RECLAMATION
Managing Water in the West

Hydraulic Laboratory Report HL-2011-06

Velocity Corrections for Froude-scaled Physical Models of Stilling Basins

U.S. Department of the Interior
Bureau of Reclamation
Denver, Colorado

January 2011

REPORT DOCUMENTATION PAGE			*Form Approved* *OMB No. 0704-0188*

The public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing the burden, to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.

PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.

1. REPORT DATE *(DD-MM-YYYY)*	**2. REPORT TYPE**	**3. DATES COVERED** *(From - To)*
01-13-2011	Technical	Oct 2007 – Dec 2010

4. TITLE AND SUBTITLE	**5a. CONTRACT NUMBER**
Velocity Corrections for Froude-scaled Physical Models of Stilling Basins	**5b. GRANT NUMBER**
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	**5d. PROJECT NUMBER**
Hanna, Leslie J.	**5e. TASK NUMBER**
	5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)	**8. PERFORMING ORGANIZATION REPORT NUMBER**
U.S. Department of the Interior, Bureau of Reclamation Technical Service Center, 86-68460 P.O. Box 25007 Denver, CO 80225	HL-2011-06
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	**10. SPONSOR/MONITOR'S ACRONYM(S)**
U.S. Department of the Interior, Bureau of Reclamation Science and Technology Program	**11. SPONSOR/MONITOR'S REPORT NUMBER(S)**

12. DISTRIBUTION/AVAILABILITY STATEMENT

Available from: National Technical Information Service, Operations Division, 5285 Port Royal Road, Springfield Virginia 22161 http://www.ntis.gov

13. SUPPLEMENTARY NOTES

14. ABSTRACT

This paper tries to present a generalized method for computing a discharge correction function that could be used to adjust discharge in a physical model to better represent prototype flow conditions at the downstream end of Reclamation type II hydraulic jump stilling basins. This may be useful not only for flow deflector design but also to represent stilling basin flow conditions more accurately for other reasons including predicting the potential for erosion downstream from a basin.

15. SUBJECT TERMS

Stilling Basins, Energy Dissipation, Terminal Structure, Choke Canyon Dam, Mason Dam, Velocity Correction, Flow Deflector, Froude scale, Physical model

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT	**b. ABSTRACT**	**THIS PAGE**	SAR		Robert Einhelig
UL	UL	UL			**19b. TELEPHONE NUMBER** *(Include area code)* 303-445-2142

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18

Mission Statements

The mission of the Department of the Interior is to protect and provide access to our Nation's natural and cultural heritage and honor our trust responsibilities to Indian Tribes and our commitments to island communities.

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.

Acknowledgments

Reclamation's S&T (Science and Technology) program provided the majority of funding for this research. Thanks also to Reclamation's Oklahoma-Texas area office and the City of Corpus Christi for their contributions in the implementation of the Choke Canyon Dam flow deflectors and in the collection of velocity field data. Peer review of this document was provided by Tony Wahl of Reclamation's Hydraulic Investigations and Laboratory Services group.

Hydraulic Laboratory Reports

The Hydraulic Laboratory Report series is produced by the Bureau of Reclamation's Hydraulic Investigations and Laboratory Service Group (Mail Code 86-68460), PO Box 25007, Denver, Colorado 80225-0007. At the time of publication, this report was also made available online at:
http://www.usbr.gov/pmts/hydraulics_lab/pubs/HL/HL-2011-06.pdf

Disclaimer

No warranty is expressed or implied regarding the usefulness or completeness of the information contained in this report. References to commercial products do not imply endorsement by the Bureau of Reclamation and may not be used for advertising or promotional purposes.

This hydraulic model study was funded by Reclamation's S&T (Science and Technology) program.

Hydraulic Laboratory Report HL-2011-06

Velocity Corrections for Froude-scaled Physical Models of Stilling Basins

Prepared: Leslie Hanna,
Hydraulic Engineer, Hydraulic Investigations and Laboratory Services, 86-68460

Technical Approval: Robert F. Einhellig, P.E.
Manager, Hydraulic Investigations and Laboratory Services, 86-68460

Peer Review: Tony Wahl, P.E.
Hydraulic Engineer, Hydraulic Investigations and Laboratory Services, 86-68460

1/20/11
Date

REVISIONS					
Date	Description	Prepared	Checked	Technical Approval	Peer Review

Table of Contents

List of Figures

List of Tables

Introduction

Past studies conducted by Reclamation's Hydraulic Investigations and Laboratory Services Group on Reclamation type II hydraulic jump stilling basins found that velocities measured in Froude scaled models of the Choke Canyon Dam and Mason Dam outlet works stilling basins matched poorly with prototype velocities measured at each dam site. These studies were conducted in the Denver laboratory to develop solutions for mitigation of abrasion damage, commonly experienced by these types of basins [1]. The typical flow pattern that occurs in type II stilling basins consists of a high velocity jet that enters the basin along the floor, then rises high into the water column at the downstream end of the basin, thus creating a vertical eddy and upstream currents into the basin in the lower portion of the water column (figure 1). Flow deflectors, developed to mitigate abrasion damage, must be positioned based on velocities measured in a vertical plane at the end of a stilling basin. Therefore it was extremely important to have an accurate representation of these velocities in order to identify the correct elevation for positioning the deflectors. Comparing prototype data with Froude scaled data for the models of the Choke Canyon dam and Mason Dam outlet works stilling basins demonstrated that even when flow conditions were matched where flow exited the high pressure regulating gates, and although the model basins were constructed with an extremely smooth surface compared with the prototype, viscous forces near the end of the basin were over-represented in the model, leading to inaccurate velocity measurements. Possible reasons for this are the high levels of turbulence in these flows and the relatively low Reynolds numbers associated with Froude-scaled models. Aerated flow and distortions associated with model scale air mixing may also be contributing factors.

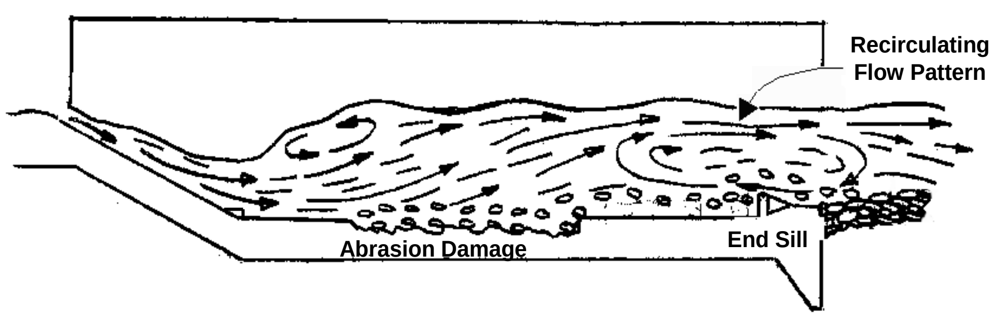


Figure 1. Typical flow pattern for Reclamation type II stilling basin.

As a result of these findings, model discharge was distorted to achieve good model-prototype agreement. This paper tries to present a generalized method for computing a discharge correction function that could be used to adjust discharge in a physical model to better represent prototype flow conditions at the downstream end of Reclamation type II hydraulic jump stilling basins. This may be useful not only for flow deflector design but also to represent stilling basin flow conditions more accurately for other reasons including predicting the potential for erosion downstream from a basin.

For this study, because of limited funding, only the Choke Canyon Dam outlet works stilling basin was used for the analysis. The Choke Canyon Dam stilling basin is a Reclamation type II stilling basin, and is located on the Frio River midway between Corpus Christi and San Antonio Texas. In June 2004, a field evaluation was conducted at the site. Data from this evaluation was compared to data collected from two different Froude scaled models of the Choke Canyon Dam outlet works stilling basin and several approaches were investigated to come up with a correction function to more accurately represent prototype flow conditions at the downstream end of the stilling basin.

Investigations

Choke Canyon Model Study 1:10 Scale

Previous research was conducted in the Denver laboratory to determine the optimal design for a flow deflector to be installed at Choke Canyon Dam for abrasion mitigation. In October 2004 a sectional model of the outlet works stilling basin was constructed on a 1:10 geometric scale. For this model study, it was determined that one bay of the twin bay design was adequate to represent the stilling basin (figure 2).

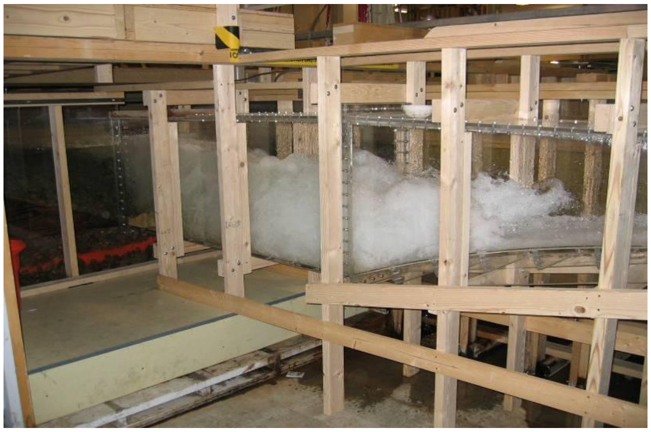


Figure 2. Choke Canyon stilling basin 1:10 scale model operating at 50% gate opening.

Choke Canyon Dam outlet works stilling basin (Appendix A, figure A-1, Reclamation drawing No. 1012-D-100) is a Reclamation type II stilling basin with twin bays with curved chutes. Prototype features modeled for the stilling basin included:

1) One 5 ft by 5 ft high pressure regulating gate.

2) One bay of the hydraulic jump stilling basin with curved entrance chute.

3) Topography downstream from the stilling basin, extending to the river channel entrance.

Froude law similitude was used to establish the kinematic relationship between model and prototype because hydraulic performance within a stilling basin depends predominantly on gravitational and inertial forces. Froude law similitude produced the following relationships between the model and the prototype:

Length ratio $L_r = 1:10$

Velocity ratio $V_r = L_r^{1/2} = 1:3.16$

Discharge ratio $Q_r = L_r^{5/2} = 1:316$

For each flow condition tested, water was supplied and measured from the permanent laboratory venturi meter system and routed to the model through the pipe chase surrounding the perimeter of the laboratory.

Model Investigations

Investigations were conducted to evaluate hydraulic conditions in the model stilling basin for the range of operating conditions previously tested in the prototype in June 2004. For the purposes of this study, only discharges up to a maximum of 40% gate opening were considered (based on maximum reservoir elevation). Higher discharges were not included since the flow at the end of the basin becomes too turbulent to accurately measure velocities and the stilling basin no longer fully contains the hydraulic jump. According to the design parameters provided in Reclamation's Engineering Monograph No. 25, the design discharge calculated for this basin geometry is reached at about 36 percent gate opening with reservoir elevation 220 ft, which was the reservoir level at the time field tests were conducted [2]. Model velocity measurements were taken with a SonTek ADV (Acoustic Doppler Velocimeter) probe to map velocity profiles at the downstream end of the stilling basin for gate openings of 10, 20, 30, and 40 percent, with corresponding discharge based on reservoir elevation 220 ft (Appendix A, fig A-2). Velocities were measured beginning several inches above the endsill at the downstream end of the basin and continuing upward along a vertical line until air entrained in the flow prevented further measurements. Vertical profiles were measured at a location over the end sill centered between the 1st and 2nd dentate from the north side, since this was the location where field measurements had been taken. Initial velocities measured at a symmetric location on the south side of the endsill also demonstrated there was no significant difference in measurements between these two locations.

All parameters described in this report, including discharge, will be presented in terms of the prototype, unless otherwise stated.

Field Data Comparison

The field evaluation conducted in June 2004 was used to evaluate the flow conditions at the Choke Canyon Dam outlet works stilling basin to determine whether or not materials were being carried into the basin by upstream currents [1]. To accomplish this, an ADP probe mounted on the downstream face of the basin endsill, were used to measure average velocity profiles in a vertical plane at the basin exit. Field data collected from these tests was compared to model velocity data collected under the same test conditions (figures 3-6). This comparison 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 prototype stilling basin. Reynolds number is defined as the ratio of inertial forces to viscous forces and in the model viscous effects are relatively over represented in the region where the hydraulic jump

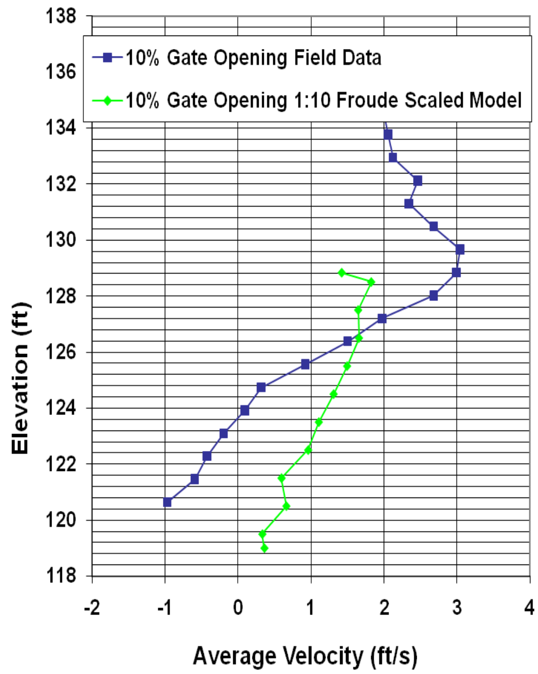


Figure 3. Vertical profiles of basin exit velocities compared at 10% gate opening for 1:10 scale model and prototype.

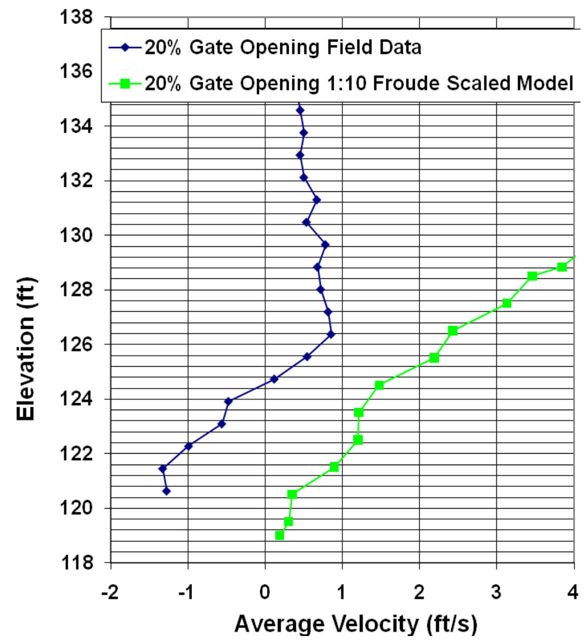


Figure 4. Vertical profiles of basin exit velocities compared at 20% gate opening for 1:10 scale model and prototype.

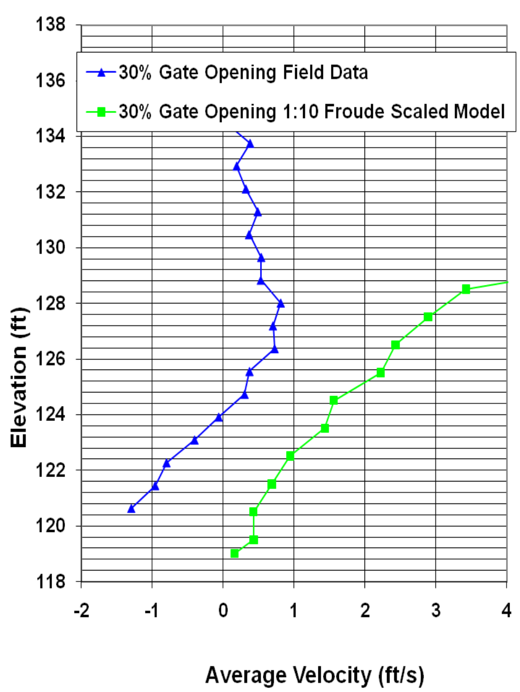


Figure 5. Vertical profiles of basin exit velocities compared at 30% gate opening for 1:10 scale model and prototype.

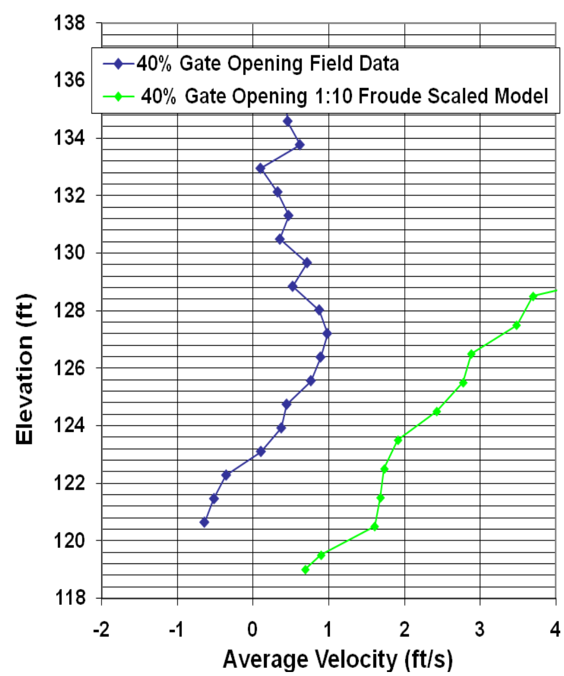


Figure 6. Vertical profiles of basin exit velocities compared at 40% gate opening for 1:10 scale model and prototype.

Since the model did not provide a good representation of the velocity profiles measured in the prototype, model discharge for each gate opening was increased incrementally above the value calculated from Froude law similitude, until velocity profiles matched reasonably well with the flow conditions measured in the prototype. Figures 7-10 show the final profile-matched velocity profiles and the original profiles (measured with Froude-scaled discharge) compared with the prototype profile for each gate opening tested. Table 1 shows the discharge tested in the prototype for each gate opening compared with the Froude scaled discharge required in the model to match the profiles. Table 1 also lists the percent increase above the Froude scaled discharge required to match the prototype profile, demonstrating that the lower the discharge (Q), the greater the percentage increase in Q required to match prototype velocity profiles. These results were encouraging but more data was necessary to determine if this relationship would remain consistent.

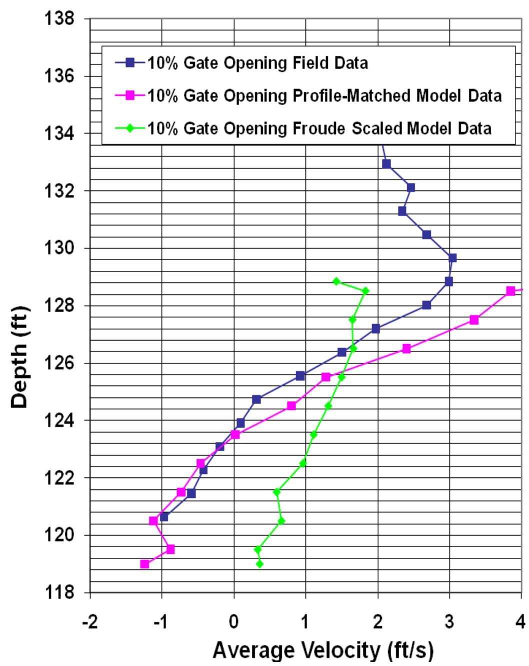


Figure 7. Vertical profiles of basin exit velocities compared at 10% gate opening for 1:10 scale model, profile matched model, and prototype.

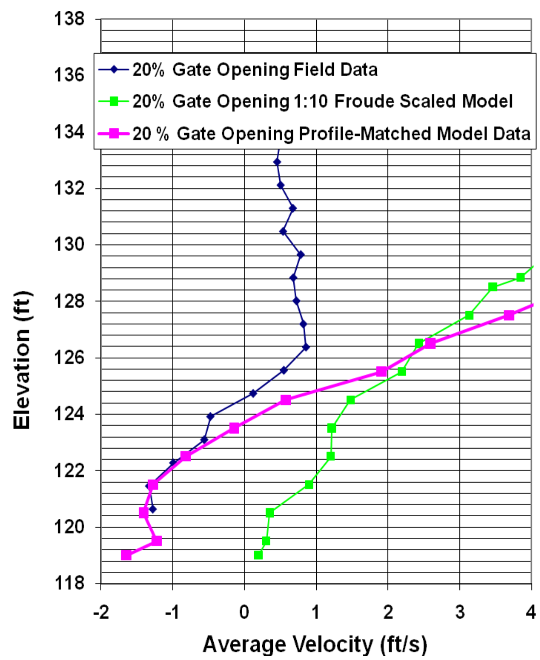


Figure 8. Vertical profiles of basin exit velocities compared at 20% gate opening for 1:10 scale model, profile matched model, and prototype.

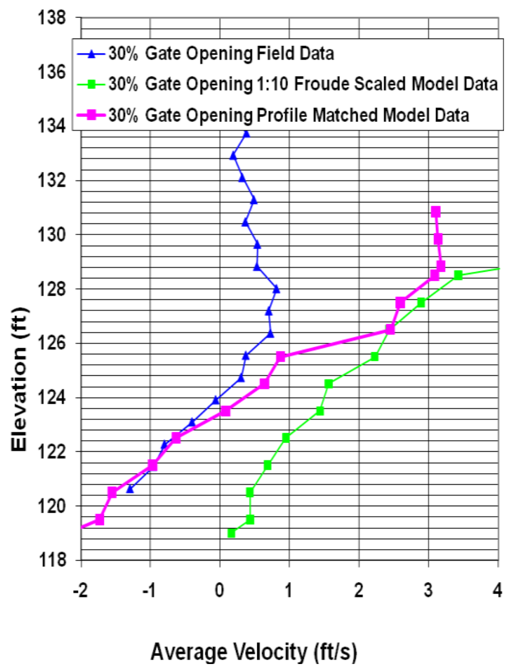


Figure 9. Vertical profiles of basin exit velocities compared at 30% gate opening for 1:10 scale model, profile matched model, and prototype.

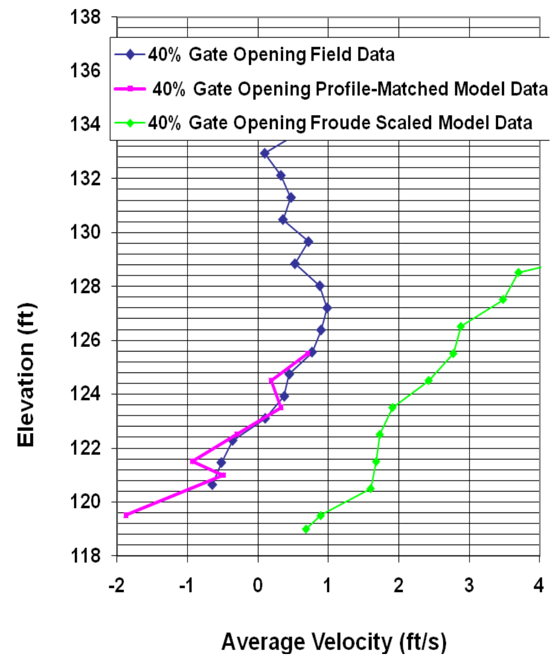


Figure 10. Vertical profiles of basin exit velocities compared at 40% gate opening for 1:10 scale model, profile matched model, and prototype.

Table 1. Profile-matched discharges tested in Choke Canyon stilling basin 1:10 model compared with actual prototype discharges tested in June 2004.

Gate Opening	Tailwater Depth (ft)	Prototype Discharge (ft^3/s)	Froude Scaled Discharge in 1:10 Model (ft^3/s)	Discharge in 1:10 Model to match Velocity Profiles (ft^3/s)	Percent Increase in Model Discharge) to match Prototype Velocity Profiles (%)
10	14.2	148	0.47	0.73	56
20	15.7	294	0.93	1.27	37
30	16.6	427	1.35	1.75	30
40	17.3	544	1.72	1.95	13

Choke Canyon Model Study 1:6 Scale

A 1:6 scale sectional model of the Choke Canyon Dam Outlet works stilling basin, was constructed in the Denver laboratory to provide additional data to determine a correction function for more accurate modeling of prototype flow conditions near the downstream end of the stilling basin (figure 11). Again just one bay of the twin bay design was modeled with the same features included in the 1:10 scale model. Initial testing was conducted using Froude law similitude, producing the following relationships between model and prototype:

Length ratio $L_r = 1{:}6$

Velocity ratio $V_r = L_r^{1/2} = 1{:}2.45$

Discharge ratio $Q_r = L_r^{5/2} = 1{:}88.2$

Figure 11. Choke Canyon 1:6 scale model stilling basin.

Velocity profiles were measured with a SonTek ADV probe at the same location as with the previous model study. Figures 12-15 show the velocity profiles measured in the 1:6 model compared to those measured in the prototype. The figures demonstrate that Froude scaled model flow conditions have again over predicted energy dissipation in the prototype.

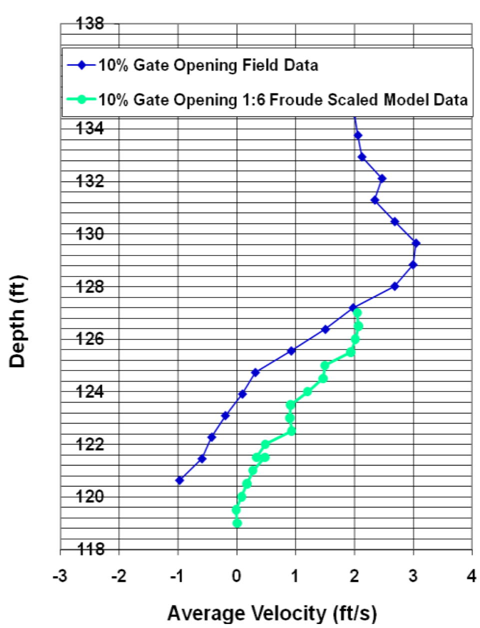


Figure 12. Vertical profiles of basin exit velocities compared at 10% gate opening for 1:6 scale model and prototype.

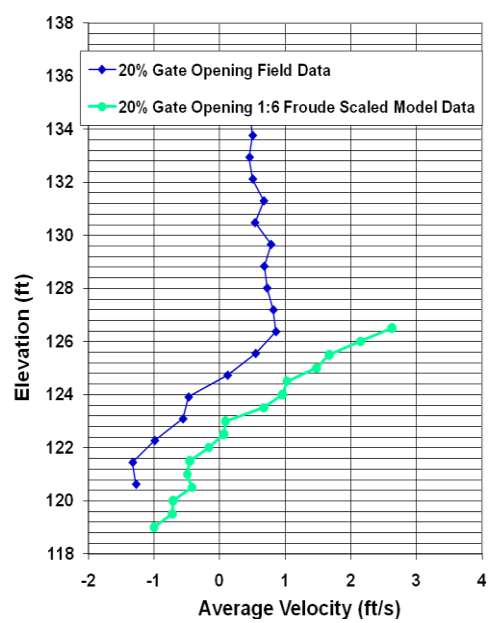


Figure 13. Vertical profiles of basin exit velocities compared at 20% gate opening for 1:6 scale model and prototype.

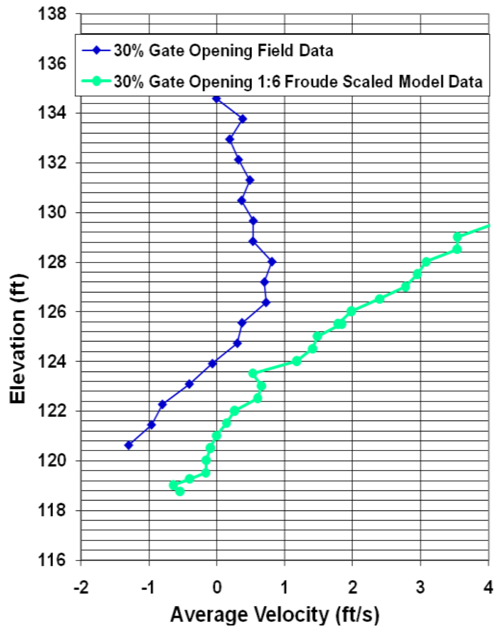


Figure 14. Vertical profiles of basin exit velocities compared at 30% gate opening for 1:6 scale model and prototype.

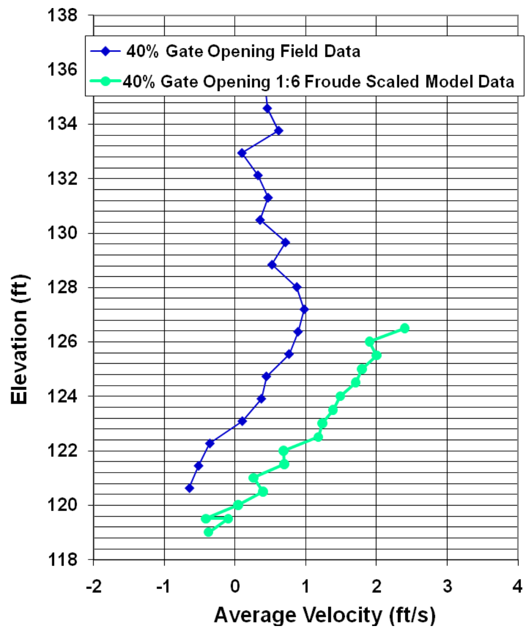
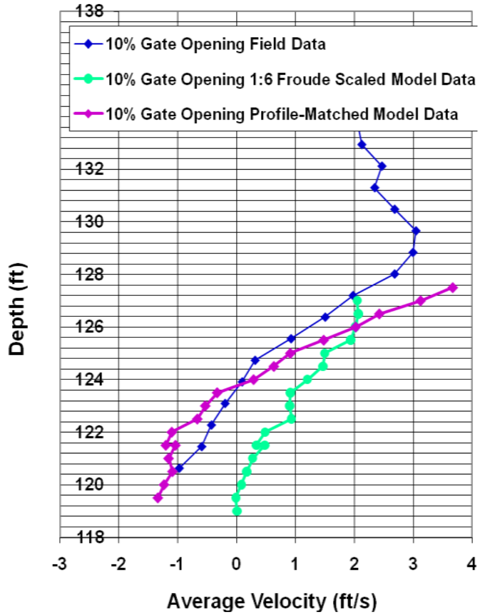


Figure 15. Vertical profiles of basin exit velocities compared at 40% gate opening for 1:6 scale model and prototype.

Similarly to the previous model, the discharge for the 1:6 scale model was increased incrementally for each gate opening, above the value calculated from Froude law similitude, until the velocity profiles matched reasonable well with the flow conditions measured in the prototype. Primarily we were trying to match profiles at the location where the curve crosses the Y axis since this value is important for the positioning of a flow deflector. Figures 16 through19 show the final profile-matched velocity profiles and the original profiles (for Froude-scaled discharge), compared with the prototype profile for each gate opening tested. Table 2 shows the discharge tested in the prototype for each gate opening compared with the Froude scaled discharge required in the model to match the profiles. Table 2 also lists the percent increase in Froude scaled discharge required to match the prototype profile. The table demonstrates once again that the lower the discharge, the greater the percentage increase in Q required to match prototype velocity profiles. In addition comparing Table 1 with Table 2 shows that the smaller the scale used in constructing the model (i.e. the larger the model) the smaller the increase in discharge required to achieve profile matched velocities.



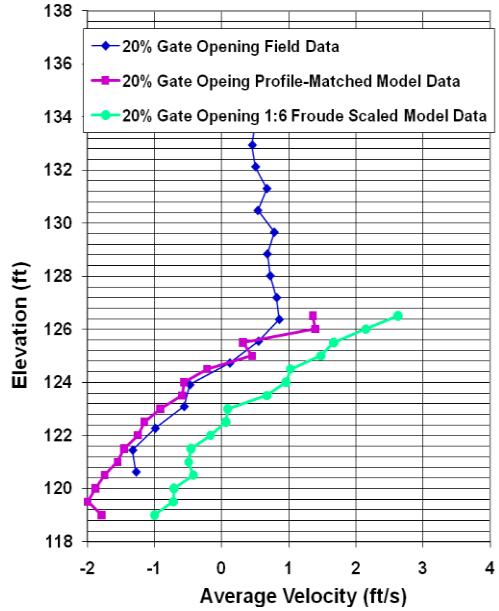
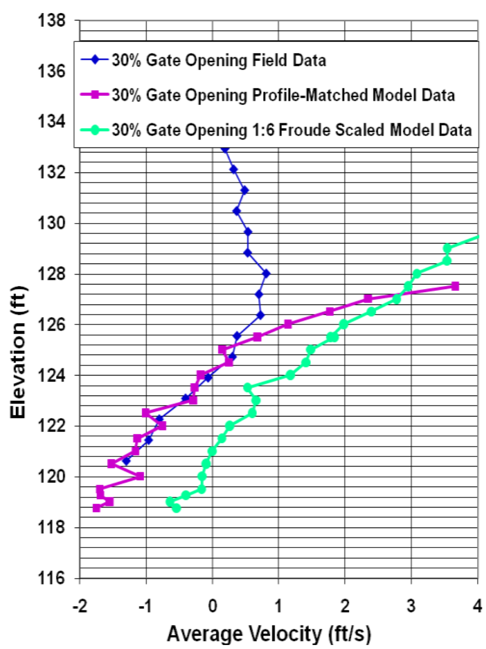


Figure 16. Vertical profiles of basin exit velocities compared at 10% gate opening for 1:6 scale model, profile matched model, and prototype.

Figure 17. Vertical profiles of basin exit velocities compared at 20% gate opening for 1:6 scale model, profile matched model, and prototype.



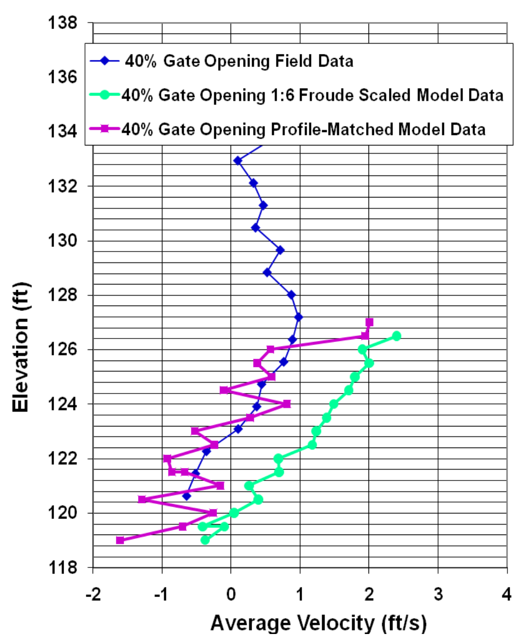


Figure 18. Vertical profiles of basin exit velocities compared at 30% gate opening for 1:6 scale model, profile matched model, and prototype.

Figure 19. Vertical profiles of basin exit velocities compared at 40% gate opening for 1:10 scale model, profile matched model, and prototype.

Table 2. Profile-matched Discharges tested in Choke Canyon stilling basin 1:6 model compared with actual prototype discharges tested in June 2004.

Gate Opening	Tailwater Depth (ft)	Prototype Discharge (ft^3)	Froude Scaled Model Discharge (ft^3/s)	Model Discharge in 1:6 Model to match Velocity Profiles (ft^3/s)	Percent Increase in Model Discharge to match Prototype Velocity Profiles (%)
10	14.2	148	1.67	2.26	35
20	15.7	294	3.33	4.2	26
30	16.6	427	4.84	5.94	23
40	17.3	544	6.17	6.63	7.5

Data Analysis

The next step was to analyze the data to determine a correction function that could be used to adjust model discharge to more accurately predict prototype velocity profiles at a basin exit for future model studies.

Generally, models of hydraulic structures with free-surface flow are based on Froude model law, since flow behavior is almost exclusively determined by inertial and gravitational forces. In the case of a stilling basin, with extreme turbulence, usually the Reynolds number is considered insignificant and the roughness of the boundaries is of relatively little importance because of the short length of flow involved. However, if a change in flow conditions causes a significant drop in the model Reynolds number, then a change in the frictional loss coefficient will occur and the influence of viscosity may become important [3].

In this case, highly turbulent flow entering the stilling basin, transitions through a hydraulic jump, into a relatively tranquil flow over the end sill. In this more tranquil flow, viscous forces suddenly take on greater importance. In some cases, model distortion can be used to compensate for Reynolds number effects, however velocity distributions over the flow cross section would no longer be simulated correctly, so this option was not considered appropriate for this case. Instead of distorting model geometry, discharge was increased to compensate for Reynolds number effects, yielding models with velocity profiles comparable to the prototype.

It was initially assumed that the discharge adjustment needed to achieve good model-prototype conformance could be related to the Reynolds number and friction factor. In an effort to establish a relation for predicting the discharge adjustment needed for future studies, Reynolds number and friction factor values were computed for both models and the prototype at several different stations along the structure.

Several potential reference Reynolds numbers were considered including:

1. Reynolds numbers at the high pressure regulating gates where flow exits into the conduit.
2. Reynolds number at the basin exit where the jet transitions into the tailrace based on:
   a. Full tailwater depth.
   b. Depth above the transition point where all flow is traveling downstream. This requires knowing the transition point in the prototype for each flow condition tested.
   c. Fifty percent tailwater depth. This is a rough estimate of the depth of flow traveling downstream, so that identifying the transition point for each flow condition tested is not required.
3. Reynolds number drop from the regulating gates to the end of the stilling basin for Reynolds number calculated based on each case identified in 2a through 2c above.

The analysis consistently showed that an increase in Reynolds number was necessary in the model to achieve similarity with prototype velocity profiles, but the size of the necessary adjustment was inconsistent. Throughout this analysis there did not seem to be any clear correlation that could be used as a correction factor for future model studies. In addition, since we were limited to using only the Choke Canyon Dam stilling basin and its models, it was difficult to extrapolate the data to other stilling basins.

As a result, a simpler approach was investigated that was based on the relationship between model geometric scale (GS), Froude law, design flow percentage, and percentage increase in discharge to match prototype velocity profiles.

Flow Correction

The approach that was used for the next analysis was based on the concept that percentage increase in discharge (to obtain profile-matched velocity profiles) was proportional to both model scale, and prototype discharge. In this case, prototype discharge will be presented as a percentage of basin design flow so that it may be applicable to other basin designs in the future. The first step in this process was to determine the design flow (Q_D) for the stilling basin based on the parameters provided in Engineering Monograph No. 25 (EM25). Please note that due to variations from EM25 in design parameters for individual basins, the primary parameters considered in calculating design discharge were velocity entering the jump, and basin length to contain the hydraulic jump.

Using these methods it was determined that the design flow corresponding to the geometry of the Choke Canyon Dam outlet works stilling basin was about 985 ft^3/s (492.5 ft^3/s each bay) which corresponds to about 35.6 % gate opening at maximum reservoir elevation 220 ft. The design

Froude number using these parameters is about 12. Next an adjusted model scale factor (F_{ms}) was determined for each test condition based on calculating the profile matched discharge from prototype discharge using Froude law similitude, so that

$$F_{ms} = (Q_p/Q_{pmm})^{(2/5)} \quad (1)$$

Where Q_p is the prototype discharge tested in prototype units, and Q_{pmm} is the profile-matched model discharge in model units. Then to normalize these results, F_{ms} for each test condition was put in terms of the percentage of geometric scale (GS_P) that was used to build the model (tables 3 and 4) so that $GS_P = (F_{ms}/GS) * 100$. Finally GS_P was plotted against percent prototype design flow ($\%Q_D$) for flows up to 100 percent design discharge for the basin, where $\%Q_D = Q_p / Q_D * 100$.

Table 3. Parameters calculated for 1:10 Scaled Model (GS = 10).

Qp **Prototype Discharge Represented in the Model (ft3/s)**	**% Q_D** **Design Flow Percentage of Choke Canyon Dam Stilling Basin (%)**	**Qfs** **Froude Scaled Prototype Discharge in Model Units (ft3/s)**	**Qpmm** **Profile Matched Prototype Discharge in Model Units (ft3/s)**	**Fms** **Adjusted Model Froude Scale Required to obtain Profile-Matched Discharge in Model (ft3/s)**	**GS_P** **Percentage of Geometric Scale () to Obtain Adjusted Scale (%)**
148	**30**	**0.47**	**0.73**	**8.37**	**83.7**
294	**60**	**0.93**	**1.27**	**8.83**	**88.3**
427	**87**	**1.35**	**1.75**	**9.01**	**90.1**
544	**110**	**1.72**	**1.95**	**9.51**	**95.1**

Table 4. Parameters calculated for 1:6 Scaled Model (GS = 6).

Q_p **Prototype Discharge Represented in the Model(ft^3/s)**	**% Q_D** **Design Flow Percentage of Choke Canyon Dam Stilling Basin (%)**	**Qfs** **Froude Scaled Prototype Discharge in Model Units (ft3/s)**	**Qpmm** **Profile Matched Prototype Discharge in Model Units (ft^3/s)**	**Fms** **Adjusted Model Froude Scale Required to obtain Profile-Matched Discharge in Model (ft^3/s)**	**GS_P** **Percentage of Geometric Scale () to Obtain Adjusted Scale (%)**
148	**30**	**1.67**	**2.26**	**5.33**	**88.8**
294	**60**	**3.33**	**4.2**	**5.47**	**91.2**
427	**87**	**4.84**	**5.94**	**5.53**	**92.1**
544	**110**	**6.17**	**6.63**	**5.83**	**97.2**

Figure 20 shows GS_p as a function of percent design flow for the 1:10 and 1:6 model scales. As the model scale approaches prototype scale (1:1), the scale distortion required becomes smaller (GS_p approaches 100%). The third curve on figure 20 shows that a 1:1 scaled "model" would require no distortion. Each of the three curves can be represented by an equation of the form $GS_p = C\ (\%Q_D)^a$ as noted in figure 20. Finally "C" and "a" were plotted as a function of geometric scale and are shown in figures 21 and 22. These figures, along with the preceding analysis were used to develop a correction function method for calculating an adjusted discharge to be used in future model studies.

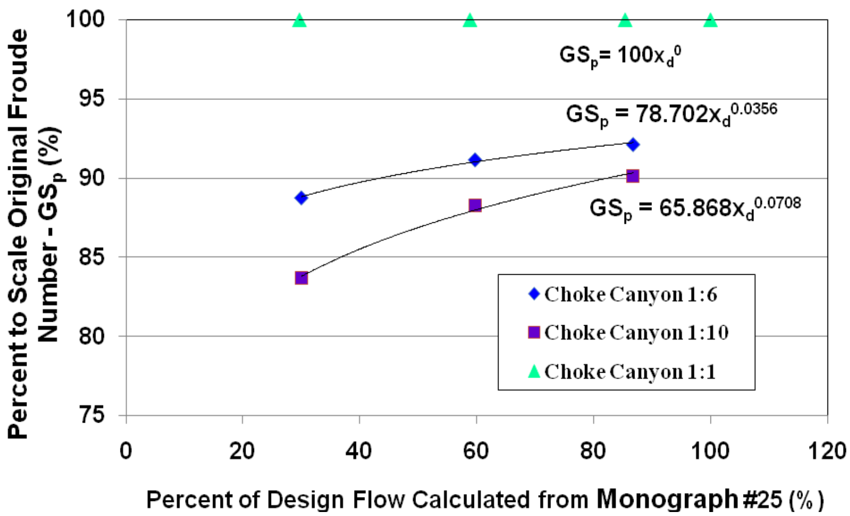


Figure 20. Percentage geometric scale (GS_P) correction factor versus percent design flow tested. ($X_d = \%Q_D$)

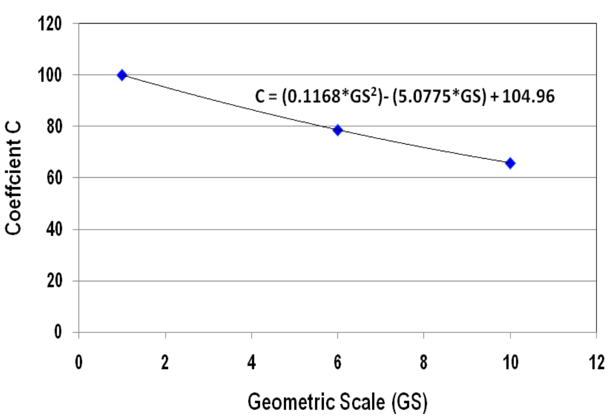


Figure 21. Coefficient 'C' as a function of model geometric scale.

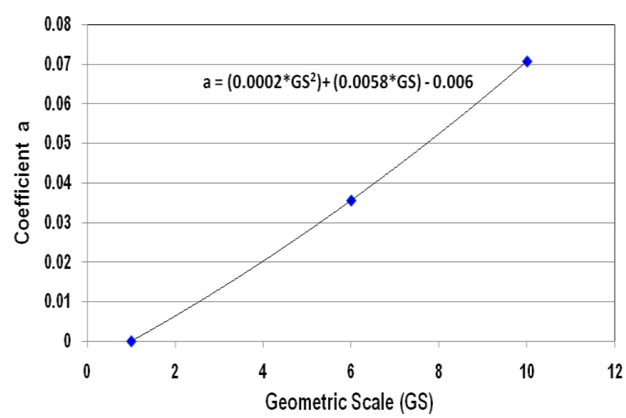


Figure 22. Coefficient 'a' as a function of model geometric scale.

Correction Function Method

To determine an adjusted model discharge, based on the previous analysis (to better simulate velocity profiles at a basin exit), the following method can be used:

First coefficients "C" and "a" can be determined from figures 21 and 22 based on the Geometric scale (GS) used to build the model. Then using these values, the curve $GS_P = Cx_d^a$ can be generated where "x_d" represents percentage of prototype design discharge ($\%Q_D$) ranging from 0 to 100. The curve can be used to determine a GS_P value for each prototype discharge (Q_p) tested. Next F_{ms} for each test condition can be calculated from:

$$F_{ms} = (GS_P /100) * GS \qquad (2)$$

Then instead of using the Froude law relationship $Q_r = L_r^{5/2}$ to calculate model discharge, the profile matched model discharge (Q_{pmm}) can be determined from

$$Q_{pmm} = Q_p / (F_{ms})^{5/2} \qquad (3)$$

Where Q_{pmm} is the adjusted model discharge (in model units) needed to produce profile matched velocities at the end of the stilling basin to more accurately represent prototype velocity profiles for each value of Q_p (prototype discharge in prototype units).

For Example:

Let's say we started with the Choke Canyon 1:6 scaled model with a gate opening of 20% at maximum reservoir elevation. First from the curve fit equations in figures 21 and 22, for GS = 6, "C" and "a" can be calculated:

$C= 0.1168*GS^2- 5.0775*GS+ 104.96$, $C= 78.7$

$a = .0002 * GS^2+.0058 * GS - .006$, $a = .036$

Then from figure A-2, Q_p = 588 ft^3/s (294 ft^3/s each bay). Since Q_D = 985 ft^3/s (492.5 ft^3/s each bay), $\% Q_D = 59.7 = x_d$.

So using $GS_P = Cx_d^a$, $GS_P = 91.2$

And from equation (2), $F_{ms} = 5.47$

Finally from equation (3), Using Q_p for one bay (294 ft^3/s), gives Q_{pmm} = 4.2 ft^3/s. Q_{pmm} is the discharge (in model units) that would be tested in the model to more accurately represent prototype velocities at the end of the stilling basin, compared with the Froude scaled value $Q_{fs} = Q_p /(6^{5/2}) = 3.33$ ft^3/s.

Mason Dam Stilling Basin Comparison

Although the Mason Dam outlet works stilling basin was not included in this study, it was important to analyze a set of independent data to see how well it fit with the velocity correction methods developed from the Choke Canyon Dam stilling basin study. As a result, existing data gathered during flow deflector research for Mason Dam were analyzed for this purpose.

Mason Stilling Basin Study Background

The Mason Dam outlet works stilling basin is a Reclamation type II hydraulic jump energy dissipation stilling basin located in southeastern Oregon. During the flow deflector investigations for Mason dam, a 1:7 scaled model was constructed in the Denver laboratory in 2002 [4]. The Mason model was operated with Froude scaled discharge based on maximum reservoir elevation (4078 ft) and velocities were measured in a vertical plane over the basin endsill similar to the Choke Canyon model study. Then two years after model investigations were completed, velocities were measured in the field and compared with model velocities. However, at the time velocities were measured at Mason Dam, the reservoir level was about 70 ft below maximum reservoir elevation (4005 ft); therefore field velocities were not expected to match very well with model velocities measured at identical gate openings. The 70 ft difference in elevation meant that the discharge that had been tested in the model was significantly higher than the Froude scaled discharge, corresponding to the prototype discharge tested at each gate opening, at the time testing was conducted in the field at the lower reservoir. Figures 23-25 show field velocities measured, compared with model velocities. So quite by accident model

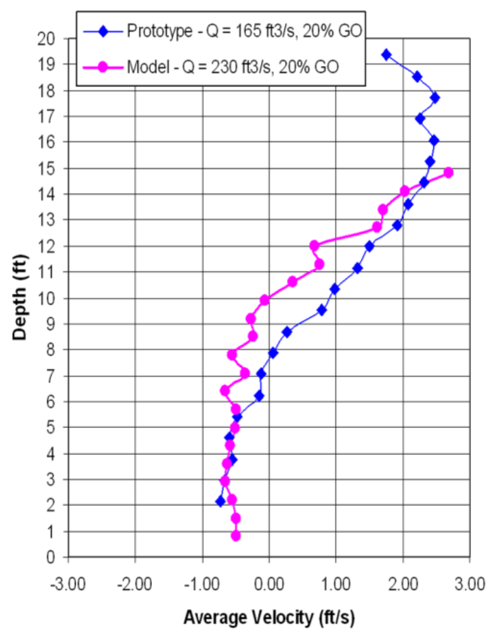


Figure 23. Vertical profiles of Mason Dam basin exit velocities compared at 20% gate opening for 1:7 scale model and prototype.

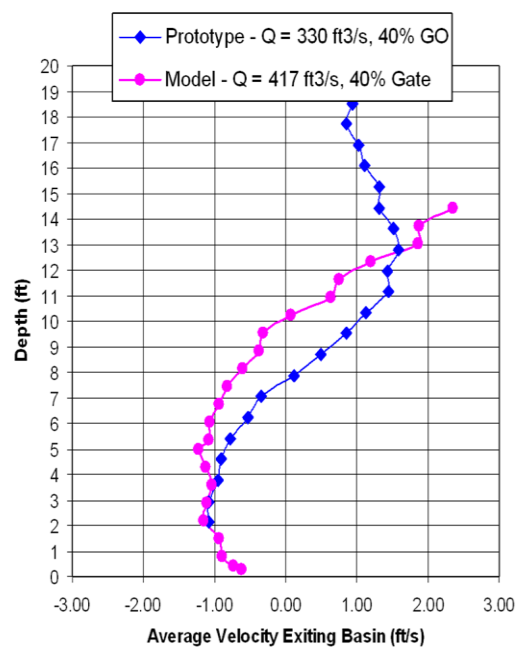


Figure 24. Vertical profiles of Mason Dam basin exit velocities compared at 40% gate opening for 1:7 scale model and prototype.

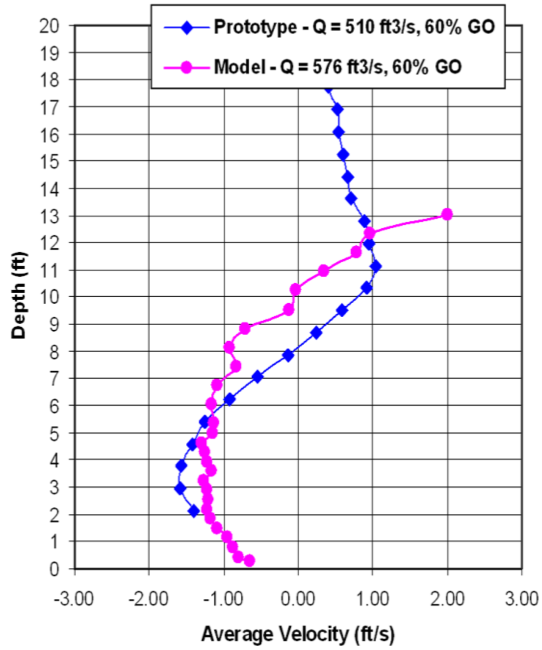


Figure 25. Vertical profiles of Mason dam basin exit velocities compared at 60% gate opening for 1:7 scale model and prototype.

discharges based on a 70 ft higher reservoir elevation provided a distorted Q value that helped compensate for scaling effects, to produce velocity profiles that compared reasonably well with prototype velocities.

Mason Model Flow Correction

The next step was to use the correction function method, developed in the previous sections, to determine what adjusted values of Q in the model should have been used to match prototype profiles. So following this process, the values of coefficients "a" and "C" for the 1:7 scale model were determined from the equations given in figures 21 and 22. The values for "C" and "a" were determined to be 75.14 and 0.044 respectively for the Mason Dam stilling basin. Then from EM25 the design discharge for the Mason Dam outlet works stilling basin was determined to be 870 ft^3/s.

Next the values for GS_P were calculated from $GS_P = C(\%Q_D)^a$ for each discharge tested in the model and are listed in Table 5. Then from equations (2) and (3), F_{ms} and Q_{pmm} were calculated for each prototype discharge tested and are also listed in Table 5. Once these values were computed, the profile matched discharge (Q_{pmm}) was compared with the Froude scaled model discharge and the model discharge actually tested during the Mason Dam model study, for each gate opening tested in the prototype (Table 6).

Table 6 shows that the profile matched discharge values for each test case are slightly greater than the values actually tested in the model. From past experience, generally when discharge is increased for the same gate opening, velocities near the bottom become stronger in the upstream direction (or more negative in this case), and velocities in the upper portion of the water column also become stronger in the downstream direction, thus flattening out the upper portion of the curve. With this in mind, looking at figures 23-25, it appears that had we used the calculated values for each profile matched discharge to test the model, velocity profiles would probably correspond well with the prototype velocity profiles. This seems to be true, especially given that the profile matched discharges are only slightly higher than the values actually tested, which already match velocity profiles reasonably well.

Finally figure 26 shows GS_P as a function of $\%Q_D$ for the Mason Dam stilling basin, plotted alongside the Choke Canyon data . The curve for the Mason Dam 1:7 scale model lies between those for the 1:6 and 1:10 scales for Choke Canyon and demonstrates that the Mason data fit reasonably well with the velocity correction methods developed in the previous sections. This gives us some verification that these methods may have some valid application to other Reclamation type II stilling basins

Table 5. Computing profile-matched discharges for 1:7 model of Mason stilling basin from prototype discharges tested.

Gate Opening (%)	Prototype Discharge Tested (ft3/s)	Design Flow Percentage %QD = x (%)	$GS_P = Cx^a$	Fms = (GS_P /100) * GS	Qpmm =Qp / (Fms)5/2
20	160	18.4	85.5	5.98	1.825
40	330	37.9	88.3	6.18	3.47
60	510	58.6	90.0	6.3	5.11

Table 6. Comparing values of Froude-scaled discharge to profile matched discharge and discharges actually tested in the 1:7 Mason Dam stilling basin model.

Qp Prototype Discharge Tested (ft3/s)	% QD Design Flow Percentage (%)	Qfs Froude Scaled Prototype Discharge in Model Units (ft3/s)	Qm Model Discharge Tested in Model Units (ft3/s)	Qpmm Adjusted Model Discharge for Profile Matched Velocities in Model Units (ft3/s)
160	18.4	1.23	1.77	1.825
330	37.9	2.54	3.22	3.47
510	58.6	3.93	4.44	5.11

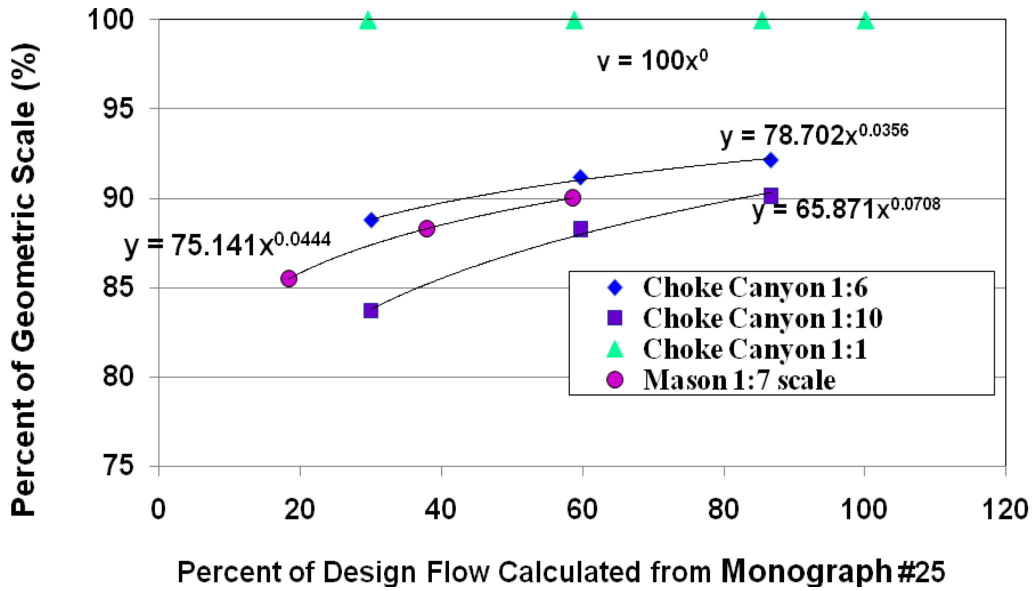


Figure 26. Mason Dam data included - Percentage geometric scale (GSP) correction factor versus percent design flow tested. ($x = \%Q_{D}$, y = GSp)

Conclusions

The correction function method presented here is a good starting point to be used as a tool for adjusting discharge in a Froude scaled model, to better simulate flow conditions at the downstream end of a Reclamation type II outlet works stilling basin. Since the correlation was based on a limited data set, it's applicability to other types of basins and to scales significantly smaller than 1:10 is untested at this time and may require further testing. However, looking at the Mason dam data gives some verification that these methods may have some application to other hydraulic jump basins.

These methods are not meant to be used to predict velocity values with high accuracy, but instead will give a more reasonable representation of average prototype velocities and vertical profiles at the basin exit, than could be obtained using Froude law similitude alone.

References

1. Hanna, Leslie, "Flow Deflectors for Mitigation of Stilling Basin Abrasion Damage," Hydraulic Laboratory Report HL-2010-01, Bureau of Reclamation, Denver, Colorado, January 2010.

2. Peterka, A.J., "Hydraulic Design of Stilling Basins and Energy Dissipaters," Engineering Monograph No. 25, United States Department of Interior, Bureau of Reclamation, Denver, Colorado, May 1984.

3. Kobus, Helmet, et al., "Hydraulic Modeling", German Association for Water Resources and Land Improvement, Bulletin 7, 1980.

4. Hanna, Leslie, "Mason Dam Flow Deflectors for Preventing Stilling Basin Abrasion Damage," Hydraulic Laboratory Report HL-2005-01, Bureau of Reclamation, Denver, Colorado, October, 2005.

Appendix A

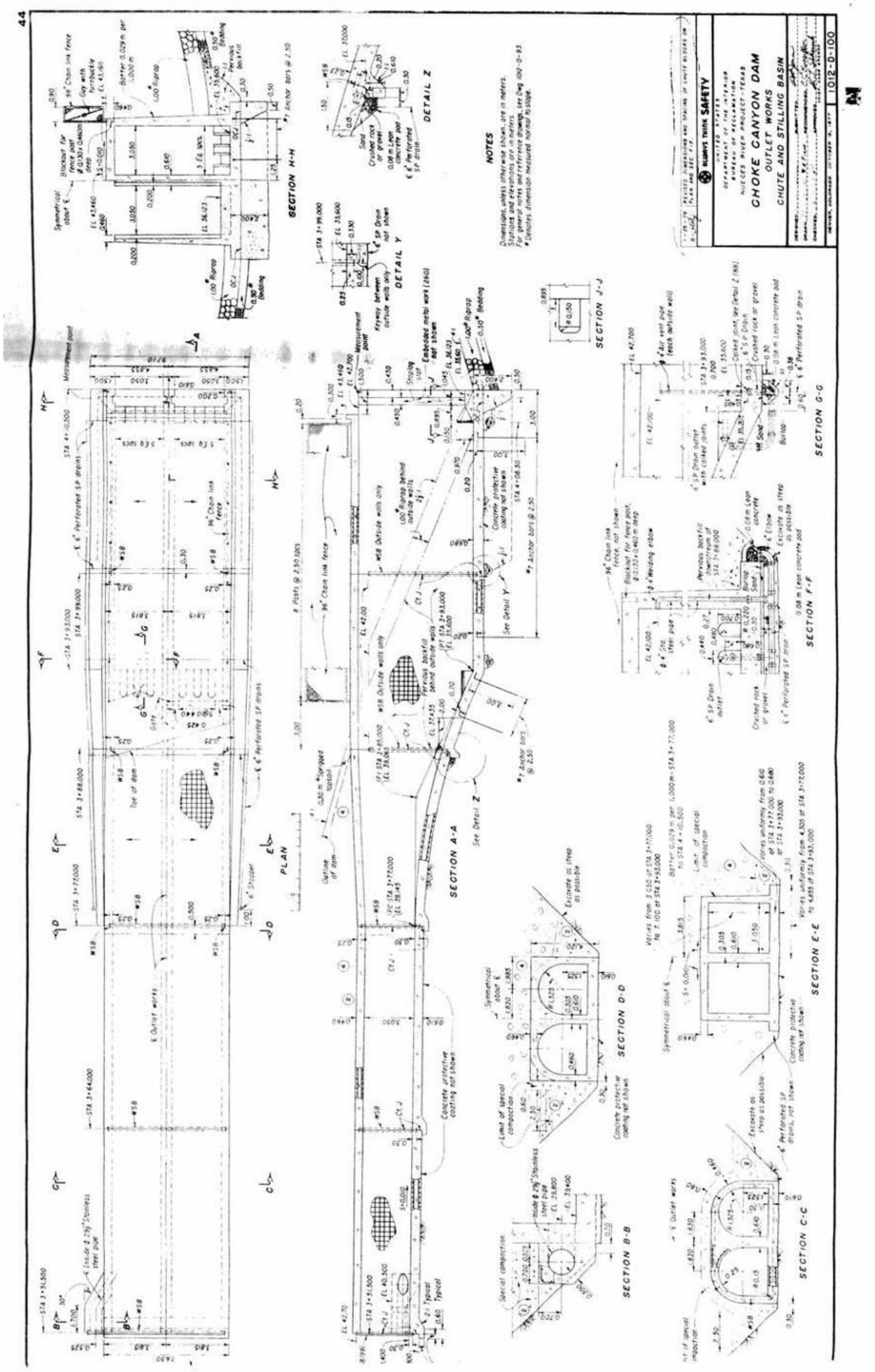


Figure A-1. Choke Canyon Dam Outlet works stilling basin, Reclamation drawing No. 1012-D-100.

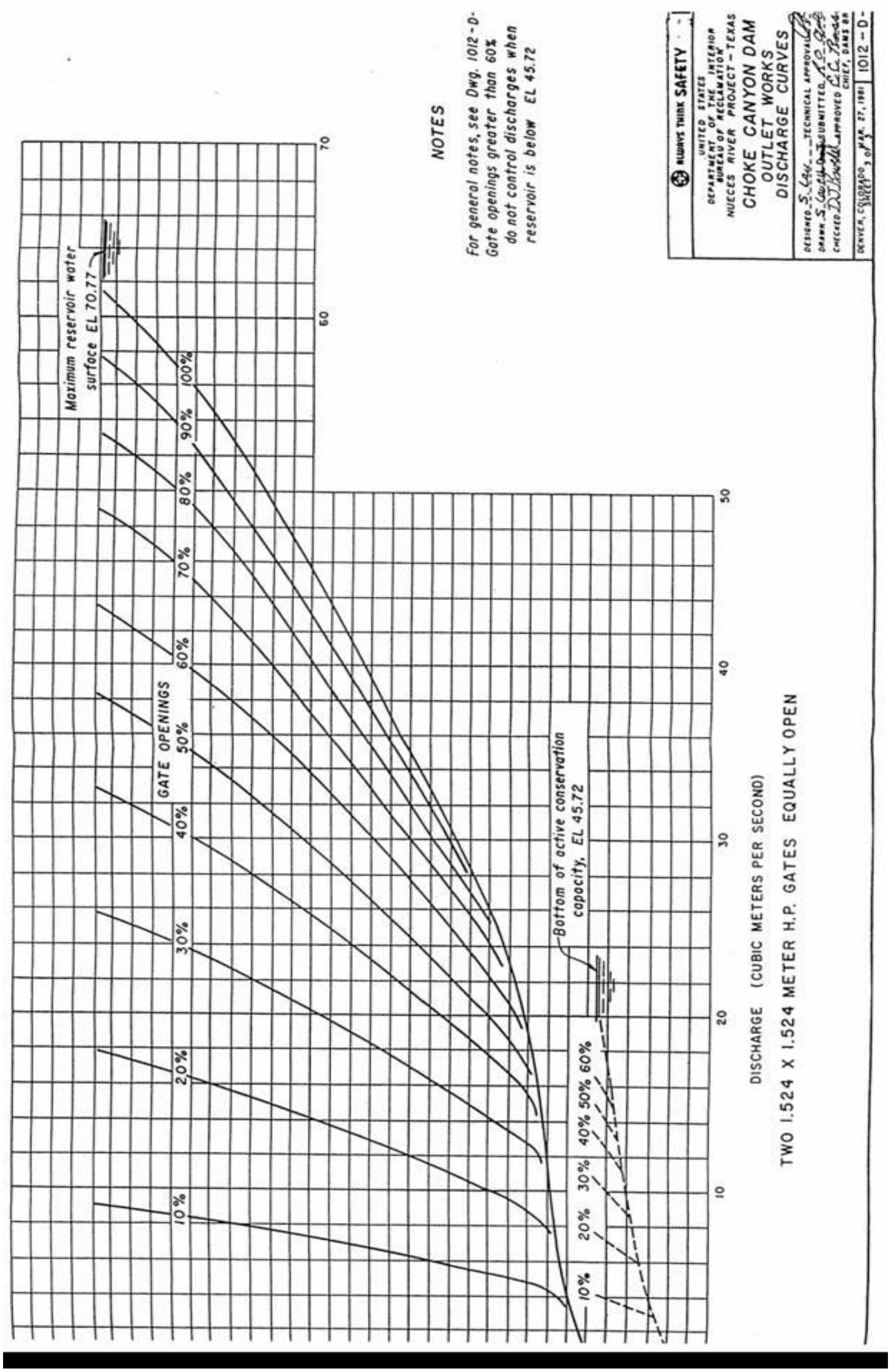


Figure A-2. Discharge curve for Choke Canyon Dam outlet works stilling basin.