Flow Deflectors for Preventing Stilling Basin Abrasion Damage

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Abstract

Research sponsored by the U.S. Bureau of Reclamation's (Reclamation) Science and Technology Program and conducted by the Water Resources Research Laboratory in Denver has demonstrated that flow deflectors can be used to mitigate abrasion damage commonly experienced by Reclamation Type II stilling basins and other standard basins of similar design. This will increase the life of the basins and reduce or eliminate the need for costly repairs.

Introduction

Stilling basin abrasion damage is a widespread problem for river outlet works at dam sites throughout the United States. Abrasion damage occurs when materials, such as sand, gravel, or rock, are carried into the basin by a recirculating flow pattern 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 abrasion damage has occurred to the extent that reinforcing bars are exposed; then when repairs are made many basins experience the same damage again within one or two operating seasons. Research conducted by Reclamation's Water Resources Research Laboratory (WRRL) in Denver has demonstrated that the installation of flow deflectors can improve flow distribution, thus minimizing or eliminating the potential for materials to be carried into stilling basins (figure 2). This can increase the life of the basins and reduce necessary repairs.

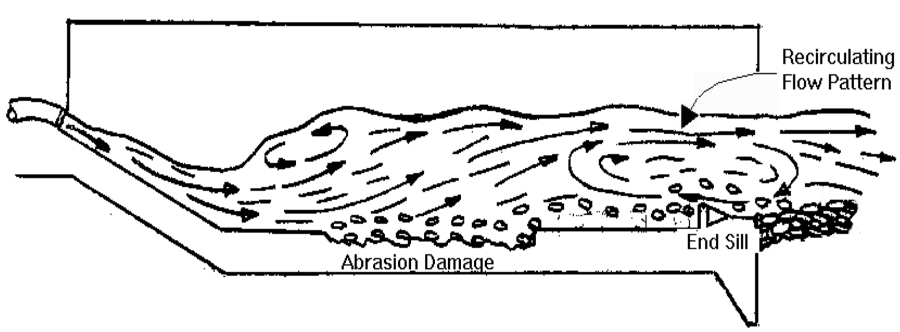

Figure 1. Recirculating flow pattern occurs during normal operation of hydraulic jump energy dissipation basin.

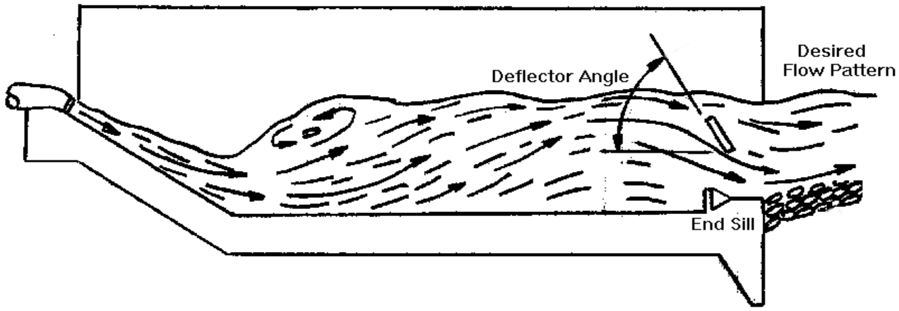

Figure 2. Desired flow pattern with flow deflector installed.

The Mason Dam outlet works stilling basin, a typical Reclamation Type II basin with a long history of abrasion damage, was determined to be an excellent candidate for a field demonstration of this technology. Mason Dam is located on the Powder River in Baker County, Oregon, approximately 17 miles southwest of the city of Baker. The dam was constructed for irrigation, and for maintaining minimum flow in the Powder River. The dam is a 173 ft high zoned earthfill embankment with a crest length of 895 ft. Reclamation owns Mason Dam; however, the Baker Valley Irrigation District (BVID) operates and maintains the facility under contract with Reclamation.

A physical model, constructed in the WRRL, was used to design a flow deflector for the basin, and a field evaluation was conducted at the prototype facility to verify the effectiveness of the design and to develop information for widespread application (a patent is pending on this technology).

The Model

A 1:7 geometric scale was used to model the Mason Dam outlet works stilling basin. Froude scale similitude was used to establish the kinematic relationship between model and prototype because hydraulic performance depends predominantly on gravitational and inertial forces. Froude scale similitude produces the following relationships between the model and the prototype:

Length ratio $L_r = 1:7$

Velocity ratio $V_r = L_r^{1/2} = 1:2.65$

Discharge ratio $Q_r = L_r^{5/2} = 1:130$

The physical model was used to investigate hydraulic conditions in the Mason Dam stilling basin and to study the effect of deflector angle and position on flow patterns over the basin end sill (figures 3 and 4).

Prototype features modeled included:

1) The two 33-in by 33-in high pressure regulating gates and upstream bifurcation.

2) The 17 ft wide hydraulic jump twin bay stilling basin with 2:1 sloping chutes, and dentated end sill.

3) Approximately 75 ft of topography downstream from the basin, constructed on a 5:1 slope with moveable bed material.

Figure 3. Looking upstream at stilling basin model with ADV probe and deflector installed near end of basin.

Velocities were measured with a SonTek acoustic doppler velocimeter (ADV) probe and were measured at the downstream end of the basin at its centerline. Tailwater elevation was set for each flow condition tested, using tailwater data obtained during Mason Dam outlet works operations. The deflector was modeled with a flat section of sheet metal spanning the 17 ft wide basin and mounted on guides attached to the basin sidewalls, to allow vertical movement of the deflector within the basin.

Model Study Investigations

Model investigations were conducted to evaluate hydraulic conditions in the stilling basin and downstream apron area for the range of operating conditions expected in the prototype. The actual flow conditions tested are listed in Table 1. Velocity data and dye streak data were collected and analyzed to define basin performance. This data was used to determine the most effective deflector angle and the best lateral and vertical locations within the basin. Although investigations were conducted up to the maximum possible discharge of 870 ft^3/s (100% gate opening at maximum reservoir), the optimum deflector design was

Figure 4 Looking through the plexiglass sidewall of the model operating at 40% gate opening.

based only on discharges up to 575 ft^3/s (60% gate opening at maximum reservoir). This is because Mason Dam's standing operating procedures (SOP) limit outlet works discharges to the maximum downstream river channel capacity of 500 ft^3/s.

Velocities were measured at numerous locations within and downstream from the stilling basin to map out resulting hydraulic flow patterns for each discharge tested. Early investigations showed that average velocities measured at the end of the basin, at its centerline, and 5.25 inches above the invert elevation provide a good representation of the bottom velocities that carry materials into the basin (all dimensions and measurements reported here are scaled to prototype dimensions). As a result, this location was used for determining deflector performance. Average bottom velocities measured at this location without a deflector ranged from -0.4 ft/s to -0.8 ft/s, with maximum upstream velocities in the range of -2.0 ft/s to -3.0 ft/s (Negative velocities indicate flow is upstream into the basin).

Table 1. Prototype flow conditions tested in model.

Gate Opening (%)	Prototype Discharge Corresponding to Maximum Reservoir Elevation (ft^3/s)	Tailwater Depth (ft)
20	230	18.2
40	420	18.8
60	575	19.5
80	735	20.0
100	870	20.7

Model Study Results

Optimal Positioning and Size

Tests were initially conducted at 40 and 60 percent gate openings only, since these conditions produced the strongest upstream bottom velocities adjacent to the riprap apron, within the maximum operating range specified by the Mason Dam SOP. Four different parameters were investigated to determine what criteria would produce best performance (all parameters are referenced from the bottom downstream edge of the deflector):

- Vertical Elevation - Deflector elevation was varied from 4 ft to 15 ft above the elevation of the basin floor (elevation 3889 ft).

- Lateral location - This is the distance from the downstream end of the stilling basin (defined as the downstream end of the basin sidewalls) to the deflector. Lateral locations were varied from 0 ft to 14 ft.

- Angle - Deflector angle was varied from 40 degrees to 90 degrees referenced from the horizontal plane as shown in figure 2.

- Size - The height of the deflector was tested at 3 ft, 4 ft, and 5 ft.

The best performance, as determined by average bottom velocities measured at the downstream end of the basin, occurred with a 5 ft deflector mounted 5 ft upstream from the end of the basin at elevation 3900 ft (11 ft above basin floor), and angled at 90 degrees.

Overall Performance
After the optimal design parameters were set, it was important to look at deflector performance with the basin operating throughout the full range of possible discharges up to the maximum flow at 100% gate opening, in case unusual circumstances should require releases above those normally allowed while the deflector is place. Table 2 shows the average bottom velocities measured without a deflector compared with those measured with the deflector set into optimal position.

Table 2. Basin performance with and without deflector.

	Average prototype velocity measured in model at end of basin with and without Deflector (ft/s)	
Gate Opening (%)	No Deflector	Optimal Deflector at 3900 ft and angled at 90 degrees
20	-0.44	1.3
40	-0.73	1.8
60	-0.82	1.4
80	-0.88	-0.5
100	-0.69	-0.2

The table shows that with the deflector in place, performance at gate openings ranging from 20% to 60% is very good. Average velocities for this range of discharges are greater than 1.0 ft/s and are in the downstream direction. For gate openings of 80% and 100%, performance is reduced significantly, however, performance is still improved over having no deflector. Therefore, the deflector design was determined acceptable over the full range of possible discharges.

In addition, if it were desired to obtain optimal performance throughout the full range of possible operations, figure 5 shows that performance at higher discharges can be significantly improved by moving the deflector to a lower elevation. This could be accomplished with a mobile deflector supported on guides to allow a range of vertical positions for operations at high and low discharges.

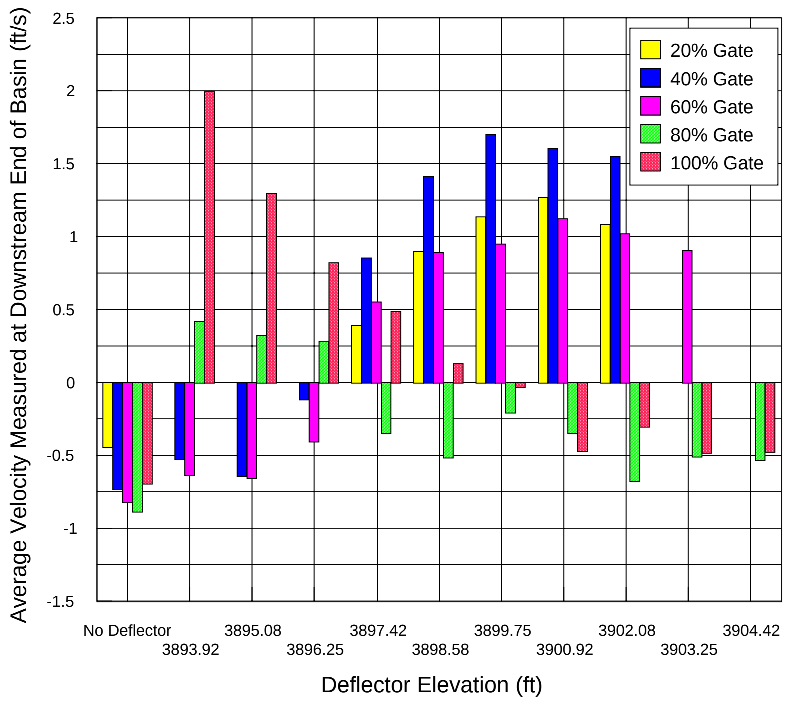

Figure 5. Average prototype bottom velocity measured in the model vs. deflector elevation for each gate opening tested with deflector angled at 80 degrees.

Hydraulically Self-Cleaning Operations

Model investigations showed that without a deflector, materials can be flushed from the basin throughout the range of operations tested, due to the nature of the flow occurring within the basin. This phenomenon occurs because turbulence within the basin periodically tosses materials high enough into the water column to be caught and subsequently carried out by the main jet exiting the basin. However, these suspended materials often hit their fall velocity as they are exiting the basin and are deposited back onto the basin end sill; thereby making them vulnerable to being carried right back into the basin by the upstream current. As a result, for a large range of discharges, although materials are flushed out, the inflow of materials is constant, thereby producing significant abrasion damage.

With the optimal deflector design in place, the model demonstrated that materials continue to be flushed from the basin throughout the range of discharges tested. However, the upstream component of velocity at the end of the basin is no longer strong enough to carry a significant amount of material back into the basin. Therefore, the source for abrasion damage can be eliminated during operations up to the maximum allowable discharge, and the basin becomes hydraulically self-cleaning. The range of sizes of materials that can be flushed from the basin will depend on outlet works operations and will be determined more precisely in future studies.

Field Evaluation

The final prototype deflector for Mason Dam was designed with a set of guides that would allow the deflector to be manually adjusted in angle and elevation for testing purposes. The contract for the fabrication of the flow deflector was awarded to Prime Machine Inc. for $27,000 including delivery to the site. In October of 2002 the flow deflector was delivered to Mason Dam and installed by the Baker Valley Irrigation District (figure 6). In addition, basin abrasion damage was repaired with new concrete at the time the flow deflector was installed. The deflector was set to optimal position as determined from the model study before seasonal operations began in April of 2003.

Figure 6. Deflector installation at Mason Dam outlet works stilling basin in October 2002.

In August 2003, after nearly 5 months of basin operations with the deflector in place, a field evaluation and dive inspection were conducted to verify the effectiveness of the deflector. Divers conducting the initial underwater inspection noted that the new concrete was very smooth and in excellent condition, with no signs of any erosion or wear. Although it may be a little early to make any conclusive statements, abrasion damage is usually evident within one to two operating seasons after repairs have been made.

In addition, divers installed an Acoustic Doppler Profiler (ADP) probe at the downstream end of the basin to measure exit velocities. The deflector was raised above the water surface and basin exit velocities were measured at each 10% increment for outlet works operations ranging from 10% gate opening up to 60% gate opening. Then the same measurements were repeated with the deflector lowered to optimal position, with bottom elevation at 3900 ft and angled at 90 degrees.

Table 3 shows the discharge tested at Mason Dam compared with the discharge tested in the model for the same gate opening. The difference in values is because the model study discharge was based on maximum reservoir elevation, and the reservoir was about 70 ft below that level at the time tests were conducted at Mason Dam.

Table 3. Prototype discharges tested in the Model and at Mason Dam.

Gate Opening (%)	Prototype Discharge tested in Model - Corresponding to Maximum Reservoir (Elevation 4075 ft) (ft^3/s)	Prototype Discharge tested at Mason Dam at Low Reservoir (Elevation 4005 ft) (ft^3/s)
10	N/A	85
20	230	163
30	N/A	250
40	420	330
50	N/A	400
60	575	500

Figure 7 shows the average prototype velocities exiting the basin, measured at elevation 3891 ft (2 ft above the basin floor elevation) for each gate opening tested, with and without a deflector. The figure shows significant improvement in the flow conditions at the downstream end of the basin with the deflector lowered into optimal position for gate operations from 10% to 30% gate opening. Average prototype velocities are greater than 0.75 ft/s and have changed from upstream in direction to downstream with the deflector in place. However, for gate operations ranging from 40% to 60% gate opening, prototype velocities measured were inconclusive due to limitations 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 main 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 endsill where the ADP probe was located. As a result, accurate velocity measurements were not possible at the higher discharges.

Figure 8 compares model and prototype average exit velocities, measured at elevation 3891 ft for each gate opening tested, with and without a deflector. The ADV probe used in the model study was not as sensitive to air concentration, therefore, velocity measurements were possible for all configurations tested. Although model and prototype discharges are not identical (due to low reservoir elevation during prototype testing) figure 8 shows a strong correlation between model and prototype velocities measured at the same location for the same gate openings. Therefore, it would be reasonable to assume, with the field verified data already acquired, that the velocities measured in the model for gate openings ranging from 40% to 60% (with the deflector in place) are also a reasonable representation of prototype flow conditions.

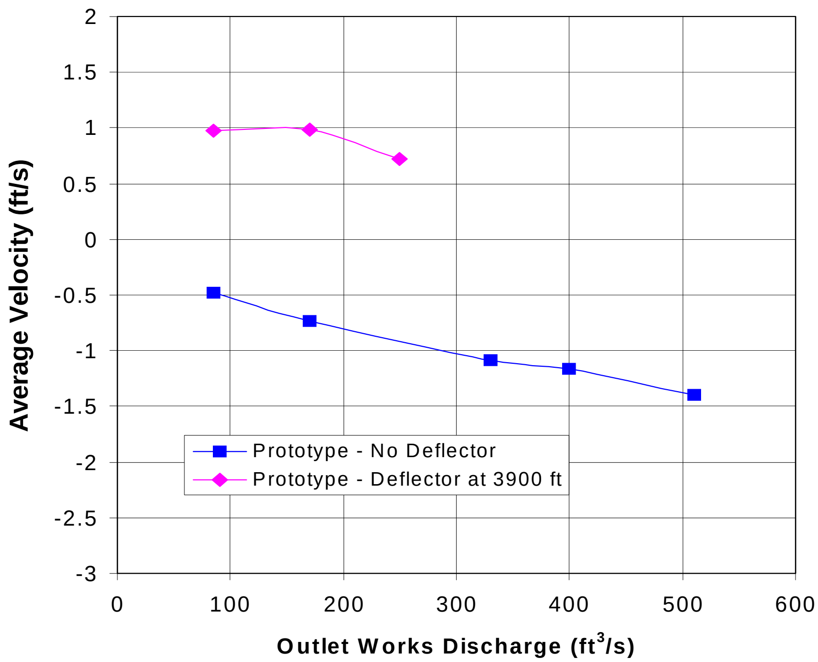

Figure 7. Average prototype velocity measured at downstream end of stilling basin at Mason Dam at an elevation 2 ft above the basin floor, with and without deflector.

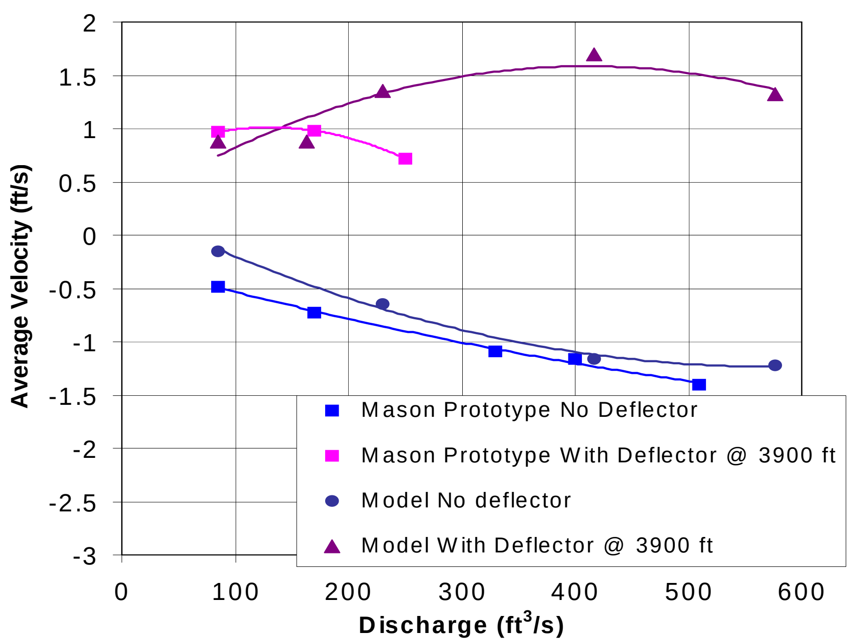

Figure 8 Average prototype velocities measured in the model and the prototype at downstream end of stilling basin at an elevation 2 ft above the basin floor, with and without deflector. Revised model data included.

A second field evaluation and dive inspection are scheduled for the Mason Dam outlet works stilling basin for August 2004. At that time, an ADV probe will be used (in addition to the ADP probe) to measure velocities at the end of the basin to further verify model data and to conduct additional testing.

Generalizing Deflector Design for Widespread Applications

The model investigations and field evaluation were used to develop a method for generalizing deflector design for Reclamation Type II and similar basins, based on velocity profiles measured at the end of the basin before a deflector is installed. For future installations, velocity data measured on-site can be used to determine the optimal design and location for a deflector for a specific basin.

At facilities where the outlet works is operated up to its full capacity of 100 percent gate opening, two different options can be considered:

- One option is to design the deflector to be effective for the most predominant range of basin operations. This would mean that when the basin was operated outside the deflector design range, some materials may be drawn into the basin. In this case, it would be recommended that the basin be operated within the designated design range periodically, to purge materials from the basin.

- A second option would be to design a moveable deflector supported on guides so that deflector elevation could be changed for different ranges of operations. In most cases this would require only two positions.

Implementation of either option would significantly reduce the amount of damage caused by abrasion and the costs associated with basin repairs.

References

Dodge, Russ, “Hydraulic Model Study of Taylor Draw Dam Outlet Works”, Water Resources Research Laboratory, Bureau of Reclamation, R-96-09, December 1996.