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HYDRAULIC MODEL STUDIES OF PLUNGE BASINS FOR JET FLOW

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16. ABSTRACT

Model studies were undertaken to develop dimensionless design guidelines for riprap-lined plunge basins. To determine the basin dimensions, depressions created by free jets dropping into water-covered gravel beds were studied. The basins described by the criteria are large enough so that no further scour would occur. Parameters considered in the study as they affect the depth, length, and width of the plunge basin are: (1) height of the outlet above tailwater surface, (2) pressure head on outlet, (3) outlet size, (4) tailwater depth, and (5) size of riprap.

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HYDRAULIC MODEL STUDIES OF PLUNGE BASINS FOR JET FLOW

by

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UNITED STATES DEPARTMENT OF THE INTERIOR * BUREAU OF RECLAMATION

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PURPOSE

To investigate some of the hydraulic parameters to be considered in designing a plunge basin for dissipating the energy of a jet from a slide gate or valve.

APPLICATION

The relationships determined by these studies allow calculation of plunge basin dimensions for feasibility designs or for final designs of smaller structures where marginal performance or excessive erosion can be tolerated. Final designs of larger structures may require individual model studies to determine the optimum plunge basin dimensions.

CONCLUSIONS

1. Plunge basin depth, width, and length (caused by scour) can be predicted through the use of dimensionless parameters that consider outlet velocity, outlet diameter, drop from outlet to tailwater, tailwater depth, and riprap size.

2. Effect of tailwater depth. – Figures 6, 7, and 8 are used to evaluate the significance of tailwater depth in determining basin depth, basin width, and basin length, respectively. By holding the total energy head (H_v + Y), the angle of penetration (H_v/Y) and the jet diameter (D_o) constant, the curves indicate that tailwater depth (T) has a significant effect on the depth of scour (D_s) only when the tailwater depth is more than 1/20 of the total energy head. Above this limit, scour depth decreases as tailwater depth increases, in a nonlinear fashion, Figure 6. Figures 7 and 8 show that basin length and width reach maximum values at specific tailwater depths. Furthermore, the reducing values of W/D_o and L/D_o at higher values of (H_v + Y)/T suggest a narrower, shorter, and deeper scour hole as the tailwater depth decreases.

3. Effect of total energy head. – Similarly, Figures 6, 7, and 8 are used to evaluate the significance of total energy head by holding all other factors constant. A constant angle of penetration (H_v/Y) necessarily dictates that H_v and Y must vary by the same percentage when varying the quantity H_v + Y. Figure 6 shows, as implied in the previous conclusion, that the total energy head must exceed the tailwater depth by 20 times before the effect on scour depth becomes insignificant. At total energy head values below this limit, the depth of scour decreases nonlinearly as the total energy head decreases. Figures 7 and 8 show that basin width and length reach maximum values at specific values of total energy head, as with tailwater depth.

4. Effect of the angle of penetration. – The significance of the angle of penetration was evaluated by holding constant the total energy head of the jet, the tailwater depth, and the diameter of the jet while varying the jet velocity head at the outlet and the drop from the outlet to the tailwater surface. The resulting observations revealed that for all three basin dimensions (length, width, and depth) there exists an angle at which their values are maximized. The maximizing angle for the basin depth was found to be 45° (H_v/Y = 1) while the maximizing angle for the basin width and length was approximately 35° (H_v/Y = 2). When the tailwater depth is greater than one-fourth of the total energy head [(H_v + Y/T) $<$ 4], the data indicate that the maximizing angle becomes steeper (H_v/Y becomes smaller) as the ratio of the total energy head to the tailwater depth becomes smaller.

5. Effect of jet size. – It was also observed that for a specific jet (a particular total energy head and a particular angle of penetration) with a specific tailwater depth, there exist only singular values for the ratios of basin length, width, and depth to the diameter of the jet at the outlet. This indicates that for a specific condition the basin dimensions are directly proportional to the jet diameter.

6. Effect of riprap size. – The effects of riprap size, although only partially evaluated, were found to be of secondary importance. Only two riprap size ranges were observed in this study, but over those ranges no effect influenced by riprap size was observed when the angle of penetration was less than 45° (H_v/Y $>$ 1). The depth of scour was found to vary with riprap size when the angle of penetration was greater than 45°. This variation became greater as the angle approached 90°. However, over the size range observed the riprap size was found to have no effect at all on the basin width or length.

7. The analysis developed is for outlets that horizontally discharge jets with compact, fairly organized cross sections. A method is developed that allows the study of outlets that are tilted downward. Prototype jets that are less organized or that have less compact cross sections than the jets studied in the model can be expected to cause less scour than predicted by the model. In this sense the analysis may be conservative, depending on the flow situation.

8. The model represents prototype scour as it would result from the washing out of material. However, it cannot represent the scour that results from abrasion,

uplift, or other processes. Thus, depending on the situation, this factor tends to make the analysis less conservative (predicting a smaller scour hole than might actually occur). Comparison with prototype information is limited but shows the analysis developed in this study to be reasonably accurate.

INTRODUCTION

Value Engineering Team No. 8 was formed within the Chief Engineer's Office of the Bureau of Reclamation to find a simpler and less expensive method than the use of a conventional stilling basin for dissipating the energy in jets from gates and valves. Since plunge basins appeared to meet these requirements, the model study described here was initiated to provide general guidelines for preparing feasibility designs of plunge basins.

A plunge basin is a deep pool into which a free jet of water (from either a spillway or an outlet works structure) falls. The hydraulic action that results dissipates the energy in the jet. The basin may be either constructed or allowed to be scoured by the hydraulic action. If the basin is constructed, the basin may be unlined or lined with riprap or concrete, depending on the circumstances. The results of this study supply length, depth, width, and location dimensions for riprap-lined basins. The data are representative of unlined basins for which the prototype rock material is adequately represented by the gravels in the model. Concrete-lined basins, sized by the results of this study, would be larger than necessary. If the basin is scoured, the added factor of scoured material deposits must be considered. As the scour occurs, degraded material is carried from the basin by high velocity flows. As the flows lose velocity and therefore sediment transport ability, the material is deposited. The result is the formation of a crescent-shaped bar just downstream from the basin. These deposits were not studied during the tests because of an emphasis on constructed basins, but the tendency for the bar to cause a smaller stable basin was noted.

THE MODEL

The initial model, Figure 1, consisted of a 1- by 1-inch [2.54- by 2.54-centimeter (cm)] sheet metal slide gate discharging from a 1- by 1-inch conduit, 12 inches (30.48 cm) long, into a bed of fine gravel contained in a box 3 feet (1.091 meters) wide by 9.5 feet (2.74 meters) long. In the first tests, about 90 percent of the gravel had an average diameter of between one-eighth and three-sixteenths inch (0.32 and 0.48 cm). Later tests in the facility used gravel ranging in size from three-eighths to one-half inch (0.95 to 1.27 cm). The top of the gravel bed was initially placed 22 inches (55.9 cm) below the invert of the gate but could easily be raised to increase the range of testing. The tailwater depth above the bed could be adjusted from 2 inches (5.08 cm) to 12 inches (30.48 cm).

Flow from the gate discharged through a short gate frame, one-fourth inch (0.64 cm) long, before falling freely to the tailwater pool. A sheet metal shield was inserted in the free jet to instantly spread and deflect the jet downward to prevent disruption of the scour pattern at the beginning and end of each test, Figure 2. Flow to the 1- by 1-inch (2.54- by 2.54-cm) conduit was from an 18- by 24-inch (45.72- by 60.96-cm) drum through a 6-inch (14.24-cm) diameter pipe and a 12-inch (30.48-cm) long transition. The flow to the drum was measured using the 8-inch (20.32-cm) orifice Venturi meter permanently installed in the laboratory supply system.

After completion of tests on the small model, a larger facility was built, Figure 3. The model consisted of a 2.75-inch (6.98-cm) diameter nozzle discharging into a

Figure 1. One- by one-inch slide gate model and plunge pool.

Figure 2. Shield to spread and deflect the jet away from the scour test area.

21-inch (53.3-cm) deep bed of gravel. Water was supplied to the nozzle through a 30-inch (76.2-cm) diameter tank and a 6-inch (15.2-cm) diameter, 36-inch (91.4-cm) long section of approach pipe, Figure 3. The 6-inch (15.2-cm) diameter approach pipe had flow straighteners through its entire length. Discharges through the nozzle were measured with a 4-inch (10.2-cm) diameter Venturi meter. The gravel bed in which the jet erodes was 14 feet (4.3 meters) long and 10 feet (3.1 meters) wide. The gravel used in this model was between 3/4 and 1½ inches (1.81 and 3.81 cm) in diameter. The top of the gravel bed was 89 inches (226.0 cm) below the invert of the nozzle. The tailwater depth above the bed could be adjusted from 0 to as much as 24 inches (61 cm).

THE INVESTIGATION

Analysis of the Problem

The investigation began by first referring to several publications concerned with the design of plunge basins or with the depth and extent of scour to be expected.[1,2,3,4,5,6]* Most of the references are concerned with a jet from a flip bucket spillway and, therefore, are not directly applicable to flow from a gate. However, from the review of these references, it was determined that the depth and extent of scour of a plunge basin will depend upon a number of hydraulic parameters, including outlet area, outlet velocity, height of fall, tailwater depth, riprap size, and the degree of aeration and disintegration of the jet. Other factors to be considered are the size or width of the channel, the duration of the scouring period, and the shape of the cross-sectional area of the jet at the point of release.

Figure 3. Large model and plunge pool.

Of these parameters, the outlet area, outlet velocity, height of fall, tailwater depth, and riprap size were studied. Aeration and disintegration of the jet, width of the channel, and shape of the cross-sectional area of the jet tend to change with structure and specific operation and are, therefore, not well suited for consideration in this general research study. Duration of the scour period is considered in the study only in that all tests were run until no additional scour occurred. Previous studies also have indicated that riprap size is of only secondary importance in affecting the depth of scour.

From this analysis, it was decided to proceed with the investigation by constructing a small model in which scour measurements could easily be made in a readily

*Superscripts indicate references

erodible material. The model was designed so that the most important of the hydraulic parameters mentioned above could be easily varied. This initial model would give both direction and preliminary solutions to the study. The data collected from this model would require refinement and extension to be of practicable use. For this reason the larger model was built and studied after the completion of tests on the small model. Test procedure and objectives on the two models were quite similar.

Efforts were then made to form dimensionless relationships among the hydraulic parameters and establish design criteria for the plunge basin and riprap requirement from the scour hole measurements. Such relationships were established from the results of the investigation.

It may be desirable in some cases, particularly for larger structures, to refine this design. Model studies of specific installations can consider factors that were beyond the scope of the study and can, therefore, provide the most economical and functional design.

In order that the model tests would represent a wide range of typical operating conditions, the discharge curves for the 4- by 4-foot (1.22- by 1.22-meter) auxiliary outlet works slide gate at Navajo Dam, Figure 4, were used to determine low- and high-head operating conditions to be tested. Thus, the 1- by 1-inch (2.54- by 2.54-cm) initial model gate provided a 1:48 scale of Navajo gate. Because of the small size of the initial model, the minimum prototype discharge that could be represented satisfactorily was approximately 600 cubic feet per second (ft^3/s) [17 cubic meters per second (m^3/s)]. This could be discharged at full gate opening with a head of approximately 30 feet (9.1 meters). Other flows up to approximately 1,800 ft^3/s (51.0 m^3/s) with a head slightly over 300 feet (91 meters) in the prototype were also represented in the model testing program.

A circular nozzle was used in the larger model instead of a square gate in order to establish a more clearly defined jet. Slide gates were tried in the larger model, but it was found that jets from slide gates were very disorganized and inconsistent. It was felt that the clearly defined jet from the nozzle would provide more precise and consistent data on extent and size of basin scour. This basin would be larger than those produced by less organized jets and should yield a conservative design. Based on the outlet cross-sectional area, the 2.75-inch (6.98-cm) diameter nozzle would represent a 1:19.7 scale model of the Navajo outlet. Prototype discharges varying from 1,550 ft^3/s (43.9 m^3/s) under a head of 145 feet (44.3 meters) to 904 ft^3/s (25.6 m^3/s) under a head of 49.8 feet (15.2 meters) were tested in the model. All of the data on both models were taken for a full open gate. It was felt that partial gate openings would create jet cross sections that were beyond the intended scope of this study.

Small Model Tests

Three different series of tests were run with the small model. The first two used 1/8- to 3/16-inch (0.32- to 0.48-cm) gravel and the third used 3/8- to 1/2-inch (0.95- to 1.27-cm) gravel. The duration of each test in the first series varied from 30 minutes to 2 hours depending upon the amount of scour and the size of the deposit from the scour.

The data shown in Figure 5 were obtained, after which the deposit of erodible material was removed and the test continued, usually for an hour, but at least until the deposit needed to be removed again. The deposit or bar appeared to stabilize the basin at a size somewhat smaller than that which would be stable if the bar were not present. These tests were run with the dimension "Z" in Figure 5 set at 22 inches (55.9 cm) and at 20 inches (50.8 cm).

The second series of tests was run using the same operating conditions but for a single "Z" dimension of 20 inches (50.8 cm). These tests were run for a duration of 30 minutes to 4 hours, depending upon the amount of scour and were not interrupted for the removal of the deposit. Instead, the deposit was removed under water by hand every few minutes as it accumulated until there was very little additional gravel material being deposited from the scoured hole.

The third series of tests was run under similar operating conditions. The "Z" dimensions were set at both 20 and 22 inches (50.8 and 55.9 cm). The tests were run for durations of from 2 to 6 hours, depending again upon the amount of scour. As with the second series, the tests were not interrupted for the removal of the deposit; instead, the deposit was removed under water by hand as it accumulated. As was previously stated, the third series was run using the larger 3/8- to 1/2-inch (0.95- to 1.27-cm) gravel.

Large Model Tests

Tests on the large model were run with "Z" set at 89 inches (226 cm). The tailwater depth was allowed to vary from 3.25 inches (8.3 cm) to 22.75 inches (57.8 cm). A gravel with stones ranging in diameter from 0.75 to 1.50 inches (1.9 to 3.8 cm) was used. The tests were run for durations of from 3 to 34 hours depending on the amount of scour. Deposits were

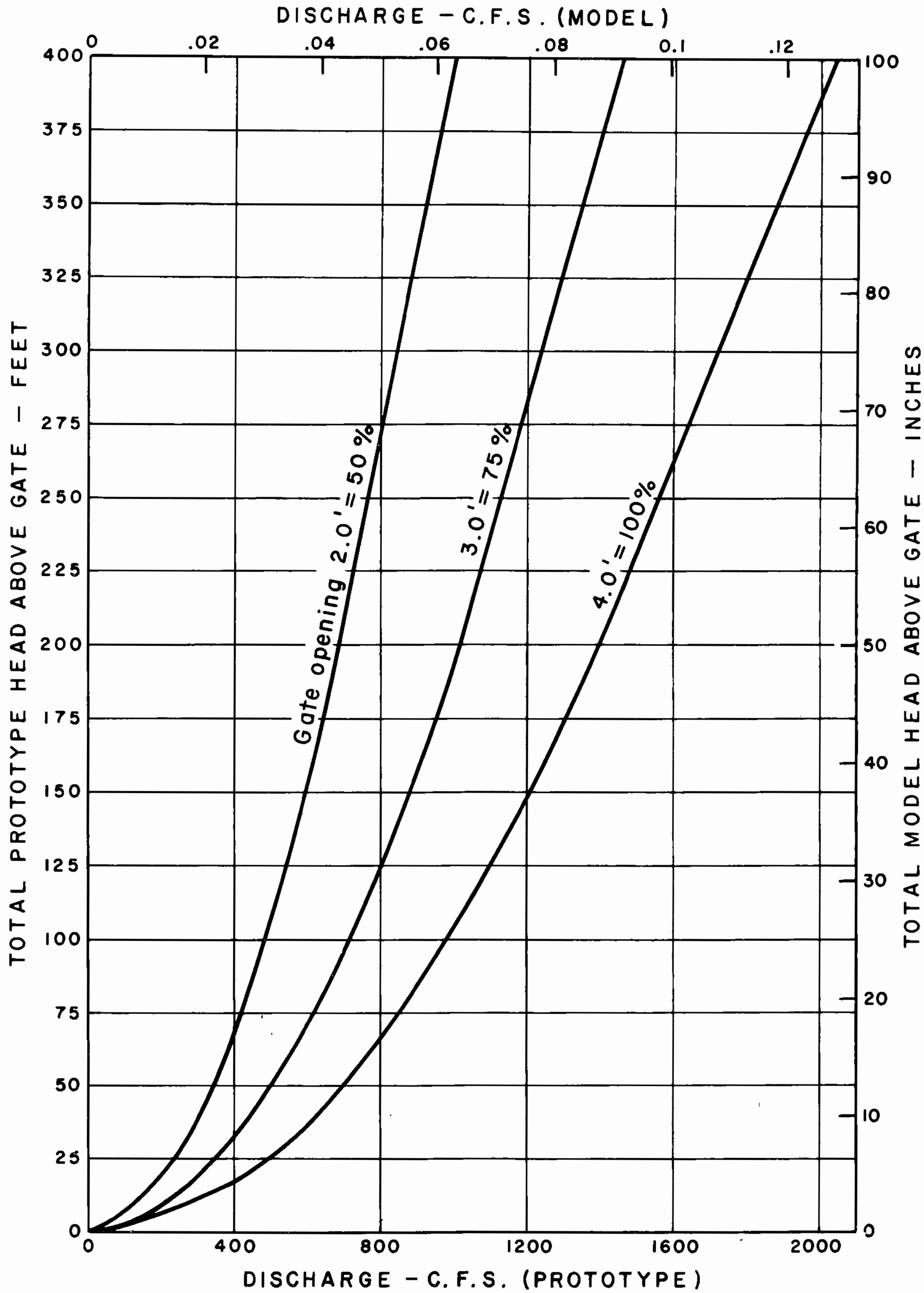


Figure 4. Navajo Dam auxiliary outlet works discharge curves (Model scale 1:48).

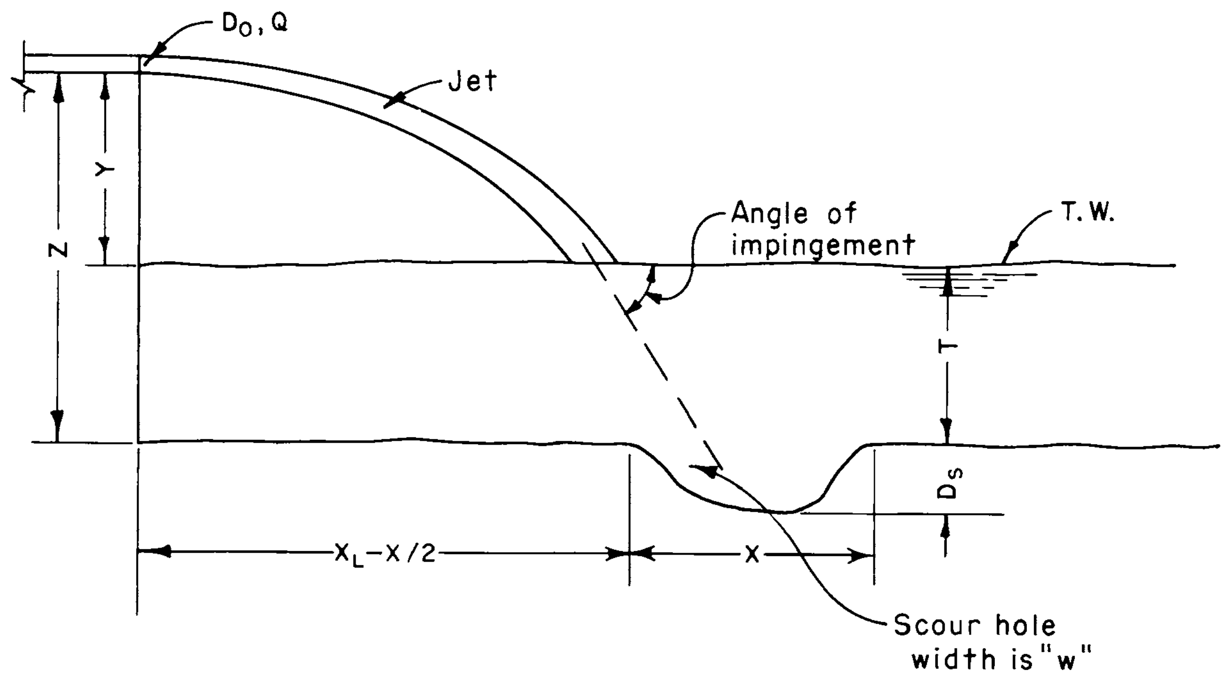


Figure 5. Definition of terms.

removed by shovel both as the test continued and when long duration tests were interrupted.

It was noticed during the tests on both models that there was considerable movement of the gravel in the scour hole and on the downstream slope of the hole, but that toward the end of the tests, the gravel was merely picked up and dropped in place rather than being moved downstream and deposited beyond the limits of the hole. It was surmised that the riprap lining in a basin designed for this scour depth would also be picked up and dropped a number of times depending upon the size of the riprap stones. This would result in abrasive erosion in the prototype. Therefore, a conservative design for the depth of basin is the minimum tailwater depth for which no erosion occurs. This was a greater water depth than any observed water depth above the bottom of a scour hole for a given operating condition.

A decision as to which criterion (zero scour tailwater depth or design curves with expected tailwater depth) should be used would consider both the comparable predicted depths from the two analyses and the particular characteristics of the structure being considered. Both the zero scour tailwater depth and the scour depth based on the actual expected tailwater depth should be evaluated and compared through the use of Figure 6. If the difference between the two depths is significant, then the characteristics of the specific structure should be considered. If the structure is expected to operate only very rarely or if only at small discharges, as compared to the structure's total capacity, then the smaller predicted scour depth (found using the expected tailwater depth) might be used. Likewise, if the penetrating jet is expected to be fairly disorganized or if additional erosion and the ensuing repairs can be tolerated, then the smaller predicted scour depth might again be used. On the other hand, if the structure is expected to operate often and at relatively high discharges or if additional erosion damage could not be tolerated, then the greater predicted scour depth (based on a zero scour tailwater depth) should be used.

Depth of Scour

With the data collected, attempts were made to develop dimensionless parameters which could be used to accurately predict the expected depth of scour. After many trials the parameters and curves shown in Figure 6 were determined. In studying the three parameters it can be observed that $(H_v + Y)/T$, the parameter of the ordinate axis, is composed of the energy head in the jet at the tailwater surface divided by the depth of water through which the jet energy is dispersed before it reaches the bed material. This parameter could, therefore, be thought of as representative of energy in the jet at the initial bed level. The parameter of the individual curves, H_v/Y, is the

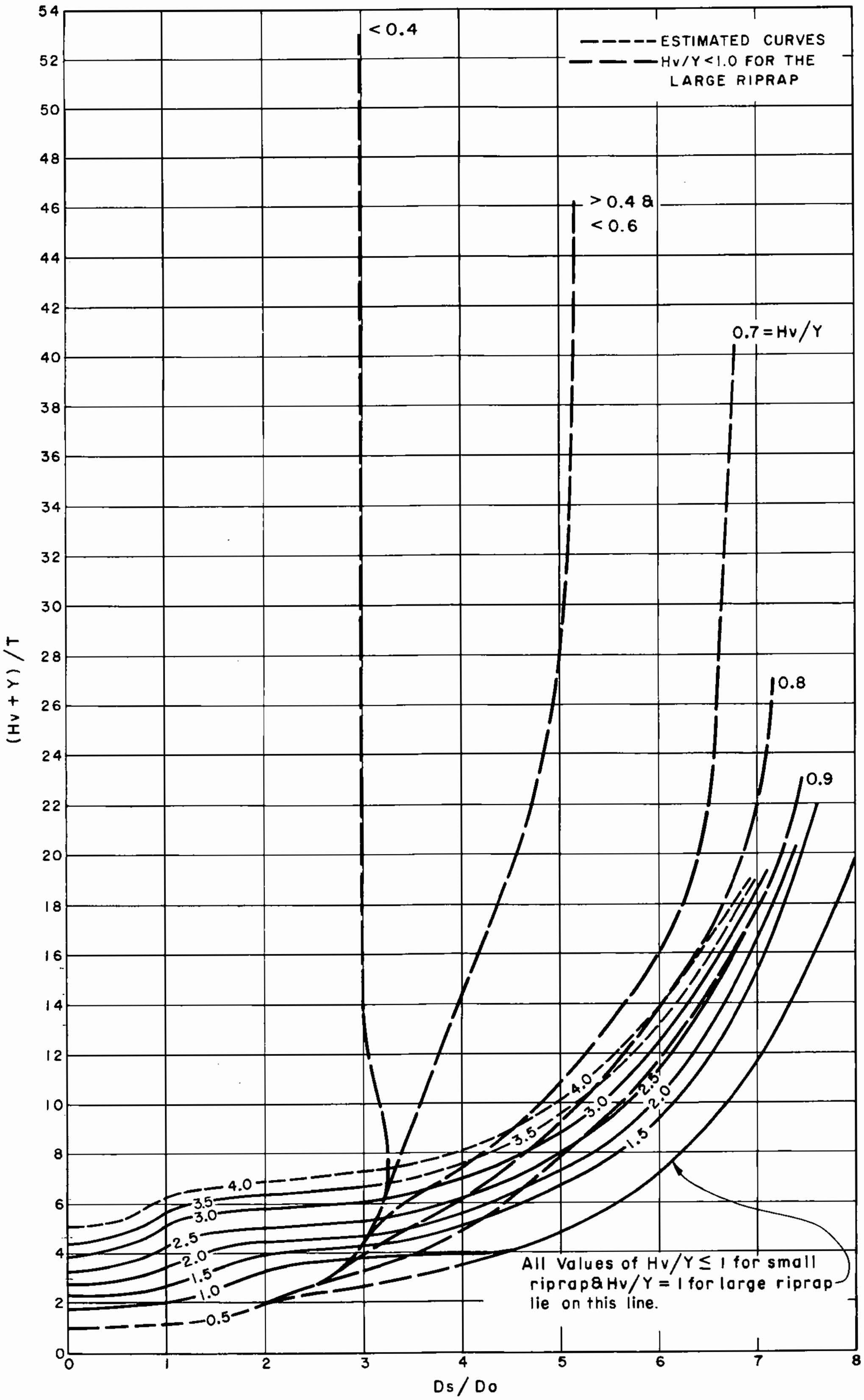


Figure 6. Basin depth design curves.

squared cotangent of the angle at which the jet penetrates the tailwater surface. For angles greater than approximately 25° ($H_v/Y < 4.6$), the impingement angle may also be considered the angle of attack of the jet on the bed. At flat angles (less than 25°) previous studies have indicated that the jet may not penetrate the pool but instead may dissipate its energy by creating surface waves. It is recommended, therefore, that 25° should be the minimum angle of penetration allowed. At times it may be desirable to tilt the gate downward to obtain a satisfactory angle of penetration. A method to analyze this will be discussed later in this report. The third parameter, D_s/D_o, is simply the ratio of the scour depth to the thickness of the jet. D_o is the dimension of a square outlet; therefore, if the outlet's shape is circular, the corresponding square dimension for an equivalent cross-sectional area should be determined. Generally, in specific problems all of the variables in these three dimensionless parameters are known except for the depth of scour. Solution is thus straightforward.

One other parameter was partially evaluated and found to be significant for angles of penetration greater than 45° ($H_v/Y < 1$). This dimensionless parameter is dd/D_o or the median riprap diameter (in inches) divided by the jet thickness (in feet). Data were obtained for two values of this parameter and thus supplied only limited insight into its overall significance. It was observed, however, that over the range tested, this parameter had no significant effect for angles of penetration less than 45° ($H_v/Y > 1$). But as the angle of penetration was increased above 45°, it was observed that the larger riprap ($dd/D_o = 0.34$) yielded significantly shallower basin depths, Figure 6. It can be reasoned that this depth reduction results from two factors. The first is simply that the larger riprap has more weight and, therefore, requires higher flow velocity to move it. The second factor is that as the angle of penetration becomes steeper, the horizontal component of the jet velocity at the tailwater surface becomes less significant. The horizontal component is needed to transport material away from the basin. The basin, therefore, stabilizes at smaller depths.

The relatively flat curves in the lower part of Figure 6 indicate that when dd/D_o is less than or equal to 0.13 (small riprap) or when dd/D_o is greater than 0.13 but less than or equal to 0.34 (large riprap) and the angle of penetration is flatter than 45° ($H_v/Y > 1$), the basin depth increases quite rapidly for relatively small $(H_v + Y)/T$ values. Flatter angles of penetration result in longer distances for the jet to flow through as it goes from the tailwater surface to the bed material. This means that the jet will have a longer time to disperse, and thus, velocities at the bed will be lower. Lower velocities at the bed in turn mean less ability to scour. As the angle of penetration increases, the path length through the tailwater decreases and the total velocity at the bed increases. However, as previously mentioned, when the angle increases, the horizontal component of the velocity decreases, which reduces the flow's ability to carry material away from the basin. This means there is an increase of depths of scour as the angle of penetration increases to 45°, and then there is an apparent lack of effect for angles above 45° ($H_v/Y < 1$). It should also be observed that for relatively high $(H_v + Y)/T$ values the various basin depths approach constant values. The curves also indicate that use of larger riprap (dd/D_o greater than 0.13) at angles of penetration greater than 45° will reduce the depth of scour. As the angle approaches 90° ($H_v/Y = 0$), the reduction becomes very significant, especially at the higher $(H_v + Y)/T$ values.

Application of these curves may take two directions as was previously said. The curves may either be applied using the expected tailwater depth to obtain a predicted depth of scour, or they may be used to determine the tailwater depth that would be required so that no scour of the bed material would occur. First of all, application of the curves using the expected tailwater depth is quite straightforward. Generally, at the beginning of the analysis the type and size of outlet (D_o), the expected tailwater depth (T), the median riprap size (dd), the elevation of the outlet (Y), and the velocity head at the outlet (H_v) would be known. Thus, $(H_v + Y)/T$, H_v/Y, and dd/D_o may be directly computed. By then applying these to Figure 6, the corresponding value of D_s/D_o may be found. This in turn yields a value for the depth of scour (D_s). To find the required tailwater depth so that no scour occurs is a somewhat more indirect operation. D_s is set to zero, thus, D_s/D_o is also set to zero. H_v/Y is then evaluated, and its intercept for $D_s/D_o = 0$ is obtained. This yields a value for $(H_v + Y)/T$. Since the values of H_v and Y are known, T (in this case the tailwater depth required so that no scour will occur) may be evaluated. If the expected tailwater depth is less than the no-scour tailwater depth, their difference can be used as a predicted depth of scour.

Length and Width of Scour

The length and width of the basin were found to be likewise related to the dimensionless parameters used in the previous analysis. The curves shown in Figure 7 for width and Figure 8 for length were developed. In general, they show that for a constant $(H_v + Y)/T$ the scour dimensions increase as H_v/Y goes from 0.2 to 2.0 (angle of penetration goes from 66° to 35°) and that the scour then decreases as H_v/Y increases above 2.0

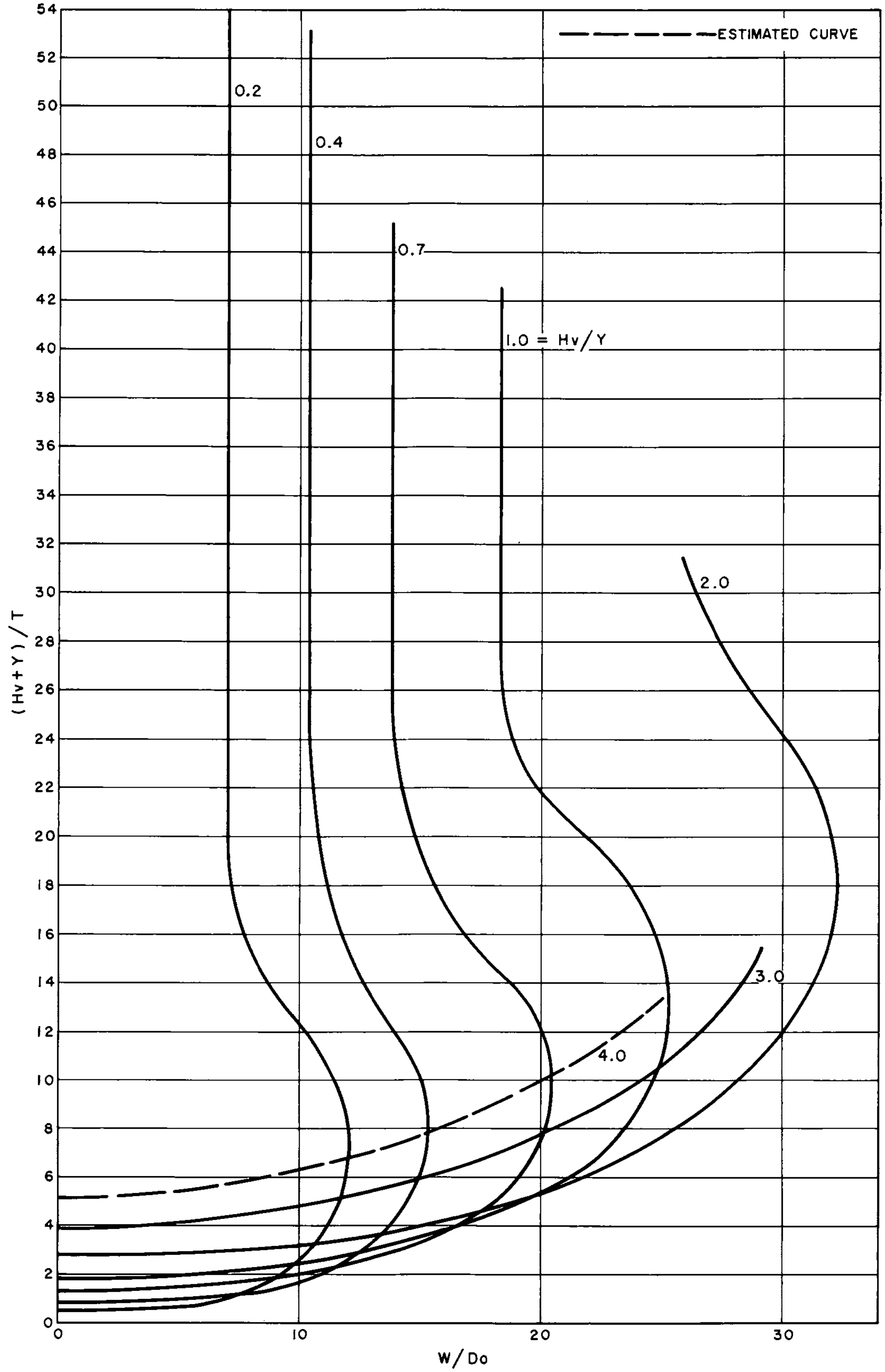


Figure 7. Basin width (W) design curves.

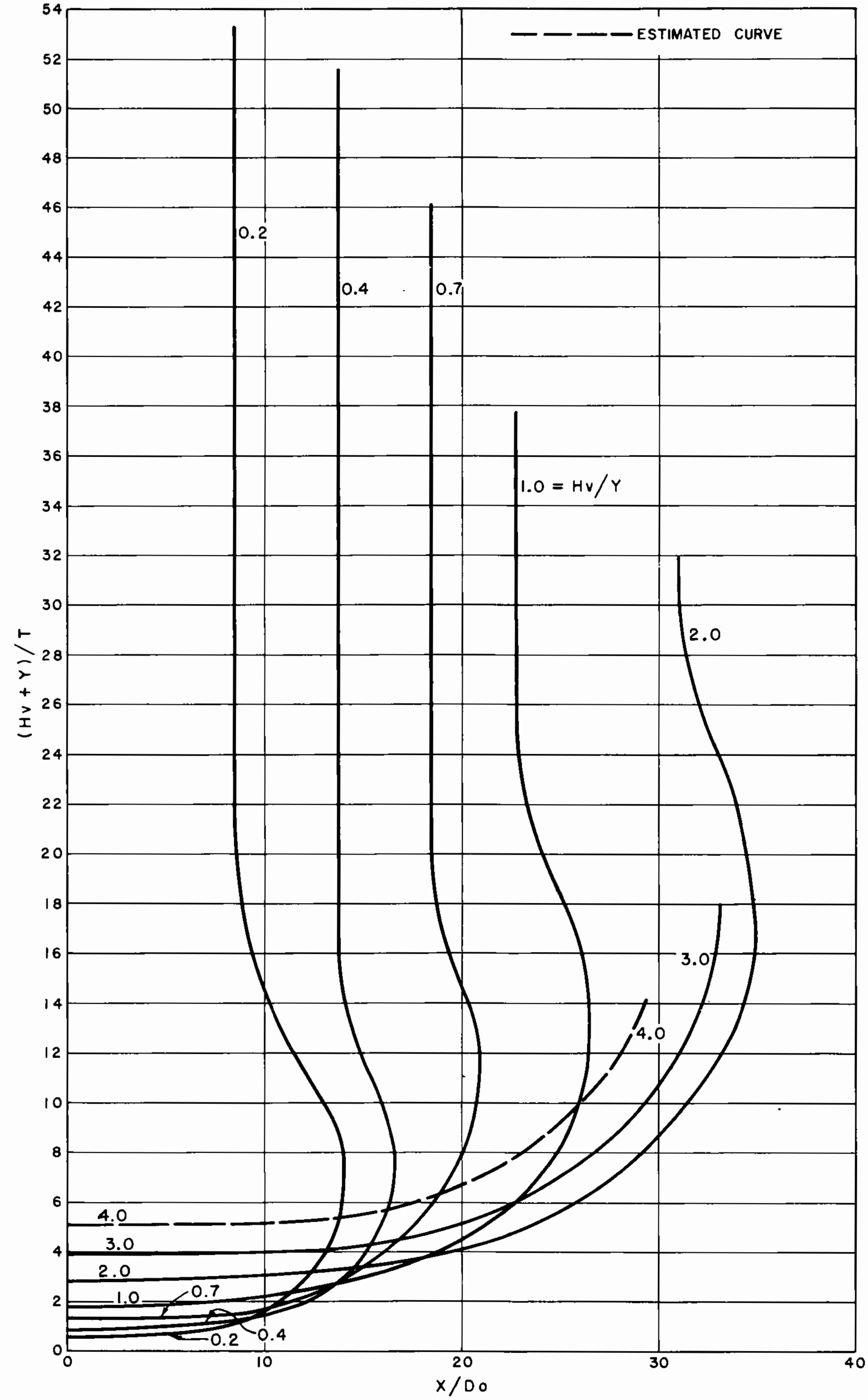


Figure 8. Basin length (X) design curves.

(angles of penetration less than 35°). These occurrences can be once again related to the conflict between the jet path length through the tailwater and the magnitude of the horizontal component of the velocity at the bed material. It was also observed that values of $(H_V + Y)/T$ existed, for given H_V/Y values, at which the scour appeared to maximize. The basin size also tended to stabilize at higher $(H_V + Y)/T$ values for specific angles of penetration. Reasons for these two trends are uncertain. The size of riprap was found to be of no significance with respect to length and width of the basin over the size range studied.

Location of Scour Hole

Rather than try to relate the basin location to total head, angle of penetration, and tailwater depth, it was decided to relate its location to the impingement point of the theoretical jet trajectory path on the channel bed.

The free jet path can be studied to yield the location of impact and angle of penetration at the tailwater surface. The path is then extended from the impact point to the bed surface as a straight line sloping at the angle of penetration. This scheme was not strictly verified in this study, but it has been observed and discussed by Mikhalev.[8] Gravitational effects on the jet would be minimal once the jet entered the tailwater, and the jet would tend to follow a straight line rather then a free-fall trajectory. Model data show reasonable agreement with this procedure.

It should be noted that as the jet passes through the tailwater, the jet is dispersed. The highest velocities would be located along the previously predicted path. The greatest depth of scour, therefore, would also be along the previously predicted path. The point of intersection between the projected path and the bed surface should thus be considered as the center point of the basin.

Analysis for Tilted Outlets

The total analysis, as previously described for outlets discharging horizontally, may be applied with caution to downward-tilted outlets. A downward-tilted outlet might be considered in situations where a horizontal outlet would release a jet whose angle of penetration is flatter than 25°. The reason that this analysis must be applied with caution is simply that only horizontal outlets were observed in the model study, and no definite observations were made of tilted outlet flow. To apply the data to tilted outlets, the jet velocity at the tilted outlet is separated into horizontal and vertical components. The horizontal component is used as the discharge velocity from a hypothetical horizontal gate. The vertical component is converted to a velocity head which is added to the Y value (distance from outlet to tailwater surface) of the tilted outlet. This summation yields the Y value for the hypothetical horizontal outlet. In effect, this procedure assumes that the jet as it leaves the tilted outlet is a jet from a horizontal outlet, part way through its free trajectory. After computation of the basin dimensions from Figures 6, 7, and 8, the location of the basin is determined by straightforward use of the equation of the trajectory of a jet from a tilted outlet.

Limitations of the Analysis

To summarize, several limitations exist in the analysis:

1. The design curves are not extensive enough to handle all possible operating conditions. Because of physical limitations in the model, tests were not run for all conceivable velocity heads, drops from the outlet to the tailwater surface, and tailwater depths that might be encountered in prototype designs.

2. Only full open gates (jets with circular, square, or at least very compact cross sections) were studied. The effects of air resistance on the free jet were therefore minimized as were the effects of jet dispersion and velocity reduction as it passes through the tailwater.

3. Only a very limited range of relative gravel sizes was studied. Although the material size appears to be a parameter of secondary importance, it did have some effect over the limited range observed. As prototype material size varies beyond the range tested, it can be expected to have greater modifying effects.

4. Scour resulting from abrasion, uplift of massive blocks, or processes other than simple erosion were not evaluated in these studies. Depending on the particular situation, they may be of significance.

These limitations should be recognized when applying the criteria in designing a plunge basin. As previously stated, over the range studied, the gravel size had little effect on length and width of scour and affected depth of scour only for angles of penetration greater than 45°. Chee and Padiyar[4] developed the equation:

$$D_m = \frac{1.235 q^{0.67} H^{0.18}}{d^{0.063}}$$

where:

D_m = Scour depth of basin below flip bucket (feet)
q = Unit spillway discharge (ft^3/s/feet)
H = Head difference between headwater and tailwater levels (feet)
d = Mean bed material diameter (feet)

This shows the riprap size to be of only minor significance since the material diameter has such a small exponent. Chee and Padiyar also quote others who have had similar experience. Their equation could be used to estimate the effects of using larger or smaller materials than those described in this report.

It should also be noted that basins designed from this report should be conservative for less concentrated and organized jets. Less concentrated jets should break up and aerate quicker in their free trajectories and reduce their velocities quicker as submerged jets. These effects combine to decrease the depth of penetration by the jet which delivers less concentrated scour energy to the bed material. The required basins would, therefore, be smaller.

Only scour resulting from the direct lifting of the material by the flow could be evaluated in the model. Scour resulting from other processes can be expected in the prototpye. In particular situations these processes can be expected to cause significant additional scour. Abrasive erosion which results from loose material being washed against the basin boundaries in a "back mill"-type action can be expected to occur to some extent at all sites. When high velocity jets impinge on massive fissured rock, uplift may result in very significant scour under certain conditions. High pressures may develop in the fissures because of stagnation of the jet's velocity. These pressures may then actually lift huge blocks out of the bed material. In any case these additional erosion processes would tend to make the required basin larger than that predicted by the analysis. Therefore, they tend to make the design less conservative and thus have the opposite effect to that of a less organized jet.

Kariba Dam[9] on the Zambezi River (between Zambia and Rhodesia) has six, gate-controlled, free trajectory jets which compose its spillway. For one of these jets:

D_o = 30 feet (9 meters)
T = 65 feet (20 meters)
Q = 49,400 ft^3/s (1,400 m^3/s)
Y = 263 feet (80 meters)

Using the analysis developed in this report, Figure 6, a depth of scour of 148 feet (45 meters) was predicted for riprap with an assumed mean diameter of 3.9 feet (1.2 meters). In comparison, the zero scour tailwater depth was computed to be 310 feet (94 meters). After 10 years of operation, the depth of the basin was observed to be 190 feet (58 meters) (about 20 percent more than predicted). The spillway was extensively used throughout the 10 years. It would seem that the difference between the predicted and observed depths probably can be primarily attributed to two major factors. The first is that more than one jet has been operated at one time. Since the six jets are arranged so that they penetrate the pool at locations fairly close to each other, the scour effects of the adjacent jets cannot be considered independently. That is, two jets operating together can be expected to cause a greater scour than one operating alone, three can be expected to cause a greater scour than two, etc. The second factor is that abrasive erosion and especially uplift of massive blocks occur at Kariba while they were not evaluated in the model. The rock at the Kariba site is massive fissured material and thus is susceptible to uplift. These additional erosion mechanisms would tend to create larger scour holes than those observed in the model.

Attempts were made to find other prototype structures that might add verification to this study's findings. No pertinent information was found on structures whose physical parameters fit within the limitations of the analysis. Two structures, the outlet works at Deer Creek Dam and the outlet works at Deerfield Dam, have riprap-lined plunge basins but offer little verification because in both cases the angle of penetration was much flatter than 25° ($H_v/Y < 4.6$). As previously stated, at these flat angles the jet will not fully penetrate the pool and high surface turbulence will occur. These conditions have been observed at the two sites. Efforts to find additional prototype verification will continue.

Shape of Basin

Although no detailed data were taken, general observations indicate that placement of the deepest scour point in the middle of the basin with the length and width centered about it yields a satisfactory design for a single discharge condition. There are, therefore, three points defined on each of the two planes which contain the minor and major axes of the basin. Three points will define a specific circular arc. These circular arcs should be used to define the minor and major basin cross sections. The intersection of the basin with the horizontal bed surface should be considered an ellipse. The rest of the basin shape should be established by smooth transition curves. To establish a basin shape that would function over a range of operating conditions, the required basin size and location for both the maximum and minimum expected operating conditions must be evaluated. The two basins are to be connected by straight line transitions to obtain the final basin design.

SAMPLE PROBLEMS

Horizontal Outlet

Assume that a 4- by 4-foot (1.22- by 1.22-meter) gate is to discharge 1,600 ft^3/s (28.3 m^3/s) at full gate opening into a pool 16 feet (4.9 meters) deep. The gate is to discharge horizontally from an invert elevation of 40 feet (12.2 meters) above the tailwater pool.

Velocity from full open gate = 100 ft/s (34.8 m/s)
Velocity head H_v = 155.3 feet (47.3 meters)
$H_v/Y = 155.3/40 = 3.88$
$(H_v + Y)/T = 195.3/16 = 12.21$

From Figure 6: $D_s/D_o = 5.65$
or D_s = (5.65) (4) = 22.6 feet (6.9 meters)
From Figure 7: $W/D_o = 24.0$
or W = (24.0) (4) = 96.0 feet (29.3 meters)
From Figure 8: $X/D_o = 28.7$
or X = (28.7) (4) = 114.8 feet (35.0 meters)

The zero scour tailwater depth may also be computed using Figure 6. If $H_v/Y = 3.88$ and $D_s = 0$ then:

$D_s/D_o = 0$
$(H_v + Y)/T = 5.0$
or T = the zero scour tailwater depth
= 195.3/5
= 39.1 feet (11.8 meters)

These calculations suggest that a basin designed with a depth of 39.1 feet (11.8 meters) would be very conservative.

Now find the location of the maximum depth:

$H_v/Y = \cot^2 \emptyset = 3.88$
or $\cot \emptyset = 1.97$
or $\emptyset$ (the angle of penetration) = 27°

and

$Y = 40 = (1/2)\, gt^2 = 16.1t^2$
or t = 1.58 seconds (sec)
$X_L = Vt + T (\cot \emptyset) = (100)(1.58) + (16)(1.97)$
= 190 feet (57.9 meters)

So the basin for the maximum jet would be as shown in Figure 9. Assuming that at a lower reservoir level, the discharge at full gate opening is 800 ft^3/s (22.6 m^3/s then:

V = 50 ft/s (15.2 m/s)
H_v = 38.8 feet (11.8 meters)
$H_v/Y = 38.8/40 = 0.970$
$(H_v + Y)/T = 78.8/16 = 4.93$

These yield:

$D_s/D_o = 5.06$ — D_s = 20.2 feet (6.2 meters)
$X/D_o = 21.0$ — X = 84.0 feet (25.6 meters)
$W/D_o = 19.05$ — W = 76.2 feet (23.2 meters)

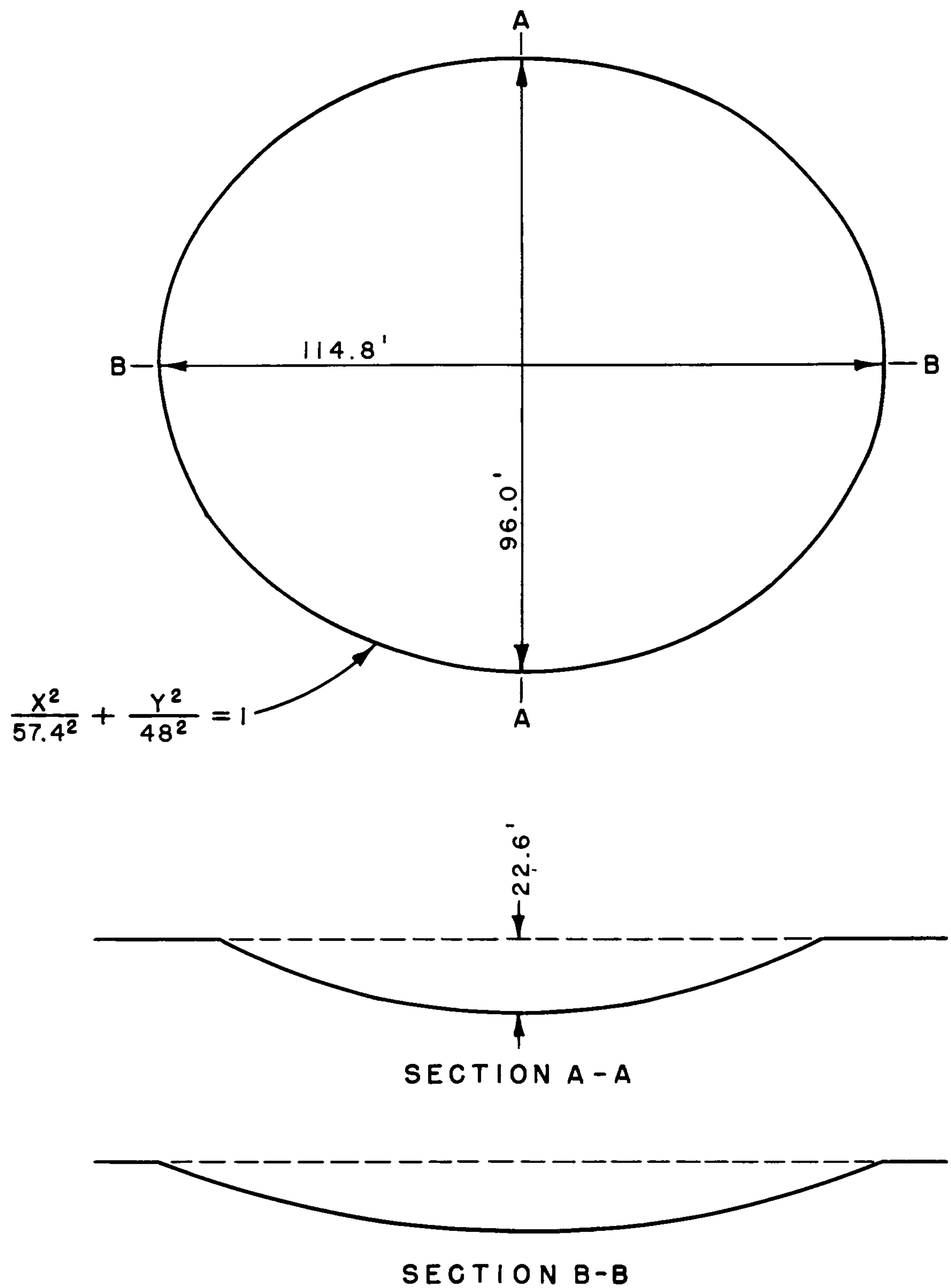
The angle of penetration is approximately 45° ($\cot \emptyset$ = 0.970):

$Y = 40 = 1/2gt^2$
or t = 1.58 sec
$X_L = Vt + T (\cot \emptyset) = (50)(1.58) + (16)(1)$
= 95 feet (29.0 meters)

So the scour depth in the final basin would vary from 20.2 to 22.6 feet (6.16 to 6.89 meters) over 190-95 or 95 feet (29.0 meters). The overall length of the basin would be 95 + 57.4 + 42 or 194.4 feet (59.3 meters). The width would vary from 76.2 to 96 feet (23.2 to 29.3 meters). The mean diameter of riprap lining could vary from 6 inches (0.13 x 4 feet) (15.2 cm) to 16 inches (0.34 x 4 feet) (40.6 cm) as desired. These riprap sizes represent the limits studied in the model.

Tilted Outlet

If the same gate is operated under the same conditions but is tilted downward at an angle of 20°, the resulting basin would be designed as follows. For the maximum reservoir head, V = 100 ft/s (30.5 m/s). At an angle of 20°, $V_{vert} = V\sin \emptyset = (0.342)(100) = 34.2$ ft/s (10.4 m/s) and $V_{horiz} = V\cos \emptyset = (0.940)(100) = 94.0$ ft/s



BASIN FOR HORIZONTAL GATE EXAMPLE

Figure 9. Basin for horizontal gate example.

(28.7 m/s). The horizontal component of H_v would be 137.2 feet (41.8 meters) and the hypothetical Y would be 40 + (155.3 - 137.2) = 58.1 feet (17.7 meters).

$$H_v/Y = 2.361$$
$$(H_v + Y)/T = 195.3/16 = 12.21$$

These yield:

D_s/D_o = 6.25 or D_s = 25.0 feet (7.6 meters)
X/D_o = 32.6 or X = 130.4 feet (39.8 meters)
W/D_o = 29.0 or W = 116.0 feet (35.4 meters)

To locate the basin, use the trajectory equation for a tilted outlet:

$$Y = V_{vert}t + \frac{gt^2}{2} = V\sin \emptyset t + \frac{gt^2}{2}$$

$$58.1 = 34.2t + 16.1t^2$$

Solution of this quadratic equation gives:

$$t = 1.115 \text{ sec}$$

$$H_v/Y = \cot^2 \emptyset = 2.361$$
$$\cot \emptyset = 1.537$$
$$\emptyset = 33^\circ$$

$$X_L = V_{horiz}\, t + T \cot \emptyset$$
$$= (94.0)\ (1.115) + (16)\ (1.537)$$
$$= 104.8 + 24.6 = 129.4 \text{ feet (39.4 meters)}$$

The deepest point in the basin is thus 129.4 feet (39.4 meters) from the tilted outlet. The downstream end of the basin is 129.4 + (130.4/2) = 194.6 feet (59.3 meters) from the tilted outlet.

Similarly, the basin size and location are determined for the low-head conditions:

$$V = 50 \text{ ft/s } (15.3 \text{ m/s})$$
$$V_{vert} = 17.1 \text{ ft/s } (5.2 \text{ m/s})$$
$$V_{horiz} = 47.0 \text{ ft/s } (14.3 \text{ m/s})$$

The horizontal component of H_v would be 34.3 feet (10.5 meters), and the hypothetical Y would be 40 + 4.54 or 44.5 feet (13.6 meters).

$$H_v/Y = 0.771$$
$$(H_v + Y)/T = 78.8/16 = 4.93$$

These yield:

D_s/D_o = 5.06 or D_s = 20.2 feet (6.2 meters)
X/D_o = 18.50 or X = 74.0 feet (22.7 meters)
W/D_o = 18.25 or W = 73.0 feet (22.3 meters)

when the mean riprap size is 6 inches (15.2 cm) — the smaller riprap tested for which dd/D_o = 0.13. If the mean riprap size is 16 inches (40.6 cm) — the larger riprap tested for which dd/D_o = 0.34, — X and W would remain the same but D_s would be decreased to 13.4 feet (4.1 meters). The low-head basin is then located:

$$Y = 44.5 = 17.1t + 16.1t^2$$
$$\text{or } t = 1.215 \text{ sec}$$
$$X_L = (47.0)\ (1.215) + (16)\ (0.878)$$
$$= 57.1 + 14.0 = 17.1 \text{ feet (21.7 meters)}$$

The deep point of the low-head basin would thus be 71.1 feet (21.7 meters) downstream from the tilted outlet. The upstream end of the basin would be 71.1 - (74.0/2) or 34.1 feet (10.4 meters) downstream from the tilted outlet. The total basin for the tilted outlet would range from 20.2 to 25.0 feet (6.2 to 7.6 meters) in scour depth if the mean riprap diameter is 6 inches (15.2 cm) and from 13.4 to 25.0 feet (4.1 to 7.6 cm) if the mean riprap diameter is 16 inches (40.6 cm). The basin would be 194.6 - 34.1 = 160.5 feet (48.9 meters) long and would range in width from 73 to 116 feet (22.3 to 35.4 meters) for any size riprap over the range studied.

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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 feet	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

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ABSTRACT

Model studies were undertaken to develop dimensionless design guidelines for riprap-lined plunge basins. To determine the basin dimensions, depressions created by free jets dropping into water-covered gravel beds were studied. The basins described by the criteria are large enough so that no further scour would occur. Parameters considered in the study as they affect the depth, length, and width of the plunge basin are: (1) height of outlet above tailwater surface, (2) pressure head on outlet, (3) outlet size, (4) tailwater depth, and (5) size of riprap.

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REC-ERC-74-9
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DESCRIPTORS. — /*plunge basins/ *scour/ riprap/ slide gates/ hydraulic models/ jets/ tailwater/ velocity head/ gravels/ discharge (water)/ model tests/ nappe/
IDENTIFIERS. — Navajo Dam, NM.

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