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Flow Deflector Design Guidelines for Mitigation of Stilling Basin Abrasion Damage


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14. ABSTRACT

Model investigations were conducted by Reclamation’s Hydraulic Investigations and Laboratory Services group in Denver to develop standard guidelines for the design of flow deflectors to reduce or eliminate stilling basin abrasion damage. Abrasion damage has been a long-standing problem for stilling basins throughout Reclamation. This document presents guidelines for determining optimal geometry and positioning of flow deflectors for the mitigation of abrasion damage.

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Flow Deflector Design Guidelines for Mitigation of Stilling Basin Abrasion Damage

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The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.

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Hydraulic Laboratory Reports

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Table of Contents

List of Figures

Executive Summary

Physical model investigations were conducted by Reclamation's Hydraulic Investigations and Laboratory Services Group in Denver, Colorado to develop standard guidelines for the design of flow deflectors to reduce or eliminate stilling basin abrasion damage. Abrasion damage has been a long-standing problem for stilling basins throughout Reclamation for many years and a number of studies have been conducted to try to understand the problem and to come up with cost effective solutions. Through these investigations of standard Reclamation type II and type III stilling basin designs, it was determined that flow deflectors can be used to mitigate abrasion damage by redirecting flow currents responsible for carrying abrasive materials into stilling basins. In addition, field evaluations of the stilling basins at Mason Dam and Choke Canyon Dam were conducted to validate physical model results and to help refine and verify the designs [1].

This document presents guidelines for deflector design that represent a culmination of what has been learned from these studies. The guidelines address deflector geometry, angle, and positioning for Reclamation stilling basins of standard design. Two design approaches are presented, one using basin velocity profiles measured in the field or in a physical model as the basis for a refined design, and a second simplified method using an oversized deflector that can be applied without the need for velocity profile data.

The guidelines presented in the main body of the report outline the method used for the precise placement and geometry of deflectors based on basin velocity profiles measured at the end of the stilling basin. This design process includes first determining whether or not stilling basin geometry matches closely with the design parameters presented in Reclamation's Engineering Monograph No. 25 [1]. If so, then the guidelines presented here can be used in conjunction with measured velocity profiles to develop a deflector design for the basin. This process includes taking into account how the stilling basin is operated to determine if one deflector is adequate, or whether two staggered deflectors are required to provide effective performance.

The simplified guidelines for designing oversized deflectors without velocity profile data are presented in the appendix of this report since they are based on only one case study; they should be used with caution as outlined in that section of the report. In this case, deflector design and placement are not as exact and the size of each deflector is significantly larger. The oversized deflector does produce significant headloss that must be taken into account. The simplified design will not require the time and expense associated with obtaining velocity profiles for the stilling basin. Although there is evidence to support the effectiveness of this design approach, further research may be required to

implement such designs with confidence.

All guidelines presented here are recommended only for stilling basins less than about 25 feet in width. Wider basins can effectively use flow deflectors to prevent materials from entering a stilling basin, however due to unique flow characteristics associated with the wider basins, a physical model study is recommended [2].

While the emphasis of this report is on design guidelines for structures at which velocity profiles can be measured in the field or in physical models, there is good potential for further development of the simplified approach used in the appendix for oversized deflectors. Additional research could reduce uncertainty that affects the determination of the deflector size and position, leading to smaller, more economical deflectors that can be designed without the need for a physical model study or field evaluation of each individual basin.

Purpose

Physical model investigations were conducted by Reclamation’s Hydraulic Investigations and Laboratory Services group in Denver to develop standard guidelines for the design of flow deflectors to reduce or eliminate stilling basin abrasion damage. Abrasion damage has been a long-standing problem for stilling basins throughout Reclamation for many years and numerous studies have been conducted to try to understand the problem and develop cost effective solutions. The Mason Dam and Choke Canyon Dam outlet works stilling basins are both Reclamation type II stilling basins with long histories of abrasion damage and repeated repairs. Both basins were modeled in the Denver laboratory to determine optimal deflector designs. In addition, field evaluations of the stilling basins at Mason Dam and Choke Canyon Dam were conducted to validate physical model results and to help refine and verify the final design [1]. This document presents guidelines for deflector design based on what has been learned from those studies and others, so that in the future deflectors can be designed without the need for a physical model study for each individual basin.

Background

Stilling basin abrasion damage is a widespread problem for river outlet works at Bureau of Reclamation (Reclamation) dam sites throughout the western United States. Abrasion damage occurs when bed materials, such as sand, gravel, or rock, are carried into the basin by recirculating flow patterns produced over the basin end sill during normal operation of a hydraulic jump energy dissipation basin (Figure 1). Once materials are in the basin, turbulent flow continually moves the materials against the concrete surface, causing severe damage, often to the extent that reinforcing bars are exposed. When repairs are made, many basins experience the same damage again within one or two operating seasons. As a result, tens of thousands of dollars are repeatedly spent by Reclamation to repair this type of damage.

The implementation of flow deflectors could produce substantial cost savings by reducing recurring O&M costs for basin repairs, dewatering, and interruptions in water deliveries [3] [4]. Figure 2 shows typical abrasion damage that has occurred at the Choke Canyon Dam outlet works stilling basin. Damage occurs most commonly in Reclamation type II and type III stilling basins (Figures 3 and 4). Both basins are Reclamation standard designs for hydraulic jump energy dissipation basins, typically used for Froude numbers greater than 4.5. The type II basin is designed for entrance velocities greater than 60 ft/s and uses chute blocks and a dentated sill at the end of the basin to help stabilize the jump to dissipate the high velocity flow before it enters the river channel. The type III basin is similar to a type II basin except that it uses baffle blocks in addition to chute blocks and a simpler end sill in place of the dentated sill to shorten the length of the jump. The type III basin is designed to dissipate the high velocity flow for basins with entrance velocities less than 60 ft/s.

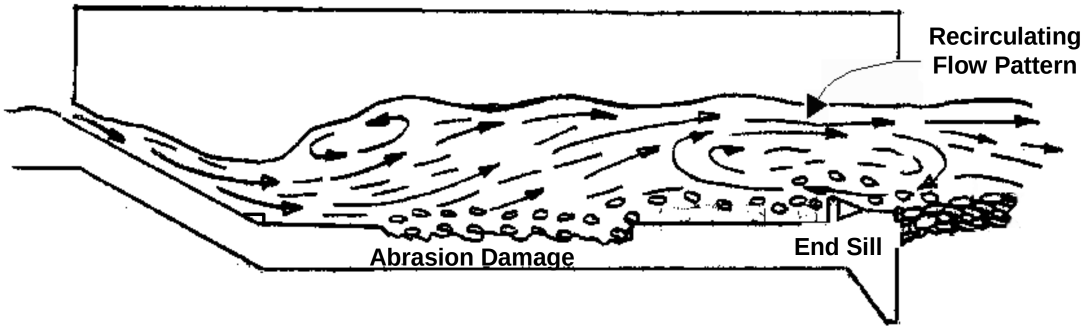

Figure 1. — Recirculating flow pattern is produced over end sill during normal operations.

Figure 2. — Typical abrasion damage (Choke Canyon stilling basin).

Research funded by Reclamation's S&T (Science and Technology) program and conducted by Reclamation's Hydraulic Investigations and Laboratory Services Group in Denver was used to identify flow currents that carry damaging materials into the basins and then to identify cost effective solutions for mitigating this type of damage. This led to the development of flow deflectors that can be used to change flow patterns occurring over the basin end sill, thus minimizing or eliminating the potential for abrasive materials to be carried into the basin (Figure 5). Collaboration with Reclamation's PN Region and Snake River Area Office led to the first prototype deflector being installed at Mason Dam in October 2002.

In addition, another set of flow deflectors was installed in December of 2006 at the Choke Canyon Dam outlet works stilling basin as a result of a collaborative effort with the Texas-Oklahoma Area Office and the city of Corpus Christi. A U.S. patent was awarded for the flow deflector design on March 20, 2007. However, the patent has since been allowed to expire.

Introduction

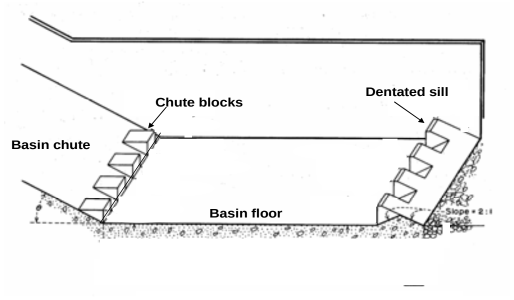

Figure 3. — Reclamation type II stilling basin.

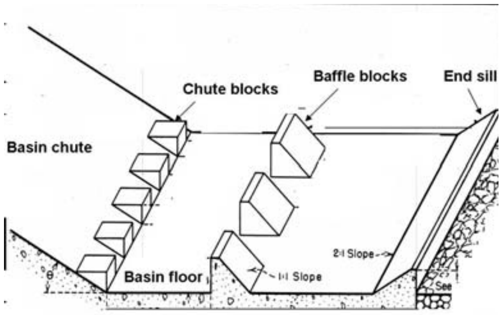

Figure 4. — Reclamation type III stilling basin.

Investigations determined that by installing flow deflectors near the end of a stilling basin, flow currents near the bottom can be redirected to prevent materials from being carried into the basin. Deflector design guidelines presented in Section I of this report were based upon the results from the hydraulic model testing of various deflector configurations studied to improve flow conditions at the end of type II and type III stilling basins. The studies began with evaluating the existing conditions for a range of operations up to maximum design flow for each basin, then progressed with testing a series of different configurations using one or more deflectors through the same range of operations, until an optimal deflector configuration was determined. (Section II provides a brief summary of these studies). Field testing was then conducted at two separate sites to verify and refine flow deflector design guidelines. In addition, model investigations demonstrated that two deflectors, staggered in position (both vertically and horizontally) can be effective at sites where large ranges of operations (discharge or tailwater variations) need to be considered in the design. This document summarizes the investigations and presents the resulting guidelines. For more detailed descriptions of each of these studies please see Hydraulic Laboratory reports HL-2010-03, HL-2007-02, and HL-2005-01 [1] [2] [5].

Section II and Appendix A, (titled "Simplified Deflector Design") describe one set of exploratory model investigations that were used to simplify deflector design and reduce costs by eliminating the requirement to measure velocity profiles at the end of the stilling basin. Although this simplified approach has been demonstrated to be effective in a limited range of physical model tests, the method has not yet been proven through field application and should thus be applied with caution at this time.

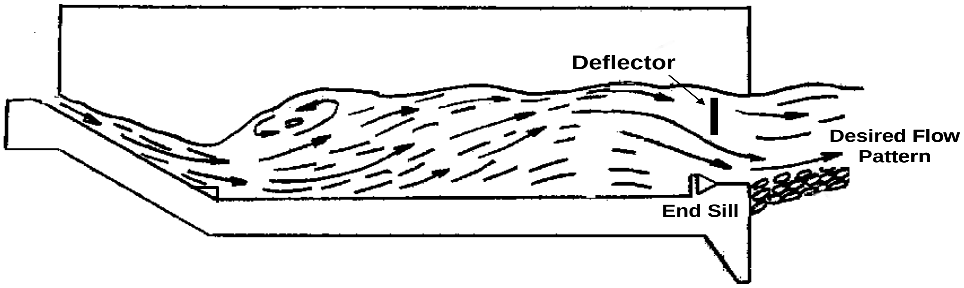

Figure 5. — Flow deflector redirects bottom currents to maintain a downstream direction.

Section I - Standardized Deflector Design

Design Procedure Overview and General Observations

Data from field studies and model investigations were compiled and analyzed to determine standard guidelines for flow deflector design. Analyses of model and field data were correlated with the design parameters calculated from Engineering Monograph No. 25 and were used to develop a method for generalizing flow deflector design for Reclamation type II and type III stilling basins. These guidelines were developed so that in the future they can be used in conjunction with a field evaluation conducted on-site to determine deflector design without having to conduct a physical model study for each individual basin.

The first step in using this set of guidelines is to determine the design flow for the basin based on actual geometry of the stilling basin and the parameters presented in Engineering Monograph No. 25(EM25) [6]. Design discharge based on actual stilling basin geometry should be calculated from EM25 and compared to the basin's site-specified maximum flow operations (Standing Operating Procedures). This will help the designer to know the limits of the deflector design as follows:

- The hydraulic jump will be contained within the concrete basin for discharges up to the design flow calculated from EM25. If the basin is operated above design flow (based on basin geometry), the hydraulic jump will extend beyond the end of the concrete basin. Once the jump moves beyond the end of the basin, a turbulence barrier at the end of the basin will help prevent flow currents from carrying materials into the basin.

This means that deflector design will not need to include flows above the calculated design flow. However, in this case freeboard may be minimal, so caution must be used to ensure that installation of deflectors does not cause overtopping of the structure.

- If the actual length of the basin is more than 10% longer than the design length needed to contain the hydraulic jump (calculated from EM 25), then the lateral positioning of the deflector may need adjustment so that it is positioned where the jet is concentrated enough to be effectively redirected.

The next step is to determine the velocity profiles at the end of the stilling basin over the operating range of the basin in 10% to 20% gate opening increments. These are average velocities measured at the end of the basin from the highest elevation of the basin end sill to the water surface, at 1 to 2 ft vertical increments, near the basin's centerline (a Sontek ADP probe or similar profiler, mounted to the basin's end sill can be used for this evaluation). The velocities measured must be those that run parallel to the basin sidewalls in the plus and minus directions. Ideally, field evaluations should be conducted over a range of reservoir elevations; however this is usually not very economical. Therefore, velocity data should be collected when reservoir elevation is near its upper range to ensure best accuracy for deflector positioning. A field evaluation is required for determining velocity profiles because deflector design is dependent on accurately identifying the elevation of the concentrated jet exiting the basin for the operations of interest. Therefore velocity profiles measured at the site are the most accurate method for defining this location for each stilling basin.

The design parameters for the optimal design of type II and type III stilling basin flow deflectors are summarized in the next two sections. These guidelines are applicable to basins that correlate well with stilling basins of standard design as outlined in Engineering Monograph No. 25. In some cases where stilling basin design falls too far outside the range of the design parameters recommended in EM25, a physical model study may be required in addition to a field evaluation, to effectively design a flow deflector.

The results from these studies indicate that the installation of a flow deflector in the basin can help improve flow conditions to minimize the potential for entraining materials in the basin, thereby extending basin life, and reducing long-term O&M costs. However, it must also be emphasized that it is important that proper concrete repair techniques be used to repair the basin when the deflector is installed [7]; otherwise, high-velocity flow can lead to concrete erosion and the release of aggregate into the stilling basin. Although much of this material may be flushed from the basin over time, even small pieces of aggregate or other materials can lead to significant abrasion damage.

Tailwater elevation can also have a significant effect on the performance of a hydraulic jump stilling basin and therefore may affect basin performance with a deflector in place. If large tailwater variations are experienced at a site, although deflector performance may be reduced, the flow conditions will still be improved over having no deflectors in place.

These guidelines are recommended only for stilling basins less than 25 feet in width. This is because wider stilling basins often exhibit additional flow characteristics that need to be addressed in the design of the flow deflector. In particular, for larger basins the hydraulic jump tends to concentrate on one side of the stilling basin and may oscillate from one sidewall to the opposite sidewall at discharges below design flow. This produces a variable strength hydraulic jump as flow is increased that affects the location of the exiting jet and thus optimal deflector elevation. In addition, a flow deflector spanning a distance greater than 25 ft may require additional structural support. Flow deflectors can be effective for preventing materials from entering these wider basins, (as in the case of Fontenelle Dam [2]) but a physical model is recommended to ensure effective deflector design and a staggered configuration of multiple deflectors will most likely be required.

Finally, investigations have shown that with deflectors in place, a type II basin potentially becomes hydraulically self-cleaning at flows well below design flow, whereas without a deflector in place, full design flow would normally be required to provide any flushing action. This means that if materials should get into a deflector-equipped basin by other means, such as persons throwing rocks into the basin or aggregate released from concrete, they can be flushed out sooner, thereby reducing abrasion damage significantly. The range of sizes of materials that can be flushed from the basin will depend on deflector configuration and outlet works operations. It also appears that two staggered deflectors are more effective than a single deflector in flushing materials from a basin.

Investigations conducted with the type III stilling basins with a deflector in place have shown that these basins do not have the same tendency to self-clean as the type II stilling basins. This is because of localized recirculation that is produced immediately downstream from the baffle blocks. So, although a deflector will prevent most materials from being drawn into the type III basin, if materials should get into the basin from another source they will not be easily purged from the basin under normal operations.

Type II Stilling Basins – Standard Design

Model investigations showed that best deflector performance is obtained with the deflector positioned at an elevation corresponding to the bottom of the most concentrated portion of the downstream jet exiting the basin. This allows the deflector to effectively redirect currents toward the bottom in the downstream direction, so that materials are prevented from entering the basin (Figure 5). Although this location can be identified with velocity profile data, this location changes as a function of discharge over the operating range of the stilling basin. As a result, optimal elevation for a type II stilling basin deflector will vary over the operational range of the stilling basin. This shift in elevation occurs because the hydraulic jump is fairly weak at low discharges and, as a result, the most concentrated portion of the aerated jet rises off the basin floor near the upstream end of the stilling basin and rises high in the water column by the time it reaches the end of the basin. Therefore, to effectively redirect flow currents near the end of the basin, the deflector must be positioned in the upper portion of the water column. At high discharges, the concentrated jet entering the basin is strong, remaining on the basin floor longer and remaining relatively low in elevation when it reaches the basin exit. Thus, the deflector must be lower in elevation to effectively redirect flow currents near the end of the basin. Further explanation of this phenomenon is provided in Section 2 of this report.

If the operating range for which the deflector is to be designed is narrow, then a single deflector may be sufficient to accommodate the shifting jet. However if the deflector must be effective over a large operating range, which is more often the case, a two-deflector staggered configuration will need to be considered. Thus, several practical approaches can be considered to achieve effective performance for the type II stilling basins:

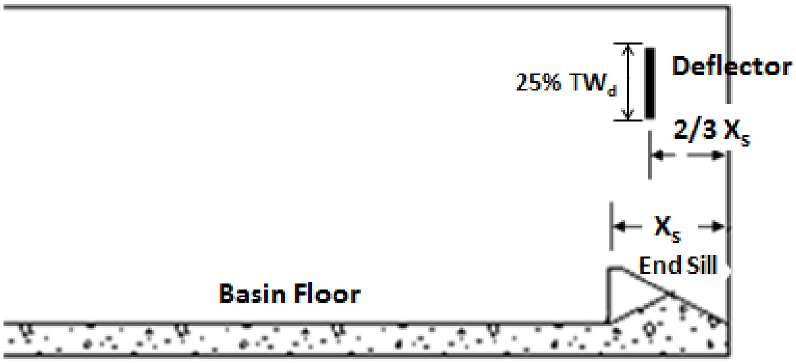

Figure 6. — Deflector lateral positioning illustrated for a Reclamation type II stilling basin.

1) Option 1. A single deflector may be used if the range of typical operations is small enough that measured velocity profiles are tightly grouped (Figure 6). Best performance for a single stationary deflector occurs when the deflector can be positioned to be effective over the most predominant operating range expected in the prototype (as with Mason Dam). This would mean that if the basin was operated outside the range for which the deflector was designed, materials may be drawn into the basin. If this should occur, the basin should be operated within the designated deflector design range when possible,

to help flush materials from the basin. In addition, inspections and cleaning of the basin may be required more frequently.

2) Option 2. For most basins where it is important to achieve effective deflector performance over the full operating range of the basin, the most practical option is to install two separate deflectors (upper and lower) staggered in position, so that flow conditions can be improved throughout the full range of basin operations (Figure 7).

Type II Stilling Basin Design Parameters

The optimal design parameters are defined as follows:

1) The deflector (both upper or lower) should be positioned vertically within the stilling basin sidewalls
2) The vertical dimension for the upper deflector should be equal to or greater than 25% of design flow tailwater depth (TW_d).
3) If a lower staggered deflector is used, it should have a vertical dimension equal to or greater than 15% design flow tailwater depth.
4) The optimal elevation for the deflector (upper or lower) can be determined as follows:
    a. Velocity profiles measured in a vertical plane at the end of the basin near its centerline will be used to identify the location of the concentrated jet exiting the stilling basin (i.e., where velocity transitions from upstream to downstream in direction parallel to basin sidewalls). The bottom of the deflector should be positioned at an elevation that corresponds to a position near the bottom of the exiting jet where velocities reach a magnitude of about 1.0 ft/s directed downstream, out of the basin, for the operating range of interest.
        i. Single deflector – If a single deflector is to be used, vertical velocity profiles measured for the predominant range of discharges expected in the prototype will be used to identify the best elevation for the deflector to be positioned.
        ii. Two staggered deflectors - If two staggered deflectors are to be used, the elevation of the upper deflector will be based on profiles measured during a selected grouping of low-range discharges that represents typical flows. The lower deflector's elevation will be based on profiles measured during operations within the remaining upper range of discharges approaching and including the design flow for the stilling basin.

    Figure 8 shows an example of how velocity profiles are used to determine staggered deflector elevations. Note that velocities in the lower portion of the water column are directed upstream into the stilling basin.

5) The optimum lateral position for the upstream face of the upper deflector can be determined as follows:
    a. Measuring upstream from downstream end of the basin end sill, the location is 2/3 the horizontal dimension of the end sill (2/3 X_S shown in Figures 6 and 7).
6) The optimum lateral position for the lower deflector (upstream face) can be determined as follows:
    a. The optimum lateral position for the lower deflector is midway between the upper deflector and the downstream end of the basin end sill or 1/3 X_S (Figure 7).

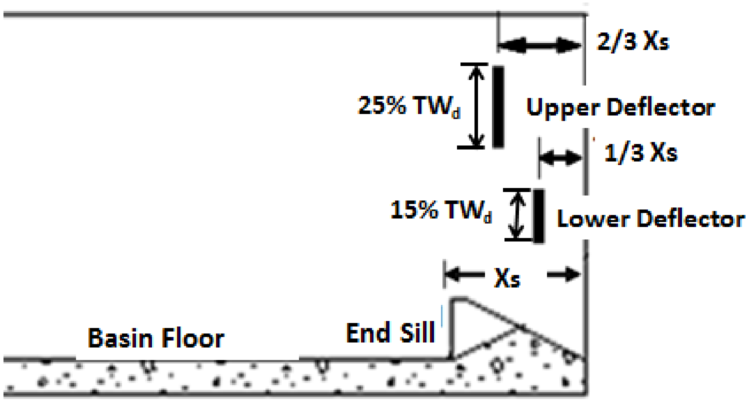

Figure 7. — Section view illustrating optimal lateral locations for upper and lower deflectors for a Type II stilling basin.

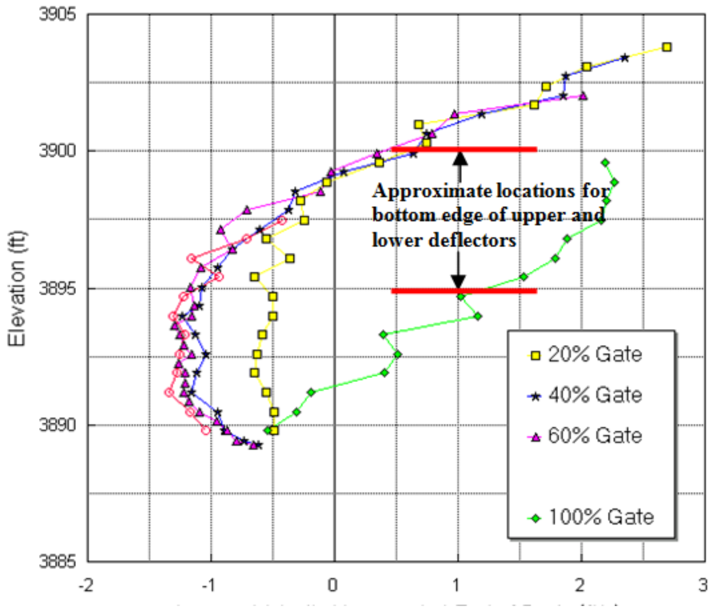

Figure 8. — Approximate elevations for upper and lower deflectors identified based on velocity profiles measured near the centerline of the basin at the downstream end.

Type III Stilling Basins - Standard Design

Model investigations of the type III stilling basins showed that basin baffle blocks help to keep the jet exiting the basin at nearly the same elevation throughout all gate operations. Thus, a single deflector is adequate to provide optimum performance throughout the full operating range of a type III basin.

The following flow deflector parameters are recommended for Reclamation type III stilling basins.

Type III Stilling Basin Design Parameters

The optimal design parameters are defined as follows:

1) The deflector should be positioned vertically within the stilling basin sidewalls.
2) The vertical dimension for the deflector should be equal to or greater than 25% of design flow tailwater depth.
3) The optimal elevation for the deflector can be located as follows:
    a. Velocity profiles measured in a vertical line at the end of the basin near its centerline will be used to identify the location of the concentrated jet exiting the stilling basin over the operating range of the basin. The bottom of the deflector should be positioned at an elevation that corresponds to a position near the bottom of the

exiting jet where velocities reach a magnitude greater than 1.0 ft/s directed downstream, for the operating range of interest.

4) The optimum lateral position for the deflector (upstream face) can be determined as follows:
    a. The type III basin deflector should be positioned with the upstream face located over the upstream third of the basin end sill, between $2X_s/3$ and X_s upstream from the downstream end of the stilling basin end sill and sidewalls (Figure 9).

Implementation of any of the above options should significantly reduce damage caused by abrasion and the costs associated with basin repairs.

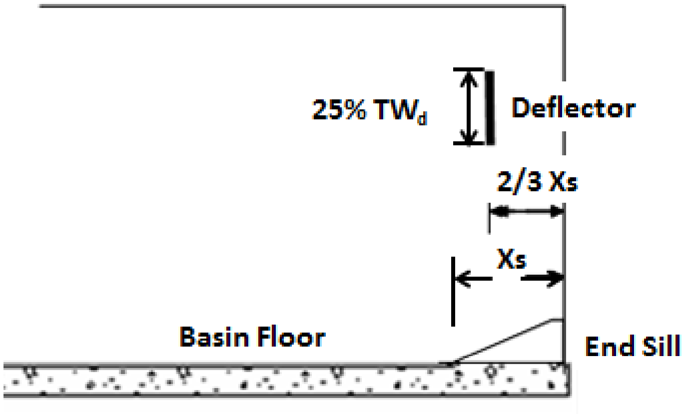

Figure 9. — Optimal deflector lateral positioning illustrated for a Reclamation type III stilling basin.

Section II - Simplified Deflector Design

During the course of evaluating flow deflector design, it became evident that the expense and limitations of field evaluations needed to precisely determine size and positioning for a deflector may deter implementation of deflectors at many sites where they are needed. These deterrents include limits on basin operations for field testing, and the need for specialized instrumentation and a dive team for installation. As a result, several exploratory model investigations, with limited funding provided by Reclamation's Science & Technology Program, were conducted with oversized flow deflectors in an effort to determine if the need for a field evaluation could be eliminated. Because this study had a limited scope, the design of a prototype deflector using the simplified approach should be approached cautiously. The greatest value of this information may be to serve as a starting point for further research; Appendix A presents the simplified design approach and discusses the limited testing performed thus far to develop the method.

Section III – Precise Deflector Size and Placement

The Models

Four separate models, representing Reclamation stilling basins of standard design, were studied in the Denver laboratory beginning in the mid 1990's [1] [2] [5]. The basins modeled included the Mason Dam, Choke Canyon Dam, and Fontenelle Dam outlet works (OW) stilling basins, (Reclamation type II basins), and Haystack Dam outlet works stilling basin (Reclamation type III basin).

The model studies were used to:

1) Identify factors contributing to the basin damage by identifying the extent and strength of flow currents in standard outlet works stilling basins over a range of operating conditions.

2) Develop guidelines for the generalized design of flow deflectors that include:
    a) Deflector position (lateral and vertical position within the basin)
    b) Deflector angle
    c) Deflector geometry

3) Evaluate deflector performance over the full range of operations.

All dimensions and measurements reported here are scaled to prototype dimensions (unless otherwise noted) and are referenced to the upstream edge of the lowest elevation on the deflector.

Model Measurement Methods

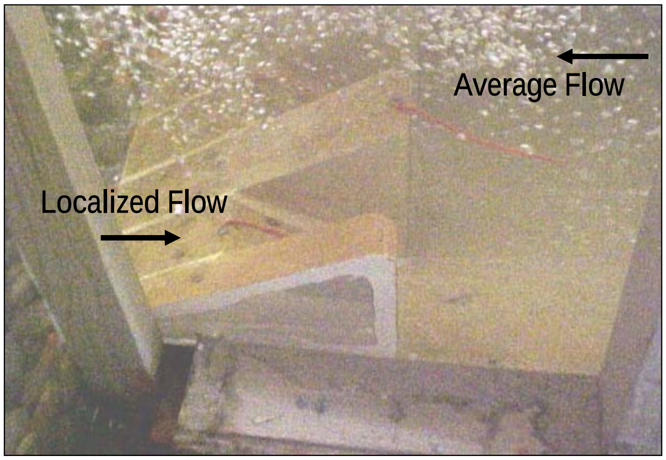

Figure 10. — Strings indicate flow direction is upstream into the stilling basin

Model investigations were conducted to evaluate hydraulic conditions in each of the four stilling basins. Velocity data were collected and analyzed to define basin performance over the operating range expected in the prototype for each stilling basin. In addition, dye and strings attached to the end sill of each basin were used as visual aids to identify the flow direction of currents near the bottom of the basin (Figures 10 and 11). Velocity measurements and flow visualization were used to help establish guidelines to define the most effective deflector design including best deflector location within the stilling basin, both laterally (X_d) and vertically (Y_d), and the best angle to position the deflector, for optimizing flow conditions (deflector design variables are illustrated in Figure 12).

Figure 11. — Strings and dye indicate flow near the bottom is redirected downstream after the deflector is installed in the Mason Dam (L) and Haystack Dam (R) stilling basin models.

Velocities were measured with a Sontek ADV (Acoustic Doppler Velocimeter) probe at numerous locations within and downstream from each stilling basin to define velocity profiles for each discharge tested. Initial velocity measurements included mapping vertical profiles measured at the downstream end of the stilling basin for each gate opening at maximum reservoir elevation.

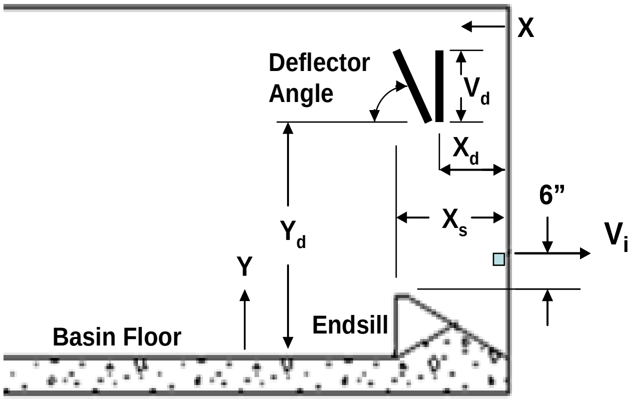

Figure 12. — Sectional view showing the downstream end of a typical stilling basin and basic parameters that define flow deflector position, size, and orientation.

Velocities were measured beginning several inches above the basin invert and continuing upward along a vertical line until air entrained in the flow prevented further measurements. Figures 13-15 shows the vertical velocity profiles measured at the downstream end of the outlet works stilling basins for Mason Dam, Choke Canyon Dam, and Haystack Dam, for the range of operations expected at each site. The profiles demonstrate that average velocities measured in the lower portion of the water column are directed upstream into the basin, indicating a strong potential for materials to be carried into the basin (negative values indicate velocity is directed upstream). These profiles are typical of hydraulic jump energy dissipation type stilling basins.

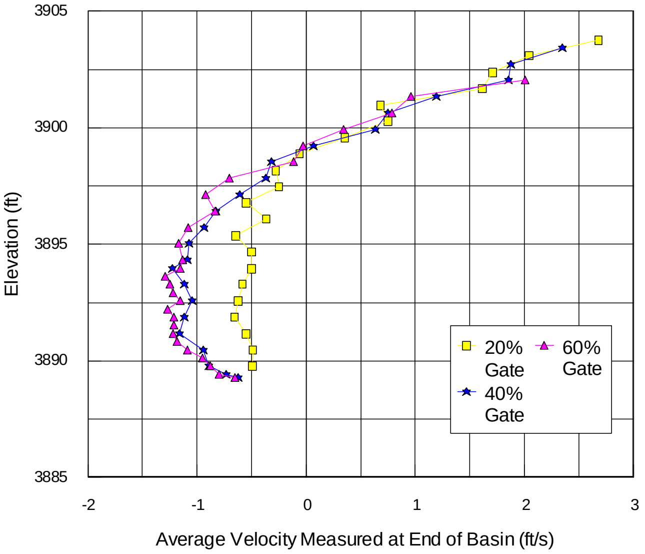

Figure 13. — Vertical velocity profiles measured at the downstream end of the Mason Dam stilling basin.

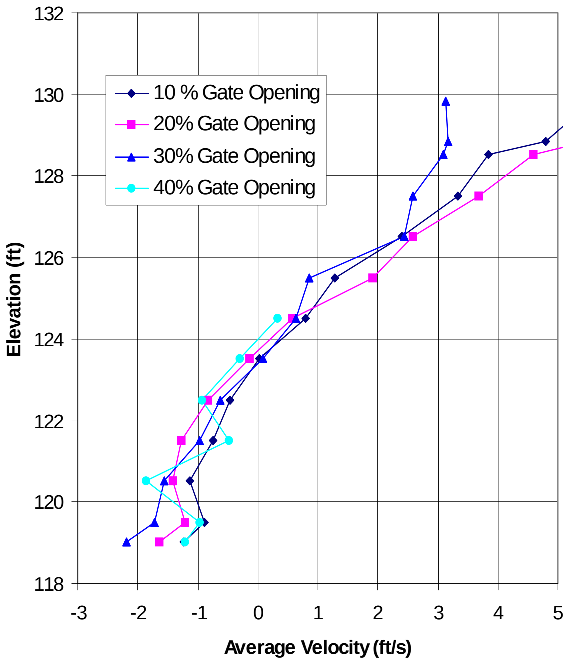

Figure 15. — Vertical velocity profiles measured in the Choke Canyon stilling basin model.

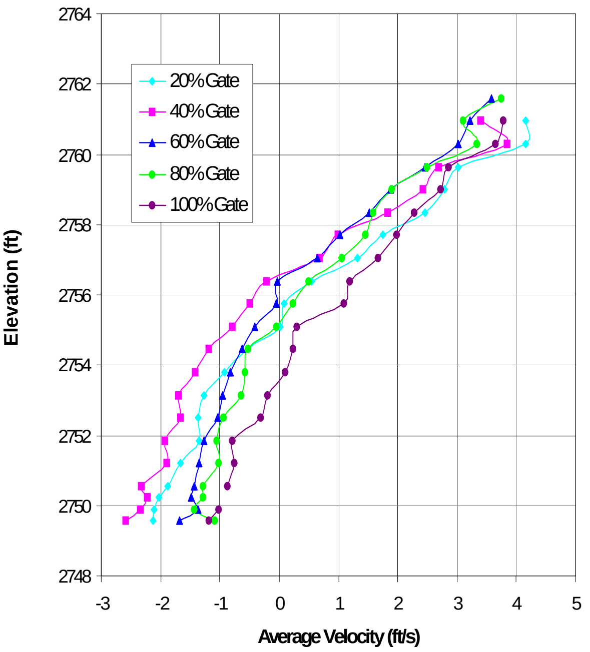

Figure 14. — Vertical velocity profiles in the Haystack stilling basin model (no deflector).

Evaluating Performance

Early investigations showed that average velocities measured at the end of each basin, at its centerline, and about 6 inches (prototype dimensions) above the top elevation of the basin end sill (between dentates, for a type II basin), provided a good indication of the bottom velocities that carry materials into the basin. Therefore, average velocities measured at this location were used as a basis to define deflector performance and will be referenced as "index velocity" or Vi for all type II and type III stilling basins tested (Figure 12). For the purpose of evaluating deflector performance it was determined that the higher the index velocity in the positive or downstream direction the better the performance (negative velocities indicate flow is upstream into the basin).

When evaluating stilling basin or deflector performance, relative performance was determined by comparing index velocities (Vi). Figure 16 shows an example of a histogram with data distribution for a case where the index velocity measured was near 0.0 ft/s. An index velocity near zero may appear to represent a flow condition where velocities are not strong enough to carry materials into the basin and thus good performance; however this is not necessarily the case since flow is surging in various directions and this is only an average velocity. Figure 16 shows that instantaneous velocity measurements for this flow condition range from 5 ft/s to -5 ft/s, therefore, some materials may be carried into the basin during upstream flow surges. This demonstrates that an index velocity near zero does not necessarily indicate adequate performance.

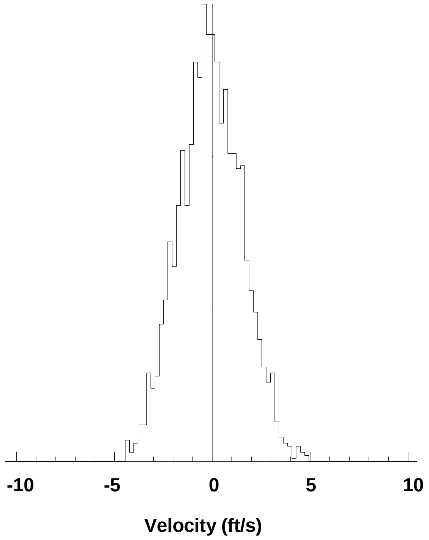

Figure 16. — Example histogram for data set containing 3,000 samples. Index velocity is near 0.0 ft/s.

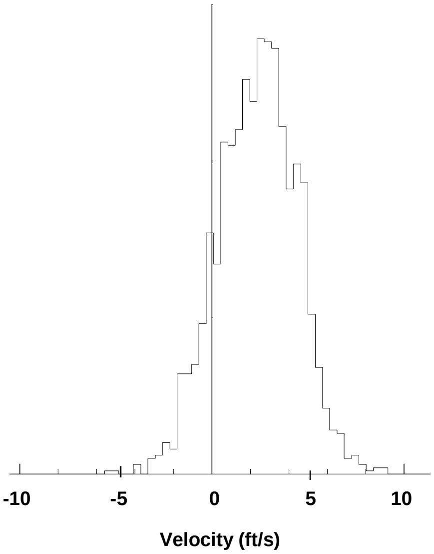

Figure 17. — Example histogram for a data set containing 3,000 samples. Index velocity is 2.3 ft/s.

Figure 17 shows the data distribution for a case where the measured value for Vi was 2.3 ft/s. This figure shows that although the index velocity is positive and directed downstream, some flow velocities in the upstream direction are as high as those in the previous example, shown in Figure 16. However, in this case, since the majority of the velocity samples measured are positive or downstream in direction, the potential for moving materials into the basin is much lower than that of the condition where Vi was near zero. Thus, higher positive index velocities indicate better performance.

Type II and Type III Basins - Physical Model Evaluations Optimal Positioning and Size

For each model study conducted, initial deflector design was modeled with a flat section of sheet metal mounted on guides attached to the basin sidewalls, to allow vertical, lateral and angular movement of the deflector within the stilling basin (Figure 18). Velocity data were collected and analyzed to determine the most effective deflector angle and the best lateral and vertical locations within the stilling basin over the operating range expected. Index velocities were evaluated and compared to determine optimal deflector performance and design parameters. Figure 19 shows average index velocity as a function of deflector elevation for a range of lateral deflector locations for the Mason Dam OW model study, with deflector position referenced to the upstream edge of the lowest elevation of the deflector. The figure shows that best performance (maximum downstream velocity) was achieved when the deflector was at a lateral location of X= 5 ft and with bottom elevation at 3899.87 ft. Similar investigations were used to determine best performance for a range of deflector angles and sizes. Then the

Figure 18. — Deflector and ADV velocity probe installed in Mason Dam stilling basin model.

whole process was repeated at incremental gate openings over the range of operations expected in the prototype to determine best overall deflector design. In each case, best performance was determined based on maximum positive velocities. This same process was used for each of the basin models investigated. Once the optimal elevation, lateral positioning , and size for each deflector was determined, these parameters were normalized with respect to design flow tailwater elevation and basin geometry.

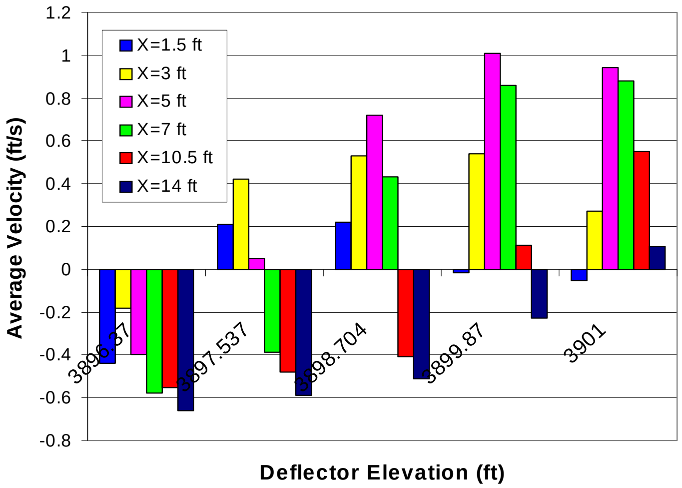

Figure 19. — Index velocity measured at the end of the Mason Dam basin model as a function of deflector elevation for 6 lateral deflector positions for basin operating at 40% gate opening). Basin floor elevation is 3889 ft.

Special Considerations

Choke Canyon Dam – An Undersized Basin

In the case of the Choke Canyon Dam OW model study the investigations showed that when the basin was operated above 40% gate opening, the concentrated jet emerging from the hydraulic jump does not rise from the basin floor before it reaches the end of the basin. In addition, the hydraulic jump began to move out of the concrete basin and onto the riprap apron. A design analysis of the basin, using parameters defined in EM25 [6], indicated that this occurs because the geometry of the concrete stilling basin was designed only to fully contain the hydraulic jump for flows corresponding to gate openings up to about 40 percent at maximum reservoir levels (Figure 20). Looking at the history of outlet works operations at Choke Canyon Dam shows that they have rarely operated above that level in the previous 20 years of operations, so this is a logical and economical design for the stilling basin. For flows greater than 40% gate opening (at maximum reservoir), the jump is simply allowed to extend out onto the riprap apron. As a result, for operations above 40% gate opening, instead of a well-defined jet exiting the basin, there is a significant amount of turbulence that occurs near the end of the basin. In this case, because the jet remains along the basin floor for the full length of the basin, it provides flushing action at operations greater than 40% gate opening. This means that for this basin or any basin of similar design it will not be necessary to design the deflector for operations above the design flow (i.e., flows at which the jump is not fully contained in the basin). However, operation of the basin with the deflector in place should be evaluated up to the maximum operating flows defined in the basin's SOP to ensure that basin sidewall overtopping will not occur (due to additional head loss caused by the deflector), since freeboard at design flow may be small. This demonstrates the importance of determining the actual design flow, based on the geometry of the stilling basin, using guidance provided from EM25. The design of a deflector for this basin should then be based on the actual design flow of the basin (i.e., in this case, the design flow tailwater depth would correspond to 40% gate flow at maximum reservoir head). Figure 21 shows the performance with and without the final optimal design in place at Choke Canyon Dam.

Figure 20. — Choke Canyon stilling basin model operating at 40% gate opening based on maximum reservoir.

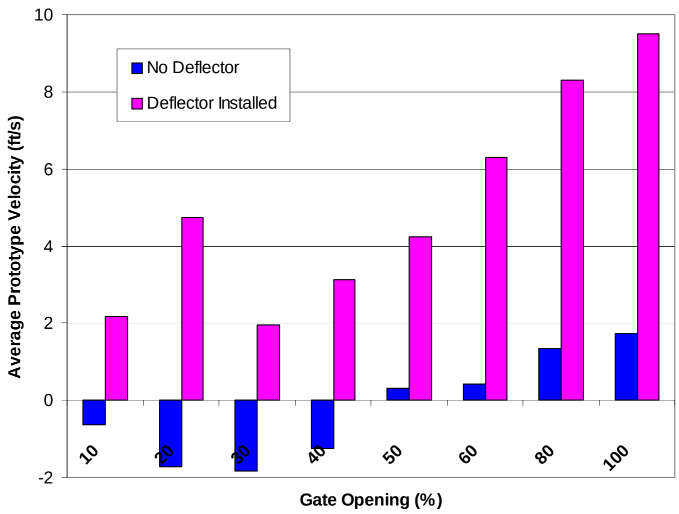

Figure 21. — Index velocities measured in the Choke Canyon stilling basin model at the end of the basin with and without optimal deflector in place.

Mason Dam – A Type II Basin with Limited Operational Range

For the Mason Dam prototype deflector, the optimal design was based only on gate operations up to 60% gate opening due to SOP limits on maximum discharge. Within this limited operating range, there was minimal shift in the jet position; therefore, a single deflector was adequate to produce effective performance. Figure 22 shows average bottom velocities measured in the Mason model without a deflector, compared with those measured with the deflector set into optimal position (as determined from the model study) for gate openings ranging from 20% to 100%. The

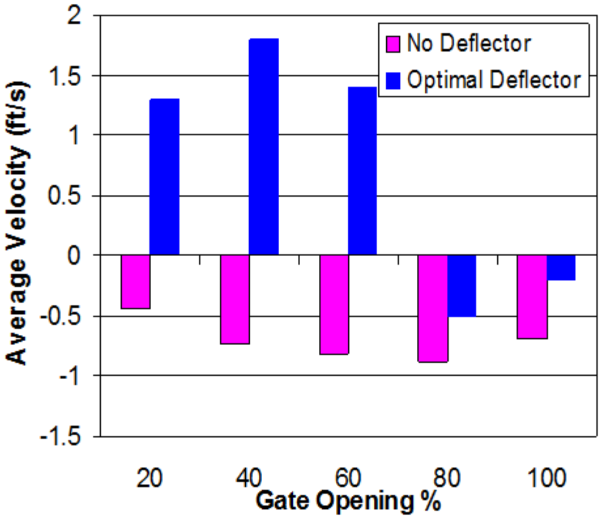

Figure 22. — Average prototype index velocities measured in the Mason Dam stilling basin model with and without optimal deflector

figure shows that performance at gate openings within the Mason deflector design range (20% to 60% gate opening) was very good. Index velocities for this range of discharges were greater than 1.0 ft/s, directed downstream. The figure also shows that for gate openings of 80% and 100%, performance was reduced significantly; although still improved over having no deflector. The reason performance is reduced at higher discharges is because as discharge is increased, the point at which the incoming jet lifts off the basin floor moves downstream considerably, and the jet does not rise as high above the basin floor. As a result, the concentrated jet remains below the elevation of the deflector when it exits the basin and cannot be effectively redirected (Figures 23 and 24). This demonstrates that the deflector design developed for the Mason Dam stilling basin would not have been adequate if effective performance had been required for operations up to 100 % gate opening. Further investigations have shown that this phenomenon is typical of type II stilling basins operating over the full design flow range of the basin.

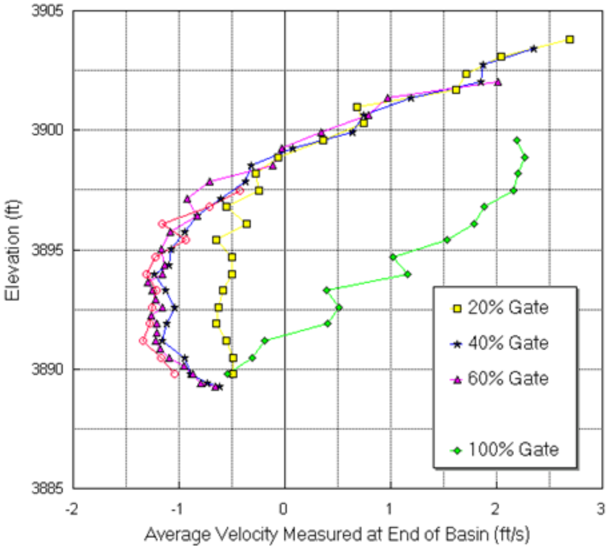

Figure 23. — Velocity profiles measured near the end of the basin at its centerline.

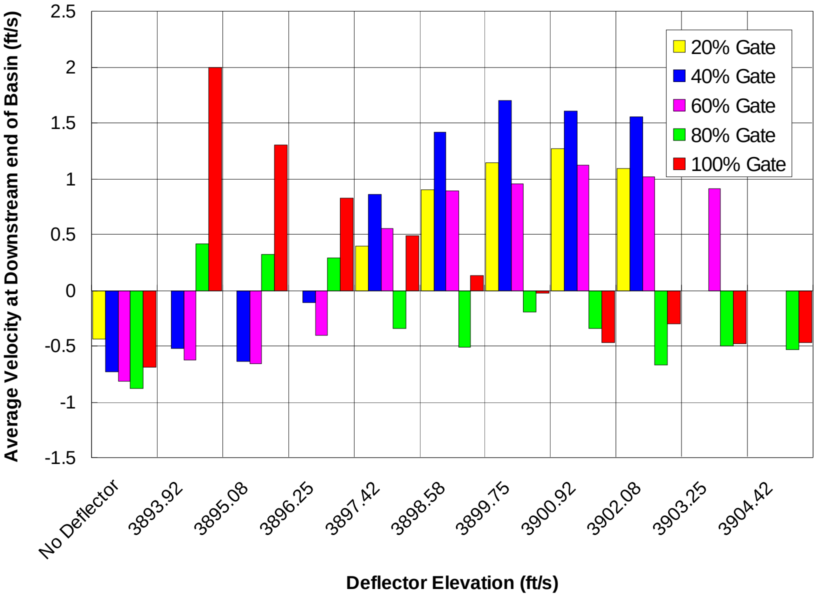

Figure 24. — Index velocity as a function of deflector elevation for the Mason Dam stilling basin model. Note that deflector elevations that are effective for 20-60% gate operations are ineffective for 80-100% gate operations, and vice versa. Basin floor elevation is 3889 ft and design tailwater depth is 20.7 ft.

Figure 25. — At lower discharge the jet rises high into the water column (left photo). As discharge is increased the aerated jet travels a longer distance along the basin floor (right photo).

Figure 25 shows index velocities measured in the Mason Dam model at the basin exit, for operations ranging from 20% to 100% gate opening, and for deflector elevations ranging from 4 ft to 15 ft above the basin floor. The figure demonstrates that when the deflector was moved to a lower elevation, performance at higher gate settings was significantly improved, but performance at lower gate settings was compromised (although still improved over the "no deflector" condition). As a result, optimal performance with a single deflector could be achieved for the full operating range of the stilling basin only with a design that allows the deflector elevation to be adjusted. This could be accomplished with a movable deflector supported on guides to allow vertical adjustments in position. However this would also require detailed velocity data to identify operations where the deflector requires adjustment for all reservoir elevations. It would also require a more complicated design to allow mobility and would require operating personnel or automation to make the necessary adjustments. As a result, in most cases, this would not be a practical solution.

Staggered Deflectors

Figure 26. — Mason Dam stilling basin staggered deflector configuration

A more practical approach to achieve effective performance over a large operating range for a type II stilling basin, is to use two stationary staggered deflectors. This option would require two separate deflectors staggered in position, both vertically and horizontally, so that flow conditions can be improved throughout the full range of operations without having to adjust deflector positioning (Figure 26). Model investigations were conducted to determine the viability of this solution. The Mason Dam model was used for initial investigations of the staggered deflector option (Figures 26 and 27). The initial test set-up consisted of keeping the original (upper) deflector in place and adding a lower deflector. The lower deflector was 3 ft in height (15% of design flow tailwater depth) and spanned the 17 ft width between stilling basin sidewalls. Since the original deflector was designed to provide optimal flow conditions for gate operations up to 60% gate opening, the lower deflector was positioned at an elevation (Y_{d2}) that would provide optimal flow conditions for gate operations above 60% gate opening.

This was accomplished by identifying the location where the downstream jet gained adequate strength or reached a velocity of 1 ft/s or greater, for operations greater than 60 % gate opening. This location was identified using analyses of dye streak data and vertical velocity profiles measured in the model at the end of the basin. Once this position was established, lateral positions were investigated to determine the best performance for gate operations up to 100% gate opening. With the final staggered deflector configuration in place, index velocities were measured for basin operations up to 100% gate opening. Figure 28 demonstrates that the staggered deflector design is effective for the full range of operations for which the basin was designed. Investigations thus far have shown that the staggered deflector design option may be the most practical solution for most type II stilling basins of standard design. However, Appendix A describes a simpli approach to deflector design that may use a single deflector to cover the full range of basin operations and has the potential to replace a staggered arrangement in the future with further studies.

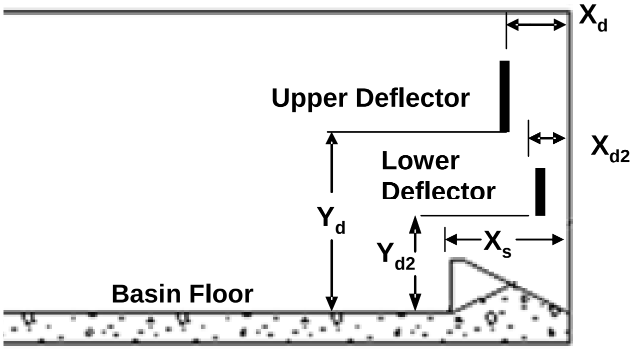

Figure 27. — Staggered deflector configuration.

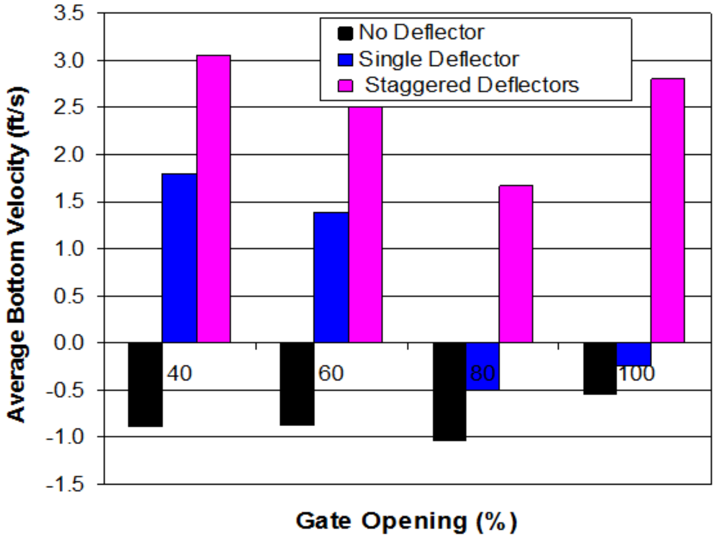

Figure 28. — Index velocities measured for final staggered deflector configuration compared with a single deflector and no deflector for the Mason Dam stilling basin model

Type III Stilling Basins

Type III stilling basins utilize mid-basin baffle blocks that stabilize the position of the hydraulic jump and the elevation of the jet at the basin exit. Figure 29 shows that the vertical velocity profiles measured at the end of a type III basin (Haystack Dam outlet works) were well defined and closely grouped throughout the full range of discharges tested, thus helping to simplify deflector design. This grouping is due to the baffle blocks, which help to lift the jet off the basin floor at a consistent distance upstream from the end of the basin for each discharge tested (Figure 30). This produces a fairly consistent profile at the end of the stilling basin, throughout its full operating range. Therefore a staggered configuration should never be required for a type III stilling basin. Performance for the final deflector design for this basin is shown in Figure 31.

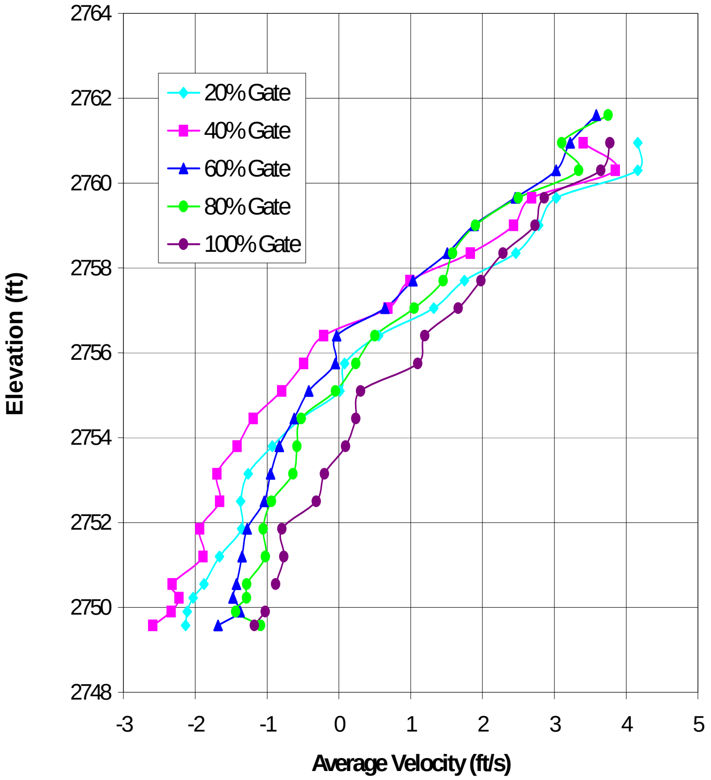

Figure 30. — Vertical velocity profiles measured for the Haystack Dam stilling basin model (no deflector).

Figure 31. — Baffle blocks help lift jet above basin floor.

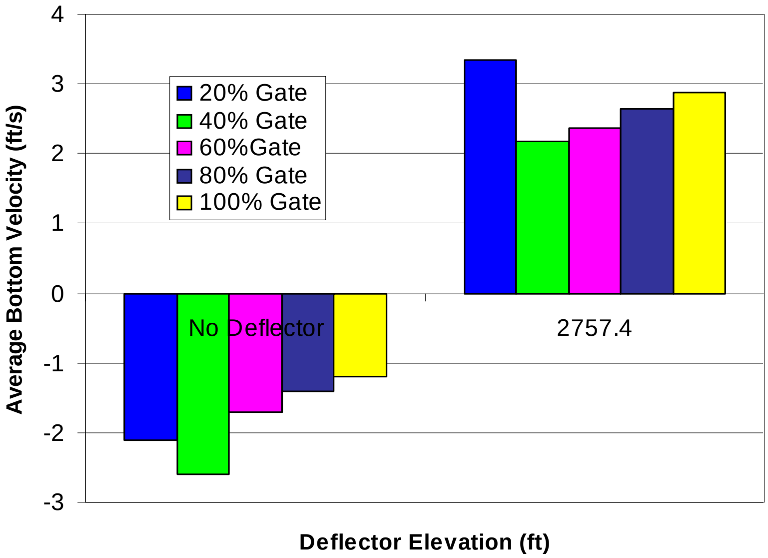

Figure 32. — Index velocities measured in the Haystack Dam stilling basin model with and without optimal deflector.

Model Study Results

Once the model studies were completed, optimal deflector size was normalized as a percentage of tailwater depth, and optimal lateral positioning was normalized based on the end-sill length (horizontal dimension, X_s) for a single or staggered configuration. Optimal deflector elevation was correlated with the velocity profiles measured at the end of the stilling basin previous to the installation of the flow deflectors. Best deflector performance for each flow condition tested was produced with the bottom of the deflector positioned just above an elevation corresponding to the bottom of the jet exiting the stilling basin where velocities transition from upstream (negative) in direction to downstream (positive) for the range of operations desired. The best lateral position for the upper and lower deflectors was at $2 X_s /3$ and $X_s /3$, respectively, upstream from the downstream end of the type II stilling basin end sill. The best lateral position for type III basin deflectors was between $2 X_s /3$ and X_s upstream from the downstream end of the stilling basin end sill. In all cases the deflector performed best when oriented at 90 degrees (vertical).

Physical Modeling Limitations

The physical modeling described in the previous sections was successful because field data was available that could be used to match prototype operations in the model. Comparisons of model and field data showed that due to Reynolds number effects in the tailrace area immediately downstream from the basin, the model had under-predicted the magnitude of the average velocities measured at the end of the stilling basin. The Reynolds number is defined as the ratio of inertial forces to viscous forces. The models were all operated initially using Froude number similarity, which maintains equal ratios of inertial and gravitational forces, the most important forces involved in free-surface flows. This necessarily means that Reynolds numbers in the model and prototype are different, causing viscous effect to be relatively over represented in the models. This significantly affects the region where the hydraulic jump transitions into the tailrace, causing more energy dissipation and leading to predictions of lower velocities exiting the basin. To offset this scale effect, model discharge was increased above the values normally calculated from Froude scale similitude to accurately match velocity profiles in the prototype [8]. In addition, air entrained in the model is not as substantial as it is in the prototype (this is another common “scale effect” that becomes more significant at smaller model scales). Therefore, the effect of air entrainment on the rising jet exiting the basin is not predicted as accurately in the model. This scale effect also causes under prediction of the air bulking in the basin, which affects measured water surface profiles in the model. This is why it was important to use field data to get an accurate representation of flow conditions and to achieve accurate placement of the deflectors.

Field Evaluation Methods

The first prototype deflectors were installed at Mason Dam in October 2002 (Figure 33) and at Choke Canyon Dam in 2006 (Figure 34). Field evaluations were conducted on-site for both basins to evaluate the performance of the deflectors and verify the models [1].

Figure 33. — Installation of first prototype deflector at Mason Dam in Oct 2002

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Figure 34. — Installation of Choke Canyon stilling basin deflectors in December 2006.

Velocity Measurements before Installation of Flow Deflectors

Vertical velocity profiles were measured at the basin exit with an ADP (Acoustic Doppler Profiler) probe at each site before the deflectors were installed. In each case a dive team was used to assist in mounting the ADP probe at the end of the basin because the probe must be installed near the bottom of the basin on the downstream face of the basin end sill and directed upward (Figure 34), since air near the water surface can interfere with data acquisition. Figures 35 and 36 show velocity profiles measured at the end of the stilling basin for the Mason Dam and Choke Canyon Dam basins respectively. However, average velocities measured in the upper portion of the water column were not accurately represented since they were measured in a zone of high air concentration. This problem will always occur during field testing with an ADP probe since the upper portion of the water column of a hydraulic jump is highly aerated. Although this can complicate the ability to identify the location where downstream velocities exceed 1.0 ft/s it can also serve as a reasonably good indicator of the elevation where the fully aerated, concentrated jet is located at the end of the basin. This can be done by identifying the break-point in the data where erroneous data begins (due to high air concentrations), thus identifying the location for positioning the bottom edge of the deflector.

Mason Dam stilling basin was not operated above 60% gate during field tests due to SOP limits on operations. For the Choke Canyon basin, velocity measurements were not possible for operations above 50% gate opening because the jet remained near the basin floor as it exited the basin and the water column was full of entrained in air. In this case, this was not an issue since deflector design was based only on operations up to 40 % gate opening at maximum reservoir.

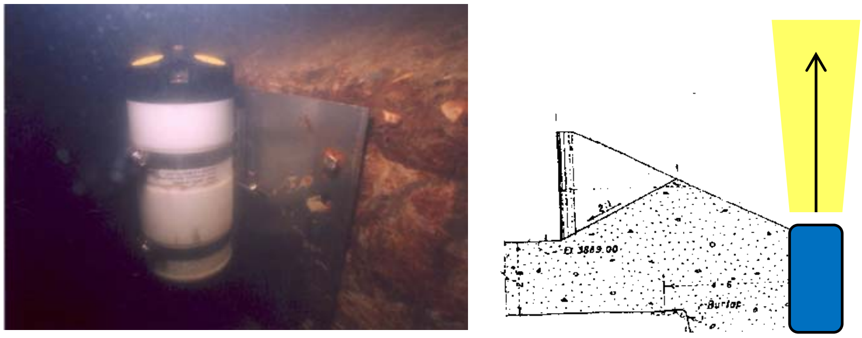

Figure 35. — ADP probe is mounted on upstream face of basin end sill and directed upward to measure velocities in the water column from bottom to top.

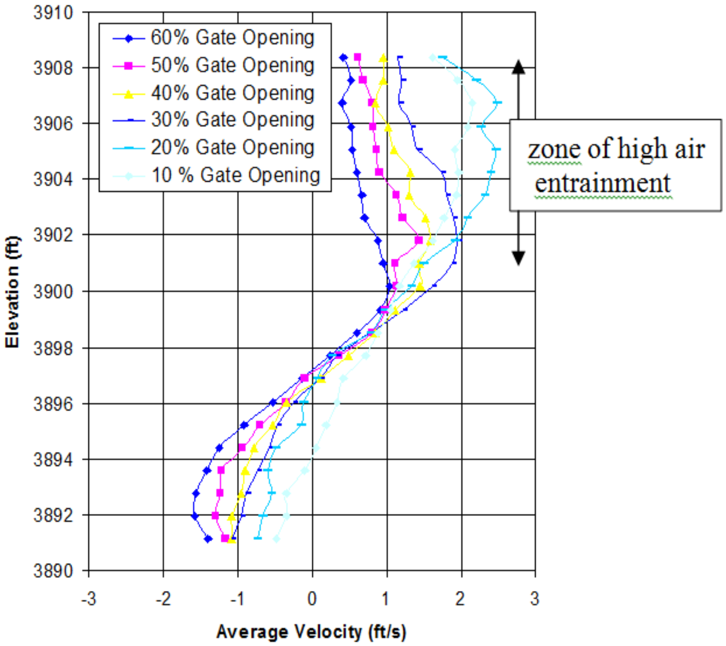

Figure 36. — Vertical velocity profiles measured at Mason Dam stilling basin with no deflector. Basin floor elevation is 3889 ft.

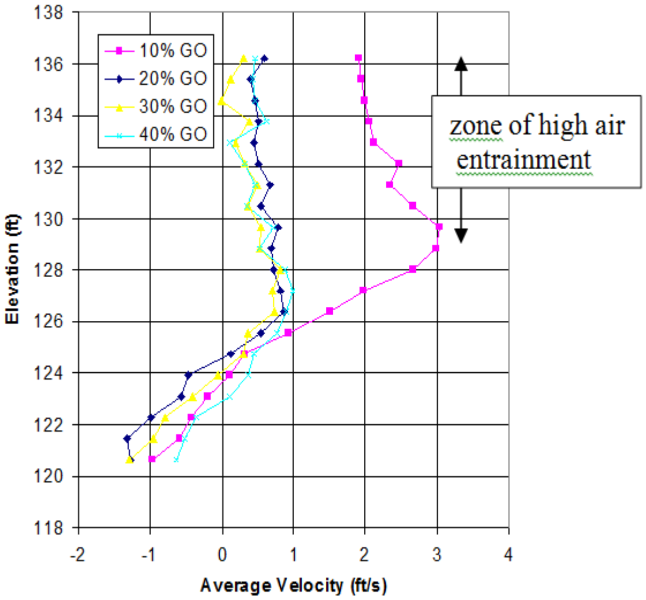

Figure 37. — Average velocities measured at the end of the Choke Canyon stilling basin as a function of elevation (no deflector) Basin floor elevation is 116.8 ft.

Velocity Measurements after Installation of Flow Deflectors

Field measurements were conducted after flow deflectors were installed in optimal position to verify performance for the Mason Dam and Choke Canyon Dam deflectors.

An ADP probe was used once again for field testing at Mason Dam. However, for the higher prototype gate settings, no reliable velocity measurements were obtained due to the inability of the ADP probe to accurately measure velocities when large quantities of air are entrained in the flow. The deflector was designed to redirect the concentrated jet exiting the basin down toward the basin end sill. Therefore, at high discharges, when the jet is highly aerated, entrained air was also redirected downward towards the end sill where the ADP probe was located. As a result, accurate velocity measurements were not possible at the higher discharges.

However velocities that were measured near the bottom of the basin correlated well with the model and are shown in Figure 37.

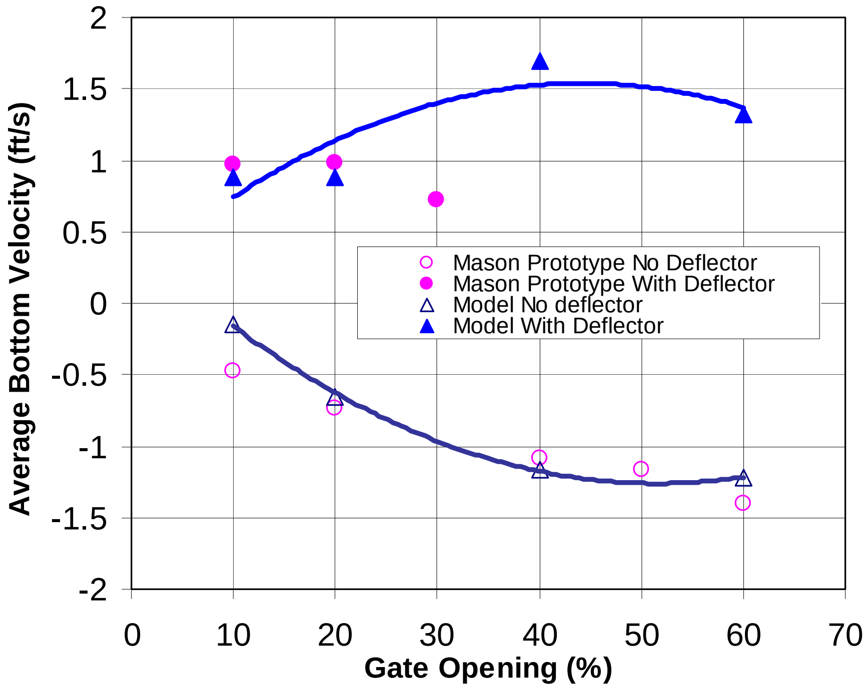

Figure 38. — Comparison of average prototype exit velocities measured in the model and in the prototype with and without a deflector

For the Choke Canyon deflector field tests, an ADV (Acoustic Doppler Velocimeter) probe was used to measure velocities near the bottom of the basin (Figure 38). This probe measured velocities only at a single point so it was not as sensitive as the ADP probe to high concentrations of air. Therefore velocity measurements were possible over a greater range of flow rates. Figure 39 shows velocities measured near the bottom before and after the deflectors were installed.

Field testing conducted at Mason and Choke Canyon Dams verified deflector performance should be effective in preventing materials from being carried into the basin by upstream currents.

Figure 39. — ADV probe.

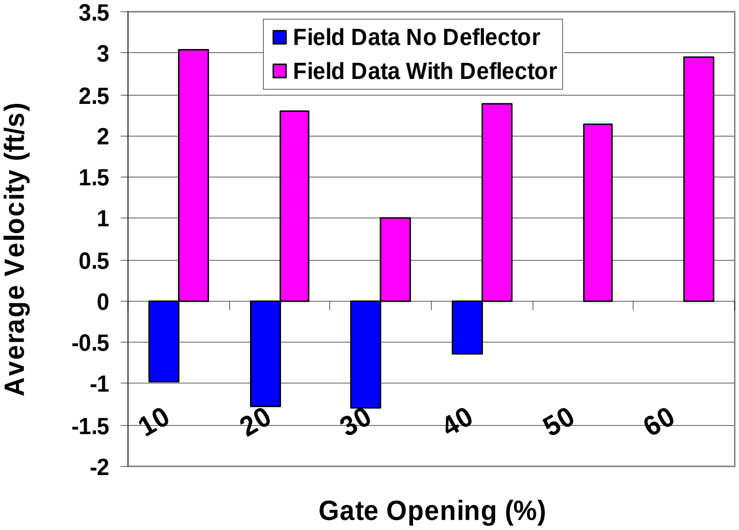

Figure 40. — Field data (index velocities) collected at Choke Canyon Dam in February 2007 with deflectors, compared with field data collected in June 2004 before the deflectors were installed. (Positive values indicate flow is in the downstream direction away from the stilling basin.

Deflector Loading

Piezometer taps installed on the upstream and downstream faces of the model deflectors were used to measure differential static hydraulic loading for flow rates up to the maximum discharge at 100% gate opening for each deflector. The maximum loads predicted for the Mason Dam prototype deflector were 6,000 lbs (0.5 lb/in^2) and12,600 lbs (1.0 lb/in^2) for 60% and 100% gate openings, respectively. The maximum differential load predicted for the Choke Canyon Dam flow deflector was about 13,500 lb (1.9 lb/in^2) at 100% gate opening, and the maximum differential load predicted for the Haystack Dam flow deflector was about 12,800 lb (1.9 lb/in^2) at 100% gate opening.

In addition to measuring average deflector hydraulic loading in the model study, loading on the Mason Dam deflector was calculated based on the momentum equation and head drop observed across the deflector, to determine how closely it matched with experimental results; thus:

$\sum F_x = \rho Q(V_1 - V_2) + P_1 - P_2$

where:

F_x = the total force on the deflector in the direction of flow

V_1 = average velocity impacting deflector upstream face

V_2 = average velocity impacting deflector downstream face

$Q = V_1 A$

$P_1 - P_2 = \gamma A (h_1 - h_2)$ = differential pressure due to the head drop across the deflector

ρ = density of water = 1.94 slugs/ft^3

γ = specific weight of water = 62.4 lb/ft^3

A = area of the upstream face of the deflector = 85 ft^2

Taking a conservative approach, V_2 is assumed to be zero, $(h_1 - h_2)$ is assumed to be about 1 ft, and V_1 = 7 ft/s based on the exiting jet occupying a depth equal to about 30 % of tailwater depth at maximum flow.

So $F_x = \rho A V_1^2 + \gamma A (h_1 - h_2)$

F_x = 8100 lb + 5300 lb = 13,400 lb

This value is about 6 percent higher than the load measured in the Mason model, and given the assumptions that were made, provides a reasonable method for calculating static deflector loading for future deflector installations. However, a factor of safety should be added to this value for design purposes.

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3. Research and Development Office Bulletin. "Flow Deflector Benefits from Water Cost Savings and Water Reliability Improvements", Bureau of Reclamation, December 26, 2007.

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Appendix A – Simplified Deflector Design

A limited study was conducted in the Denver lab in an effort to eliminate the field evaluation requirement in the deflector design process. This study focused on using "oversized" deflectors that required less precision for placement, to accomplish the same goal of redirecting flow currents for mitigation of abrasion damage. A Reclamation type II basin of standard design, modeled on a 1:8.5 scale, was used for the study. In addition, data collected from the previous study of the Mason Dam staggered deflector configuration was used to facilitate with determining design criteria for the oversized deflector design.

It is important to be aware that the recommendations presented here were based on analyses of data from only two studies of basins of similar design, and no field testing has been conducted, so designers should use caution in applying these results. Also note that head drop across the oversized deflectors is considerably higher than with the previous designs, so this must be taken into account when determining loading on the flow deflectors and structure. This also means that implementation of the oversized deflector design will reduce freeboard that is available at maximum discharge, so overtopping the basin sidewalls may be an issue. In addition, it may not be advisable to use the oversized design if there is a ceiling over the stilling basin structure since negative or fluctuating pressures can be substantial between the turbulent water surface and the top of an enclosed structure.

A description of the study used to develop the oversized deflector design guidance is included in subsequent sections of this report. Further investigations may be desired to provide increased confidence and refinement of the design.

With these considerations in mind, the following is a list of "lessons learned" and a starting point for the design of the oversized deflectors:

1) Either two staggered deflectors or a single larger deflector can be used, positioned vertically, spanning the full width of the stilling basin between the sidewalls.
2) If a staggered configuration is used, the parameters are defined as follows (Figure A - 1):
    a. Each deflector should have a height equal to 1/3 of the tailwater depth at design flow (future investigations may show that this size can be reduced). The two deflectors should be positioned laterally (referenced to the upstream face) as follows:

        i. Upper: Measuring upstream from the downstream end of the basin end sill, the location is 2/3 of the horizontal dimension of the basin end sill or 2/3 X_s, Figure A – 1.
        ii. Lower: The lateral position for the second deflector is midway between the upper deflector and the downstream end of the basin end sill or 1/3 X_s, Figure A – 1.
    b. Vertical positioning (h_a) for the deflectors are as follows:
        i. The bottom edge of the lower deflector should be positioned at an elevation equal to 25% of the tailwater depth at design flow.
        ii. The upper deflector should have a 0.5 ft overlap in elevation with the top of the lower deflector.

3) If a single deflector is used,
    a. The total height for the deflector should be 2/3 of the tailwater depth at design flow (future investigations may show that this size may be reduced).
    b. The lateral position for the deflector should be at the 1/3 X_s positioned as shown in Figure A - 2.
    c. Vertical positioning (h_a) for the single deflector should be with bottom edge of the deflector positioned at an elevation equal to 30% of tailwater depth at design flow.

A single larger oversized deflector produced about 0.5 feet greater head drop across the deflector than with two staggered oversized deflectors for the design flow of the basin. The total head drop at design flow was 3.5 ft and 4.0 ft respectively for the staggered and single configurations. These values are significantly greater than the head drop (less than 1 ft) that occurs for the smaller deflectors described in Section I of this report.

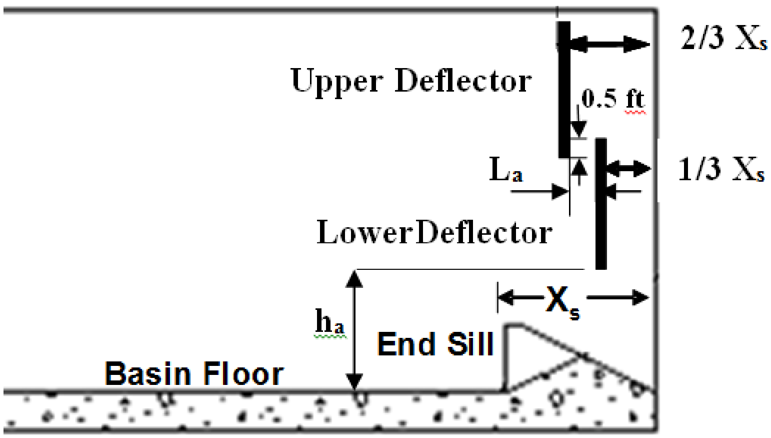

Figure A-1. — Section view showing optimal lateral locations for oversized staggered deflectors for a Type II stilling basin.

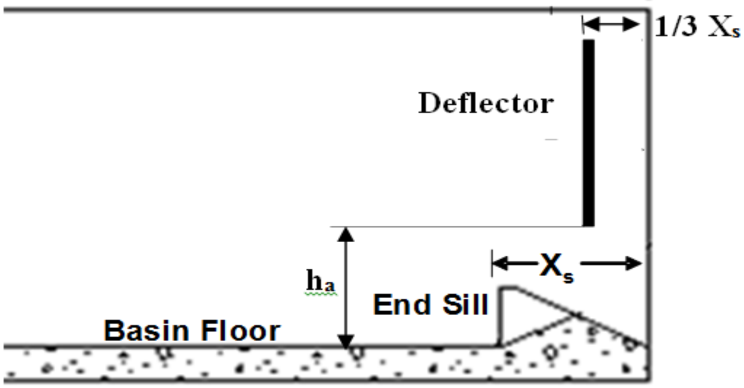

Figure A-2. — Section view showing optimal Lateral locations for an oversized single deflector for a Type II stilling basin.

The guidelines given above were based on results from a limited study (described in the next section), so further research may be necessary to refine these guidelines and to determine if the size of the deflectors can be reduced so that head drop across the deflectors can also be reduced.

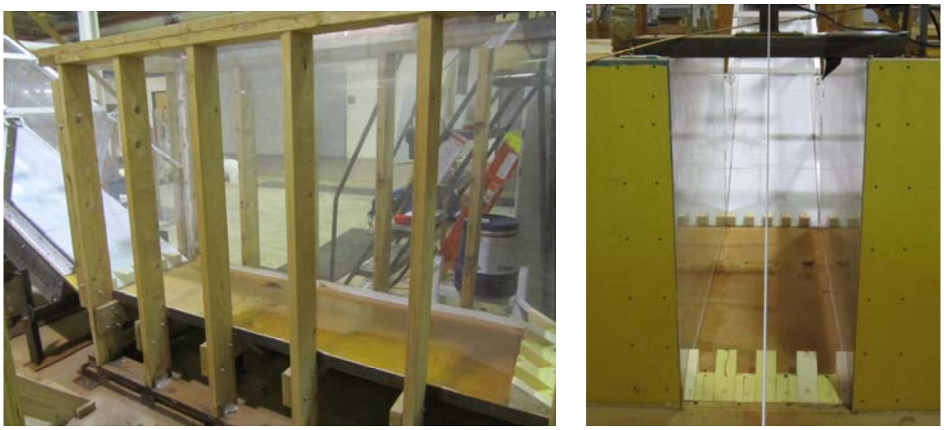
a) **b)**

Figure A-3. — Model of type II stilling basin a) looking through Plexiglas sidewall and b) looking upstream from the downstream end.

Oversized Flow Deflectors – Modeling

An existing model was modified to represent a Reclamation type II stilling basin of standard design (Figure A-3). The basin was modeled on a 1:8.5 geometric scale. Engineering Monograph No. 25 was used to define the parameters for the design of the basin.

Similitude between the model and the prototype is achieved when the ratio of the major forces controlling the physical processes are the same. Since gravitational and inertial forces dominate open channel flow, Froude scale similitude was used to establish a kinematic relationship between the model and the prototype. The Froude number, which represents the ratio of inertial to gravitational forces, is

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where *v* = velocity, *g* = gravitational acceleration, and *d* = flow depth. When equal Froude numbers are maintained in the model and prototype, specific scaling relationships exist between the model and prototype values of key flow parameters. In the equations that follow, the *r* subscript refers to the ratio of the prototype and model values:

Length ratio: $L_r = L_m/L_p = 8.5$

Discharge ratio: $Q_r = L_r^{5/2} = (8.5)^{5/2} = 210.64$

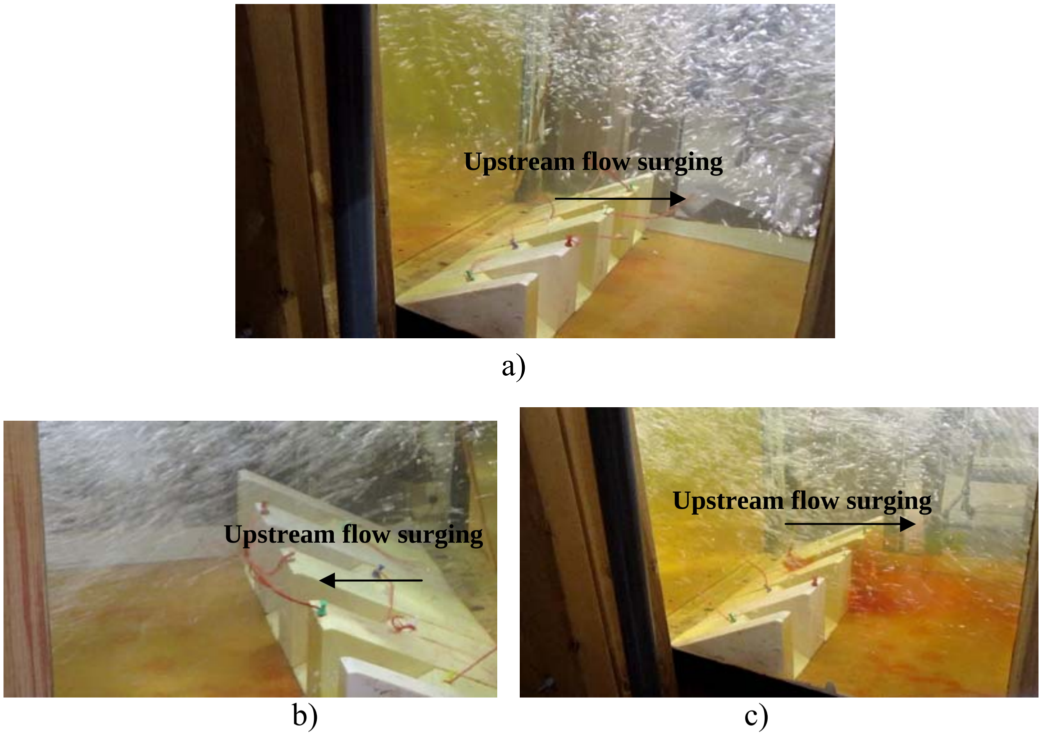
In terms of the prototype, the basin was 17 feet wide with a design flow of 956 ft^3/s. Calculated tailwater depth for conjugate depth at design flow was about 21 ft. (All dimensions/values described here will be in terms of the prototype. Conjugate depth is the depth theoretically needed to cause a hydraulic jump to occur in the basin, given a specific set of inflow conditions.) Due to limited time and funding, the performance of the deflectors in all test cases was evaluated using visual observations of dye streaks and strings attached to the basin end sill to indicate flow direction. Previous investigations showed that visual methods proved to be good indicators of performance.

Tests were conducted at flow rates of 956 ft^3/s, 746 ft^3/s, 569 ft^3/s, 396 ft^3/s and 200 ft^3/s. Tests were first conducted without any deflectors installed, and observations of overall flow direction or surging currents near the basin end sill are indicated in Table 1. At design flow, the jet exiting the basin remains low over the end sill, preventing upstream currents near the bottom (Figure A-4). At the lowest flow tested, 200 ft^3/s, flow currents were too weak to move the strings attached to the basin end sill. For all other flows tested, flow currents often surged in the upstream direction, indicating the strong potential to carry materials into the stilling basin (Figure A-5).

Table A-1. — Observations of upstream flow current for discharges tested in the model.

Flow Rate (ft^3/s)	Significant upstream currents or surging near basin end sill (yes/no)
956	No, jet sweeps downstream near end sill
746	yes
569	yes
396	yes
200	No, flow current is too weak to move strings in either direction.

Figure A-4. — At design flow (956 ft^3/s) the jet typically stays low and near the bottom, preventing upstream currents from carrying materials into the stilling basin.



a)

b) c)

Figure A-5. — Strings and dye indicate currents surging upstream over the basin end sill with potential to carry materials into the stilling basin at flow rates a) 396 ft^3/s, b) 746 ft^3/s, and c) 569 ft^3/s.

Based on a review of previous data and analyses from investigations with a staggered deflector configuration, two staggered deflectors each with a vertical dimension equal to 1/3 of the conjugate tailwater depth (7 ft) were selected for the first series of tests [1]. The deflectors were positioned laterally as described in Section I of this report (1/3 X_s and 2/3 X_s, Figure A-1). The bottom deflector was tested with its bottom edge at elevations of 5.1 ft and 6.2 ft above the stilling basin floor. The lower deflector was positioned with a vertical overlap in elevation of 0.5 ft for each case (Figure A-6).

Figure A-6. — Oversized staggered deflector configuration tested in model.

The next round of testing used a single deflector with a vertical dimension equal to 2/3 of the conjugate tailwater depth or 14 ft (Figure A-7). The single deflector was positioned laterally at 1/3 $X_{S.}$ The single deflector was tested with the bottom edge positioned 5.1 ft and 6.2 ft above the basin floor.

Figure A-7 — Single oversized deflector installed in model.

All tests with the staggered and single oversized deflectors produced good performance for preventing bottom currents from surging upstream into the stilling basin (as observed with dye streaks and strings attached to the basin end sill), therefore any of these configurations should perform well to prevent materials from being carried into the basin (Figure A-8 through A10). However, at the full design flow vortex structures developed in the corners of the basin upstream from the deflector, for all deflector configurations tested. In most cases it appeared that the vortices extend downstream beneath the deflectors without impacting any part of the basin end sill or structure. However, turbulence and vortex action appeared to be more pronounced for a single deflector positioned with the bottom edge located 5.1 ft above the basin floor Figure (A-11). This suggested that a lower limit for the elevation of the bottom edge of the deflector should be defined based on minimizing vortex action.

Next, the bottom elevations tested were defined in terms of percentage of tailwater depth at design flow (TW_d). This percentage came to about 24% and 30% respectively for bottom elevations 5.1 ft and 6.2 ft above the basin floor. Observations of flow conditions and initiation of vortex action was used as the basis for setting the lower limits for the bottom edge of the deflectors. These observations suggested that for two staggered deflectors, a value of 25% could be used for the lower limit for the bottom edge of the lower deflector and that a value 30% could be used as the lower limit for a single deflector. However, as stated previously, further investigations may be desired to refine this criterion.

Head drop across the deflectors was measured for each configuration at the design flow rate. For the staggered configuration the head drop was about 3.5 ft for both bottom edge elevations tested (figure A-12). For the single deflector the head drop was about 4 ft for both bottom edge elevations tested (figure A-13). The head drop values for the oversized deflector designs were considerably higher than the values measured across the deflectors described in Section I of this report (less than 1 ft), which were designed on the basis of velocity profile measurements over the end sill. This means that the designer will need to account for this additional loading as well as ensure there is adequate freeboard available to accommodate the higher water surface elevation that occurs with the oversized deflector design.

Figure A-8. — Staggered deflector configuration at 396 ft^3/s, with lowest deflector bottom edge located 6.2 ft. above basin floor.

Figure A-9. — Staggered deflector configuration at design flow (956 ft^3/s) with lowest deflector bottom edge located 6.2 ft above basin floor.

Figure A-10. — Single deflector at 746 ft^3/s with deflector bottom edge located 5.1 ft above basin floor. Bottom velocities appear to be below the threshold where significant vortex development occurs.

Figure A-10. — Single deflector at design flow (956 ft^3/s) with deflector bottom edge located 5.1 ft above basin floor.

Figure A-112. — Flow over the top of a single deflector at design flow (956 ft^3/s), with deflector bottom lip located 6.2 ft above basin floor.

Figure A-123. — Flow over the top of staggered deflectors at design flow (956 ft^3/s) with the lowest deflector bottom edge located 6.2 ft above basin floor.