velocities less than 2 fps, the incoming jet could possibly ride underneath the hanging baffle. Thus, this basin is not recommended with velocities less than 2 fps. It is believed that the possibility of cavitation or impact damage to the baffle can be prevented if an entrance velocity of 50 fps is not exceeded with this device. The general arrangement of the Type VI basin and the dimensional requirements based on the width of the structure are shown in Figure 6.

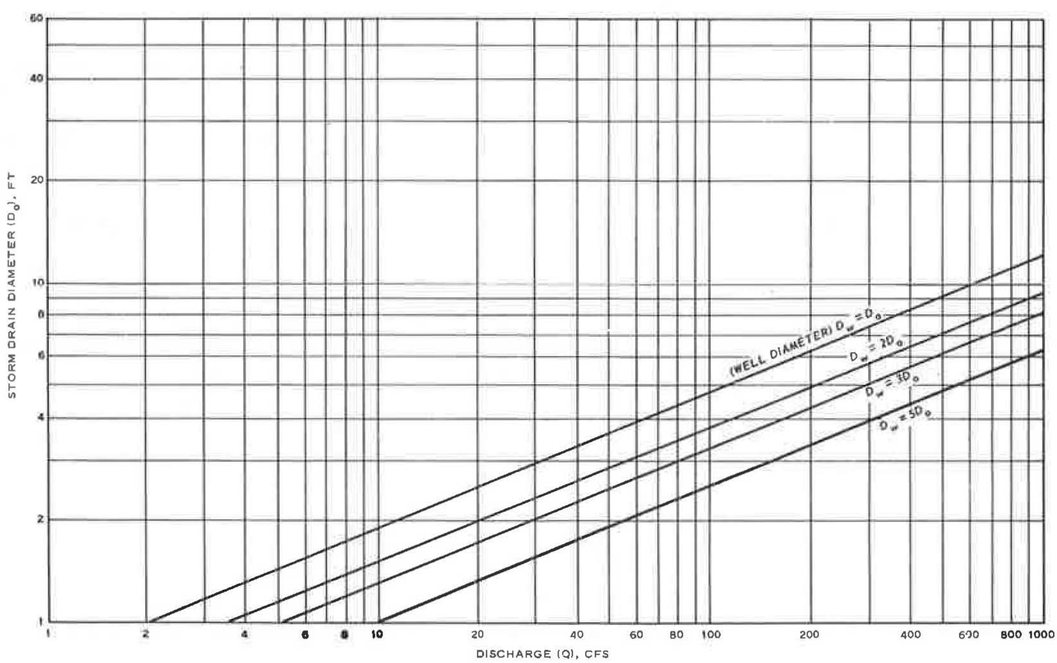


Figure 5. Storm drain diameter versus discharge for stilling well.

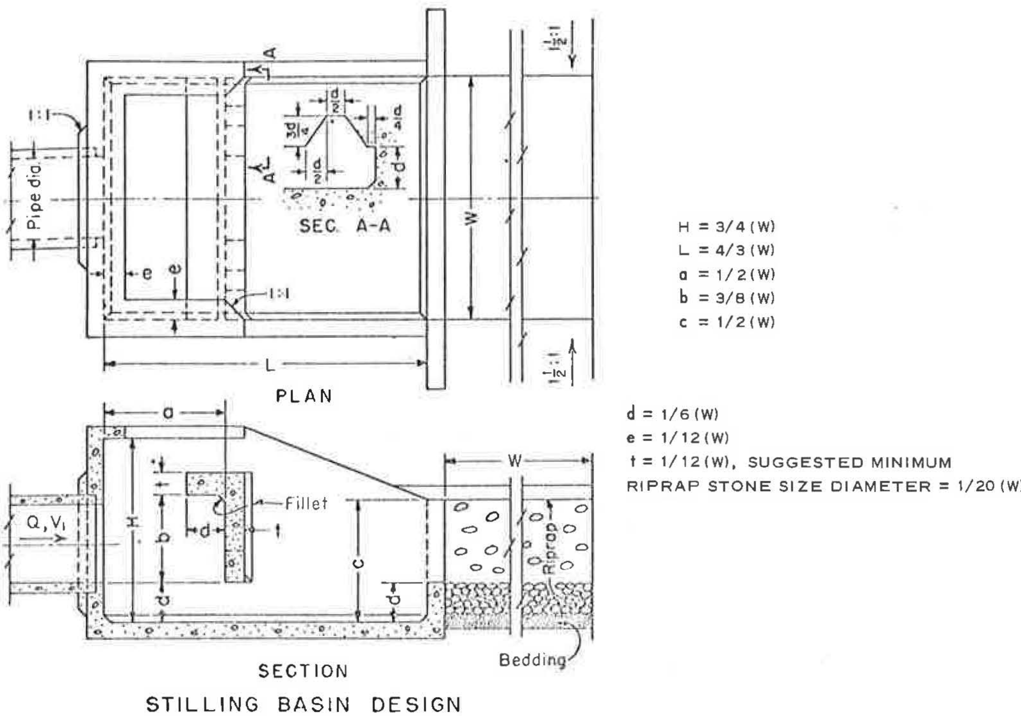


Figure 6. USBR Type VI basin.

Only one model was used to test the limitations of the Type VI basin. The model was 3.3 ft wide and was designed according to recommendations reported by Beichley (3). Results of tests with the subject model basin, which had a width 4 times the diameter of the incoming pipe, indicated that the limiting $Q/D_o^{5/2}$ ratio was approximately 7.6. This value was slightly less than that recommended by Beichley (3) in terms of the Froude number at the storm drain outlet. However, the results from his study were used, with slight adjustment, to obtain conservative design criteria for other basin widths. The results of this analysis are given in Table 1.

Photographs of flow conditions with the model basin are shown in Figure 7. The recommended relations among discharge, outlet diameters, and basin widths are shown in Figure 8. If the discharge and the size of the incoming pipe are known, the required width of the basin can be determined from the design curves, and other dimensions of the basin can be computed from the equations shown in Figure 6.

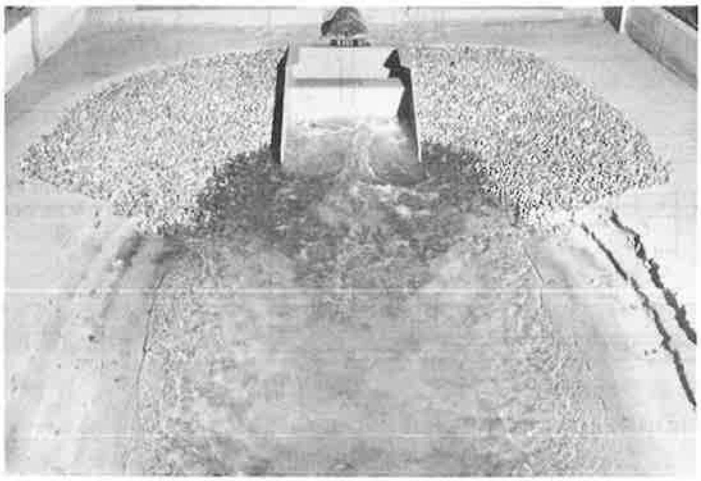
TABLE 1

RESULTS OF TESTS WITH ENERGY DISSIPATORS

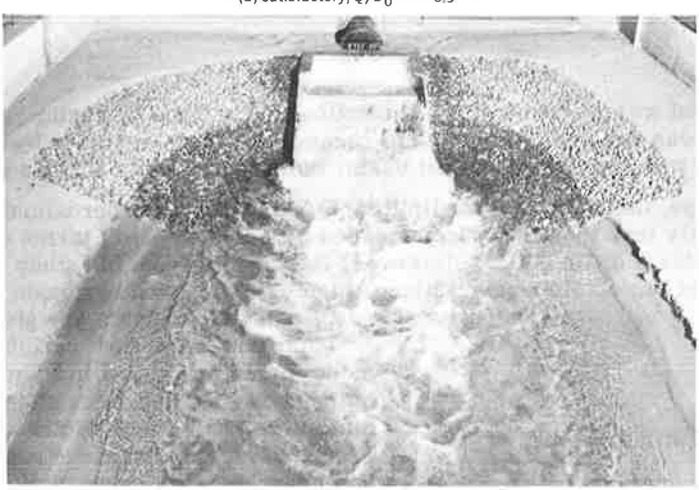
Type of Energy Dissipator	Relative Diameter, D_o	Maximum $Q/D_o^{5/2}$
Stilling well	1	2.0
	2	3.5
	3	5.0
	5	10.0
USBR Type VI basin	1	0.6
	2	2.2
	3	4.5
	4	7.6
	5	11.5
	7	21.0
SAF stilling basin	1	3.5
	2	7.0
	3	9.5

SAF BASIN

The St. Anthony Falls stilling basin is a hydraulic jump basin. All the dimensions of this basin are related in some way to the hydraulic jump. A reduction in the basin length from that of a natural hydraulic jump is achieved through the use of appurtenances con-



(a) satisfactory, $Q/D_0^{5/2} = 6.9$



(b) unsatisfactory, $Q/D_0^{5/2} = 13.5$

Figure 7. Flow conditions with USBR Type VI basin.

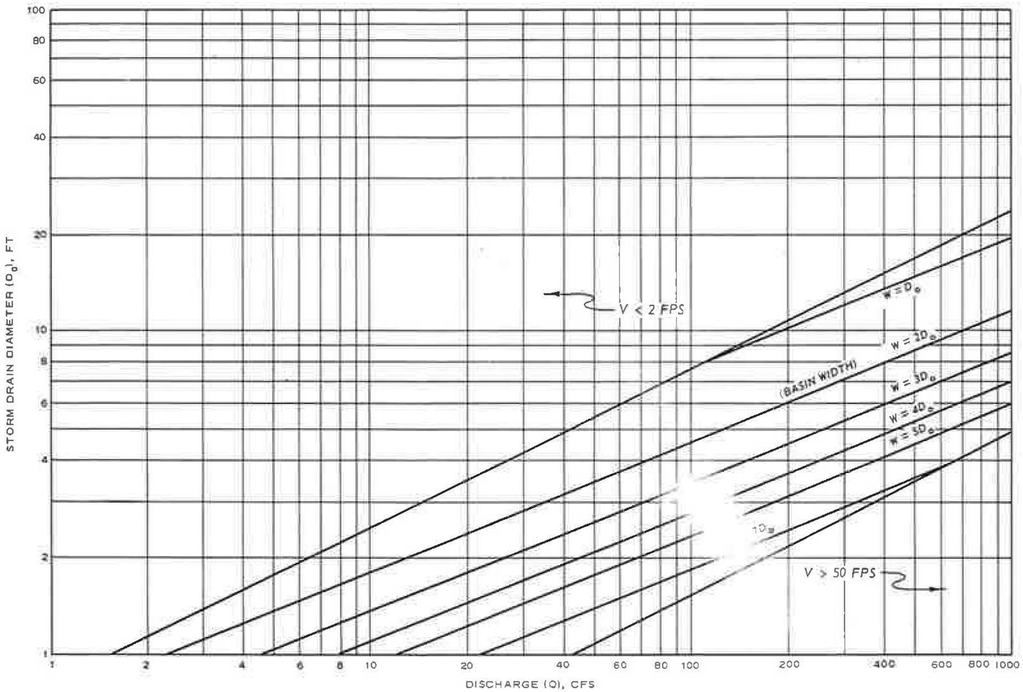
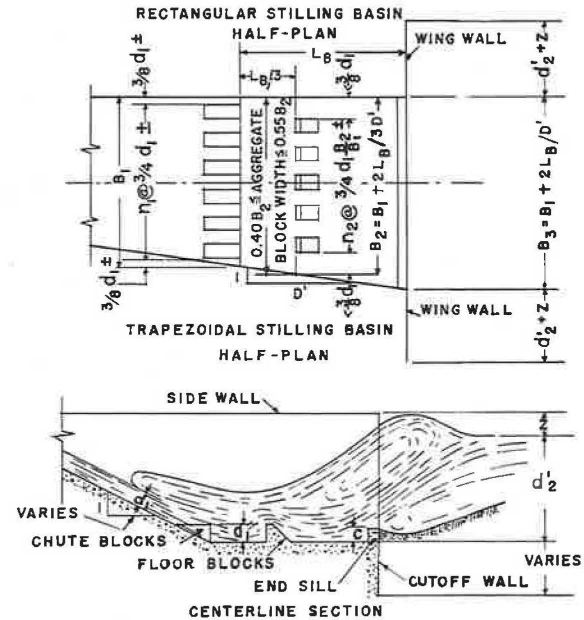


Figure 8. Storm drain diameter versus discharge for USBR Type VI basin.



DESIGN EQUATIONS

(1) $F = \frac{V_1^2}{gd_1}$ (2) $d_2 = \frac{d_1}{2}(-1 + \sqrt{8F + 1})$

(3a) F = 3 TO 30 $d_2^1 = (1.10 - F/120)\,d_2$

(3b) F = 30 TO 120 $d_2^1 = 0.85\,d_2$

(3c) F = 120 TO 300 $d_2^1 = (1.00 - F/800)\,d_2$

(4) $L_B = \frac{4.5d_2}{F^{0.38}}$ (5) $Z = \frac{d_2}{3}$ (6) $c = 0.07d_2$

Figure 9. SAF stilling basin.

sisting of chute blocks, floor blocks or baffle piers, and an end sill. General details of the SAF basin are shown in Figure 9. Dimensions of the chute blocks and floor blocks may be modified slightly to provide reasonable construction dimensions without materially affecting the efficiency of the structure.

Models of 6 different SAF basins were tested. These basins were constructed according to recommendations made by Blaisdell (4) from model tests at the St. Anthony Falls Hydraulic Laboratory. Stilling basins that were 1, 2, and 3 times as wide as the outlet were tested with drops from the invert of the outlet to basin floor of ½ and 2 times the outlet diameter. The basins with widths of 2 and 3 times the outlet diameter were flared 1 on 8 with respect to the centerline of the structure. Maximum discharges in the range that the basins could be expected to operate were chosen for design. The size of the basin elements and the basin length were adjusted for the 2 apron elevations tested. The velocity of flow entering the basin was assumed to be the same as the velocity at the outlet of the storm drain for the basins with a drop from the invert of the outlet to the basin floor of one-half the outlet diameter. A slight increase of the velocity at the outlet was assumed for the velocity entering the basin ($V_b = 1.15\ V_o$) with a drop from the invert of the outlet to the basin floor of 2 times the outlet diameter. With the discharge, velocity entering the basin, and the basin width known, the depth of flow entering the basin was then computed. These values were used to design the basin according to the design equations shown in Figure 9. Comparisons of flow conditions for the various basins were made with tailwater depths that were just sufficient to produce a hydraulic jump in the basin (approximately 0.85 the theoretical depth required for a hydraulic jump).

Results of tests indicated that within the limits investigated the drop from the invert of the outlet to the basin apron had little effect on the limiting $Q/D_o^{5/2}$ ratios. Maximum values of 3.5, 7.0, and 9.5 respectively were indicated for 1 D_o, 2 D_o, and 3 D_o wide SAF stilling basins. These values compared favorably with those used for the design

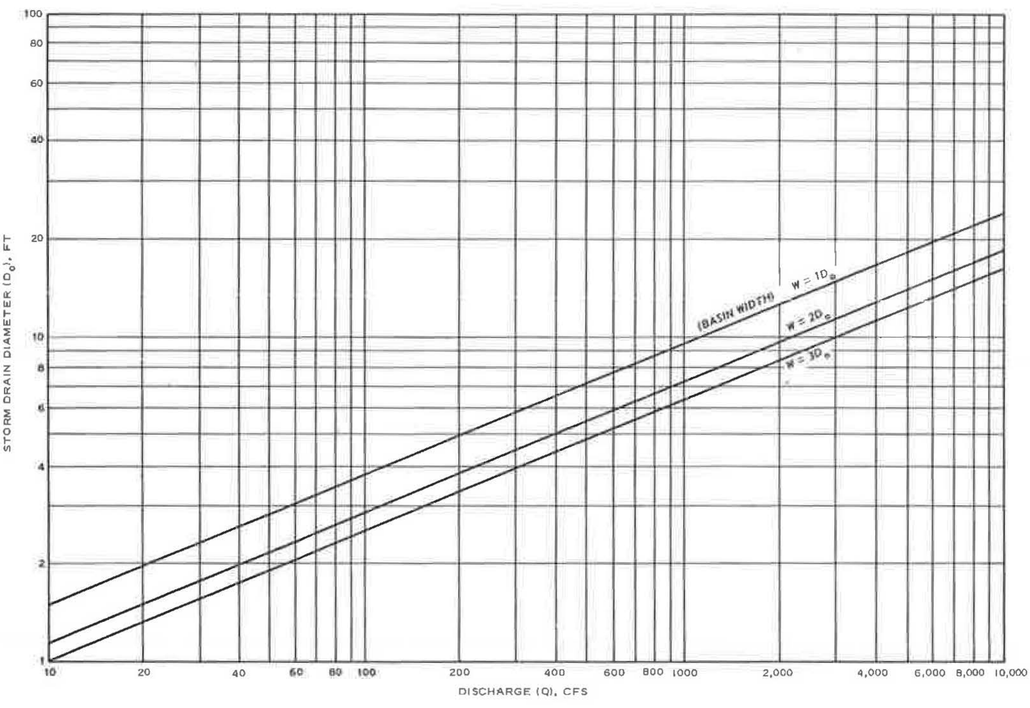
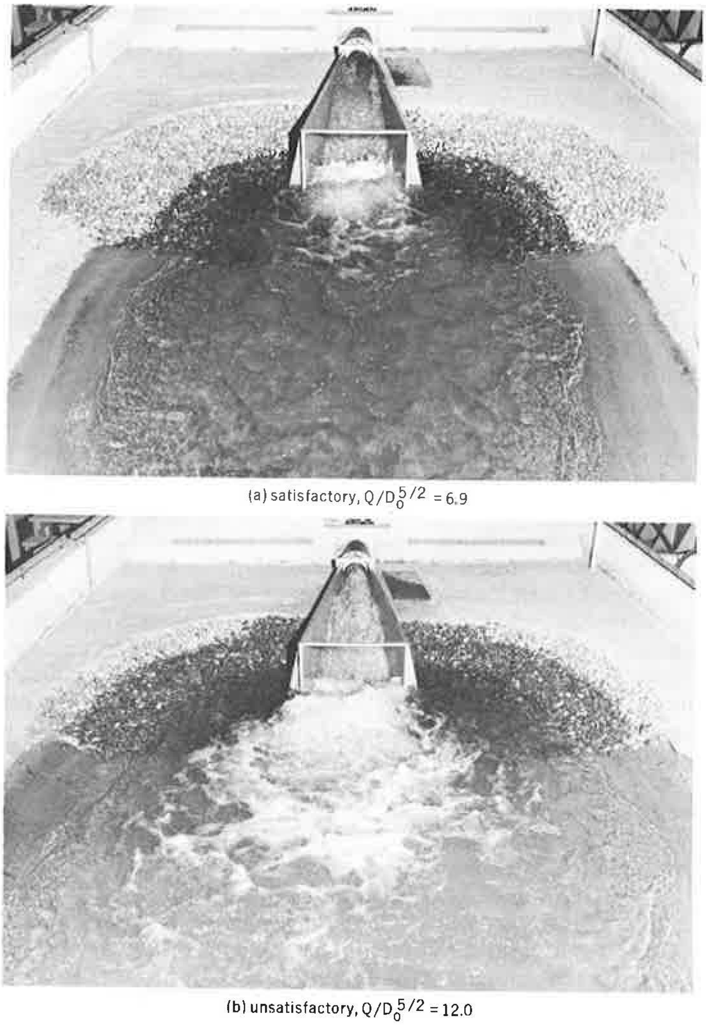


Figure 10. Storm drain diameter versus discharge for SAF stilling basin.



(a) satisfactory, $Q/D_0^{5/2} = 6.9$

(b) unsatisfactory, $Q/D_0^{5/2} = 12.0$

Figure 11. Flow conditions with SAF stilling basin.

of the basins. These results were used to determine the relations recommended for design and are shown in Figure 10. Photographs of flow conditions with the SAF stilling basin are shown in Figure 11.

DISCUSSION OF TESTS

The practice of siting outlets, equipped with or without energy dissipators, high relative to a stable downstream grade in order to reduce quantities of pipe and excavation is the primary cause of gully scour. Erosion of this type may be of considerable extent depending on the location of the stable section relative to that of the outlet in both the vertical and downstream directions. Storm drain outlets and energy dissipators should be located at sites where the slope of the downstream channel or drainage basin is naturally mild enough to remain stable under the anticipated conditions or else it should be controlled by ditch checks, drop structures, or all of these other means, to a point where a naturally stable slope and cross section exist.

A scour hole or localized erosion is to be expected downstream of an outlet even if the downstream channel is stable. The severity of scour depends on the conditions existing or created at the outlet. Guidance relative to the extent of scour to be anticipated downstream of a culvert or storm drain outlet is presented in another report (1) as well as size and extent requirements of horizontal blankets of riprap for protection of outlets. These generalized results offer considerable guidance because one can estimate the extent of localized scour to be anticipated in stable channels of cohesionless soils downstream of an outlet and then decide what degree of protection is required. For example, is the anticipated scour hole that is a good energy dissipator permissible with an appropriate cutoff wall that protects the outlet? Are the size and extent of riprap required for a stable horizontal blanket practicable? Is it practicable to compromise depth of scour and size of riprap by providing a preformed and riprap-lined scour hole? Is an energy dissipator required?

The tests and data analyses reported here are given in Table 1 to indicate the range of applicability or maximum discharge capacity for various widths of 3 commonly used energy dissipators relative to the diameter of the incoming culvert or storm drain outlet, D_o. Based on these values of the relative maximum discharge capacity for comparable relative widths of the 3 energy dissipators, the stilling well is particularly suited to the lower range of discharges, the USBR Type VI basin to the intermediate range of discharges, and the SAF stilling basin to the higher range of discharges. However, all 3 energy dissipators are applicable for general drainage and erosion control practice. Comparative cost analyses will indicate which of the devices is the most economical energy dissipator for a given installation.

With information such as that developed for each of the 3 energy dissipators, the designers can, knowing the outlet diameter and design discharge, determine the applicability and necessary dimensions of each type of energy dissipator. In some cases, more than one type of dissipator may be applicable and in such cases local terrain, tailwater conditions, and cost analyses will determine the most practical energy dissipator for protecting the outlet. For example, with a 60-in. diameter culvert and a design discharge of 390 ft^3/sec, either a 10-ft wide (2 D_o) SAF stilling basin or a 20-ft wide (4 D_o) USBR Type VI basin or a 20-ft diameter (4 D_o) stilling well could be used. With a 48-in. diameter culvert and a design discharge of 110 ft^3/sec, either a 4-ft wide (1 D_o) SAF stilling basin or an 8-ft diameter (2 D_o) stilling well or a 10-ft wide (2.5 D_o) USBR Type VI basin could be used.

Some form of protection consisting of expansions either paved or riprap-lined or both is required to prevent excessive scour downstream of energy dissipators. It is considered that either horizontal or vertical expansion or both to permit dissipation of excess kinetic energy in turbulence rather than direct attack of the channel boundaries is most practical. Guidance is needed in this area as well as for selection of the size and extent of riprap required downstream of energy dissipators. In general, the unpublished results of WES investigations of riprap protection downstream of hydraulic structures indicate that the minimum average size of stone required for protection of an exit channel downstream of an energy dissipator can be described by the following empirical relation:

$$d_s = D\left(V/\sqrt{gD}\right)^3$$

where

d_s = minimum average size of stone, ft, usually termed d_{50} indicating that 50 percent by weight of a graded mixture is finer than the respective diameter,
D = depth of flow in channel downstream of structure, ft,
V = average velocity of flow in channel, fps, and
g = gravitational acceleration, ft/sec.

The protection should be extended downstream for a minimum distance equivalent to the width of the energy dissipator.

Additional options are desired that are more economical than these commonly used energy dissipators, and WES is continuing research to develop several simple stilling devices that will be more appropriate for the range of low and intermediate discharges. Efforts will be concentrated to develop practical guidance relative to preformed, riprap-lined scour holes or plunge pools and paved aprons with and without end sills.

REFERENCES

1. Erosion and Riprap Requirements at Culvert and Storm-Drain Outlets. U. S. Army Engineer Waterways Experiment Station, Corps of Engineers, Vicksburg, Miss., Res. Rept. H-70-2, Jan. 1970.
2. Impact-Type Energy Dissipator for Storm-Drainage Outfalls Stilling Well Design. U. S. Army Engineer Waterways Experiment Station, Corps of Engineers, Vicksburg, Miss., Tech. Rept. 2-620, March 1963.
3. Beichley, G. L. Progress Report 13—Research Study on Stilling Basins, Energy Dissipators, and Associated Appurtenances: Section 14, Modification of Section 6 (Stilling Basin for Pipe or Open Channel Outlets, Basin VI). Bureau of Reclamation, U. S. Department of the Interior, Rept. HYD-572, June 1969.
4. Blaisdell, F. W. The SAF Stilling Basin. Agricultural Research Service and St. Anthony Falls Hydraulic Laboratory, Agricultural Handbook 156, April 1959.