2000 Joint Conference on Water Resources Engineering and Water Resources Planning & Management
July 30 - August 2, 2000 — Minneapolis, Minnesota

Laboratory Testing and Numerical Modeling of Coanda-Effect Screens

Tony L. Wahl (1) and Robert F. Einhellig (2)

(1) Hydraulic Engineer, U.S. Bureau of Reclamation, Water Resources Research Laboratory,
P.O Box 25007, Mail Code D-8560, Denver, CO 80225; Phone: 303-445-2155;
Fax: (303) 445-6324; email: twahl@do.usbr.gov

(2) Hydraulic Engineer, U.S. Bureau of Reclamation, Water Resources Research Laboratory,
P.O Box 25007, Mail Code D-8560, Denver, CO 80225, Phone: 303-445-2142;
Fax: (303) 445-6324; email: reinhellig@do.usbr.gov

Abstract

This paper describes the mechanics of flow over and through a Coanda-effect screen, a unique type of self-cleaning screen constructed from wedge-wire panels installed on supercritical slopes. The paper presents a numerical model for determining the flow rate through a Coanda-effect screen and discusses the variation of screen discharge capacity as a function of screen geometric parameters and the Froude number of the flow over the screen. The model was developed and calibrated using data collected in laboratory tests of several different screen configurations, and can be used to evaluate the hydraulic performance of custom designs, which should facilitate future application of Coanda-effect screens.

Introduction

Coanda-effect screens are an emerging technology that offers the potential for high-capacity, low-maintenance screening of fish and fine debris from water diversions, such as those used for irrigation and small hydropower development. The structures make use of an inclined wedge-wire screen panel installed in the sloping downstream face of an overflow weir. The flow to be diverted passes through the screen into a conveyance channel beneath the weir structure, while bypass flow, fish, and debris are carried off the toe of the screen (fig. 1). Typical screen openings are 1-mm or less, making it feasible to exclude fish eggs, larvae, and very fine debris. The screens are substantially self-cleaning for most types of debris due to the high sweeping velocity down the screen face (usually exceeding 2 m/s). Total head drop across these structures has typically been about 1.25 to 1.5 meters, although designs for lower drop heights are also possible.

A handful of pre-fabricated screen designs have been available commercially for several years, but detailed quantitative information on their hydraulic performance has been lacking, and the ability to develop custom designs for reduced drop heights or alternative screen configurations has been limited by a lack of understanding of the mechanics of the flow over and through the screens. To address the need for more detailed design information, the Bureau of Reclamation (Reclamation) has conducted a series of full-scale laboratory tests of several configurations of Coanda-effect screens. These tests have led to the development of a numerical model and computer program that can be used to predict flow profiles down the face of a screen and the total flow through a screen. This model is used in this paper to analyze the sensitivity of Coanda-effect screen performance to variations in several screen design parameters.

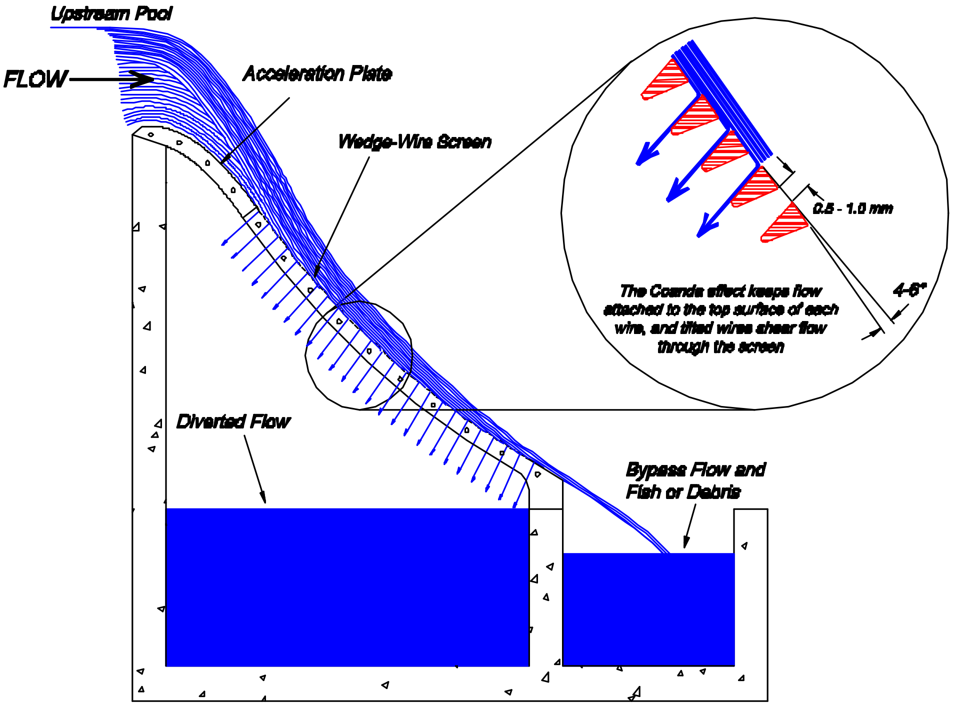

Figure 1. — Features and typical arrangement of a Coanda-effect screen structure.

Coanda-Effect Screens

Inclined overflow screens have been used to separate liquids and solids for many years in the mining, food-processing, and wastewater treatment industries. Most of these screens utilize standard wedge-wire screen panels in which the top surface of each wire is parallel to the plane of the screen panel. Coanda-effect screens are an evolution of this screen design utilizing a tilted-wire screen panel, and in recent years have been applied to problems of debris and fish screening at irrigation diversions and small hydropower intakes. One specific Coanda-effect screen configuration is marketed under the trade name Aqua Shear Static Intake Screen by Aquadyne, Inc., Healdsburg, CA. Some aspects of this screen design are covered under U.S. Patent 4,415,462 (Finch and Strong, 1983).

The important features of a Coanda-effect screen installation are illustrated in figure 1. The screen panel is installed on the downstream face of a hollow overflow weir. Flow passes over the crest of the weir, across and down a solid acceleration plate, and then across and through the screen panel, which is constructed of wedge wire with the wires oriented horizontally, perpendicular to the flow direction across the screen. Flow passing through the screen is collected in a conveyance channel below the screen surface. Flow passing over the screen carries fish and debris off the screen. If the inflow to the screen is not large, all of the flow will pass through the screen. For the best self-cleaning operation and whenever fish passage down the screen face is needed, it is desirable to maintain some bypass flow off the screen so that no portion of the screen is dry. For this reason, it is important to accurately know the screen capacity.

Typically, the screen panel is a concave arc with a radius of curvature of approximately 3 to 4 m, although planar screen panels can also be used. The crest of the weir and acceleration plate can be either an ogee-shaped profile (i.e., the natural trajectory of a free jet) or a simple circular arc;

the primary objectives are to provide a smooth acceleration of the flow as it drops over the crest, and to deliver the flow tangent to the screen surface at its upstream edge.

Coanda-effect screens of this basic design have been applied at a number of field sites for debris removal upstream of small hydropower projects (Strong and Ott, 1988; Ott et al., 1987), and for exclusion of unwanted fish and other organisms from wetlands (Strong, 1989). Coanda-effect screens are also beginning to be applied as fish screens in situations where fish passage and fish survival are the objectives. Buell (2000) has found favorable results in evaluation of passage of chinook salmon fry and steelhead fry and smolts over a prototype screen installed at the East Fork Hood River irrigation diversion near Parkdale, Oregon.

A key feature of Coanda-effect screens is the tilting of the screen wires in the downstream direction to produce shearing offsets into the flow above the screen. The typical tilt angle is 5° (see fig. 1), but angles of 3° to 6° are available from most screen manufacturers. Wires are typically spaced to produce 1 mm or smaller openings. Flow passes through a Coanda-effect screen through the combined action of orifice flow through the slots and shearing of flow through the offsets created by the tilted wires. The shearing action is enhanced by the fact that the flow remains attached to the top surface of each wire and is thus directed into the offset created at the next downstream wire (Wahl, 1995). This attachment of the flow to the top surface of each wire is an example of the Coanda effect, the tendency of a fluid jet to remain attached to a solid flow boundary. If the wires were not tilted, the flow would travel from the trailing edge of one wire to the leading edge of the next, and the only flow that would pass through the screen would be that due to the orifice flow component.

Numerical Model for Predicting Screen Structure Performance

Flow over the surface of a Coanda-effect screen can be modeled using the energy equation for spatially varied flow with decreasing discharge, as presented by Chow (1959). Since the flow is supercritical, computations begin at the top of the screen and proceed in the downstream direction. Modeling is simplified by the fact that flow over a Coanda-effect screen is frictionless, since the boundary layer is being continually removed from the bottom of the water column by the screen. This fact has been confirmed with velocity measurements made in Reclamation’s laboratory facility using a Pitot tube.

Computation of the flow profile begins with the assumption of potential flow (i.e., zero friction or form loss) over the crest and down the acceleration plate. The head-discharge relation for ideal flow over a broad-crested weir of infinite width is $q=CH^{1.5}$, where q is the unit discharge, C is a discharge coefficient equal to $(2/3)^{3/2}g^{1/2}$, H is the head on the crest. For flows over more efficient crests, such as ogee-shaped spillway crests, a higher flow is obtained for a given head, a fact that is usually accounted for by an increase in the discharge coefficient. Alternately, the increased discharge can be attributed to an increased effective head acting on the crest. This increase is caused by the suction effect associated with increased streamline curvature over the crest (increased over that which would occur due to gravity alone). This effective head can be computed from $H=(q/[(2/3)^{3/2}(g)^{1/2}])^{2/3}$. Once the effective head on the crest and the additional vertical drop from the top of the crest to the start of the screen are known, one can compute the depth, $d_1=q/V_1$, and free-stream velocity at the start of the screen, $V_1=[2g(H_t-d_1\cos\theta_0)]^{1/2}$, where H_t is the effective head on the crest plus the drop height of the acceleration plate, and θ_0 is the angle of screen inclination above horizontal at the top of the screen.

Computations proceed wire-by-wire down the face of the screen, with the model determining the increment of flow diverted through the screen surface at each slot and the depth and velocity of the flow remaining above the screen face at the downstream end of each slot. Calculations continue until the flow reaches a depth of zero, or until the end of the screen is reached. The output from the model is either the wetted length of screen or the discharge through the screen and the bypass flow off of the screen.

The unit discharge, q, through a screen slot is computed from the relation

$$q = C_{d,Total}(t + y_{off})\sqrt{2gE}$$

where E is the specific energy of the flow, $E = D\cos\theta + V^2/2g$, D is the flow depth (measured normal to the screen surface), V is the flow velocity, g is the acceleration of gravity, θ is the slope angle of the screen surface, t is the slot width, y_{off} is the height of the offset created by the tilted wire, and $C_{d,Total}$ is a discharge coefficient for the screen opening. If the screen is concave with radius of curvature r, the specific energy is increased by an amount DV^2/gr to account for the centrifugal acceleration of the flow. The offset height can be computed knowing the wire size, w, the slot width, t, and the wire tilt angle, ϕ, as

$$y_{off} = w\sin\phi\cos\phi + t\sin\phi$$

or approximated for small tilt angles ($\phi \leq 8°$) by

$$y_{off} \approx (w + t)\phi \qquad (1)$$

where ϕ is expressed in radians.

A Model for the Screen Discharge Coefficient

Consider the case of a planar, tilted wire screen that is subjected to impounding of water above the screen or flow across the top of the screen while the underside of the screen is vented to the atmosphere. In a highly supercritical flow (i.e., Froude number, $Fr = V/(gD\cos\theta)^{1/2} >> 1$), water will pass through the slots primarily due to the shearing of thin layers of flow off the bottom of the water column by the offsets created by the tilted wires. The flow rate per unit width through the screen should be proportional to the height of the shearing offsets and the velocity of flow across the screen

$$q_{sh} = C_{d,V}\left(y_{off}V\right)$$

in which $C_{d,V}$ is a discharge coefficient that may vary as a function of several variables, such as the sharpness of the screen wire, the spacing of the wires, boundary layer development along the screen face, etc.

In a decidedly subcritical flow ($Fr << 1$), water primarily passes through the slots in the familiar manner of flow through an orifice. Discharge through the screen is a function of the depth of water above the screen face (i.e., the pressure head on the orifice), the width of the slot, and a discharge coefficient

$$q_o = C_{d,D}\left(t\sqrt{2gD\cos\theta}\right)$$

with g being the acceleration of gravity and θ the angle of inclination of the screen panel. If the screen were concave in shape, the effective head on the orifice slot would be increased from $D\cos\theta$ to $D\cos\theta + V^2 D/gr$.

In the intermediate case (Froude numbers not dramatically less than or greater than 1), the total discharge through the screen should be some combination of the discharges arising from the shearing action and the orifice behavior. If we simply sum these quantities, we obtain

$$q = C_{d,V}\left(y_{off}V\right) + C_{d,D}\left(t\sqrt{2gD\cos\theta}\right) \tag{2}$$

In an intermediate flow, we cannot independently measure q_{sh} and q_o to determine $C_{d,D}$ and $C_{d,V}$. However, we can determine the values of the discharge coefficients by multiple linear regression if the discharge, q, velocity, V, and depth D are measured for several different flow conditions. We could also determine $C_{d,D}$ independently through a simple test in which V is zero. However, it would be quite difficult to determine $C_{d,V}$ independently, since a flow with zero depth would have infinite velocity.

A simplified model might express the total discharge in terms of a total discharge coefficient and the total head above the screen surface (i.e., the specific energy, E)

$$q = C_{d,Total}\left(t + y_{off}\right)\sqrt{2gE} = C_{d,Total}\left(t + y_{off}\right)\sqrt{2g\left(D\cos\theta + V^2/2g\right)}$$

We can obtain a useful relation for the total discharge coefficient by rearranging the total discharge equation

$$C_{d,Total}\left(t + y_{off}\right)\sqrt{2gE} = q = q_{sh} + q_o = C_{d,D}\left(t\sqrt{2gD\cos\theta}\right) + C_{d,V}\left(y_{off}V\right)$$

$$C_{d,Total}\left(t + y_{off}\right) = C_{d,D}\,t\sqrt{\frac{D\cos\theta}{E}} + C_{d,V}\,y_{off}\frac{V}{\sqrt{2gE}} \tag{3}$$

and combining the equations for the Froude number

$$\mathrm{Fr} = \frac{V}{\sqrt{gD\cos\theta}}$$

and the specific energy

$$E = D\cos\theta + \frac{V^2}{2g}$$

to obtain

$$\sqrt{\frac{D\cos\theta}{E}} = \sqrt{\frac{2}{2 + \mathrm{Fr}^2}}$$

$$\frac{V}{\sqrt{2gE}} = \sqrt{\frac{\mathrm{Fr}^2}{2 + \mathrm{Fr}^2}}$$

Substituting these back into equation (3) we obtain

$$C_{d,Total} = \frac{C_{d,D} t \sqrt{\frac{2}{2+\mathrm{Fr}^2}} + C_{d,V}\, y_{off} \sqrt{\frac{\mathrm{Fr}^2}{2+\mathrm{Fr}^2}}}{t + y_{off}} \tag{4}$$

This equation can be viewed as a weighting function in which the weighting factors are the ratios of the offset height to the slot width and ratios of the two terms based on Fr^2. The parameter $2/(2+\mathrm{Fr}^2)$ could be described as the depth energy fraction and $\mathrm{Fr}^2/(2+\mathrm{Fr}^2)$ as the kinetic energy fraction. This equation can also be applied to flows over curved (e.g., concave screens) using a modified Froude number, $\mathrm{Fr}=V/[g(D\cos\theta+V^2D/gr)]^{1/2}$, with the quantity V^2D/gr being the increase in pressure head at the screen face caused by streamline curvature.

The total discharge coefficient, $C_{d,Total}$, expresses the relative flow-passage efficiency of an opening in a tilted-wire screen. Since a screening surface is made up of both slots and corresponding wires that block a portion of the flow area, the overall flow-passage efficiency of a screening surface is better evaluated using the parameter

$$C_{d,Total}(p) = C_{d,Total}\frac{t + y_{off}}{t + w} = \frac{C_{d,D} t \sqrt{\frac{2}{2+\mathrm{Fr}^2}} + C_{d,V}\, y_{off} \sqrt{\frac{\mathrm{Fr}^2}{2+\mathrm{Fr}^2}}}{t + w} \tag{5}$$

where the ratio $(t+y_{off})/(t+w)$ is an effective screen porosity made up of two parts

$$p = p_{orifice} + p_{offset} = \frac{t}{t+w} + \frac{y_{off}}{t+w}$$

Differences in screen performance related to variations in the orifice porosity will be most noticeable at low Froude numbers, where the depth-energy fraction is large and $C_{d,Total}$ is strongly influenced by the orifice component of flow. Since the orifice porosity, $t/(t+w)$, is affected by changes to either t or w, we should expect changes in screen performance at low Froude numbers when the wire size and slot spacing are varied.

Differences in screen performance due to variations in the offset porosity will be most noticeable at high Froude numbers, where the kinetic energy fraction is large and $C_{d,Total}$ is dominated by the shearing component of flow. Recalling from eq. (1) that the offset height $y_{off} \approx (t+w)\phi$, the offset porosity is approximately $(t+w)\phi/(t+w) \approx \phi$. Thus, changes in the wire width or slot size will have little effect on screen performance at high Froude numbers, but the wire tilt angle ϕ will have a direct effect.

Values of Screen Discharge Coefficients

A small screen section (76 mm long × 70 mm wide) with wires that are 2.381 mm (3/32 inch) wide, a 1 mm slot spacing, and a 5° wire tilt, was tested in Reclamation's hydraulics laboratory, installed in a 30.5 cm (1 ft) wide test flume on a 37° slope. The Froude number was varied from about 2 to 8, and flow rates through the screen were measured to determine values of $C_{d,Total}$. Multiple linear regression showed that $C_{d,V} \approx 0.45$ and $C_{d,D} \approx 0.43$. Additional tests of other screens are planned, but assuming for now that these values are constant over wider ranges of Froude numbers and for other screen configurations, the general forms of the $C_{d,Total}$ and $C_{d,Total}(p)$ functions and the influence of differences in screen geometry can be examined. Computed curves of $C_{d,Total}$ and $C_{d,Total}(p)$ vs. Froude number are shown in figure 2 (arithmetic scales) and figure 3 (log-log scales) for four screens with different wire sizes, slot widths, and wire tilt angles, at Froude numbers ranging from 0.1 to 20. The data obtained from the tested screen are also shown. It is notable that in figure 3 the $C_{d,Total}$ vs. Fr curves are not linear when plotted on log-log scales, although if one were to limit the view to a narrower range of Froude numbers, a linear relation in log space leading to a power-curve relation in arithmetic space might be assumed.

General Observations – Sensitivity to Screen Geometry

The plots of $C_{d,Total}$ illustrate the fact that changes in any single parameter of screen geometry (i.e., wire width, slot size, or wire tilt angle) have opposite effects on the value of $C_{d,Total}$ at small and large Froude numbers. In a middle range of Froude numbers, the value of $C_{d,Total}$ is relatively unaffected by changes in screen geometry, but is sensitive to the value of the Froude number.

The plots of $C_{d,Total}(p)$ show that at high Froude numbers the only aspect of screen geometry that significantly affects flow through the screen is the wire tilt angle. However, at low Froude numbers, changes in wire width and slot size can have a significant effect, while the sensitivity to the wire tilt angle is reduced. Finally, at low Froude numbers the amount of flow through a screen for a given specific energy, as represented by $C_{d,Total}(p)$ is significantly increased over that obtained at high Froude numbers.

Performance of Complete Screen Structures

When evaluating total discharge through typical Coanda-effect screen structures, a range of Froude numbers are present over the length of a screen, varying from relatively low Froude numbers at the top of the screen where velocities are still relatively low and flow depths are relatively large, to very high Froude numbers near the toe of the screen slope, where velocities are high and depths are very shallow. For structures operating with little or no bypass flow, the average Froude number over the length of the screen will typically be in the middle to upper range of that shown in figures 2 and 3, where flow through the screen is relatively insensitive to the wire width and slot size (i.e., the orifice porosity). However, as the depth of flow on a screen is increased (likely leading to some overflow off the toe of the screen), the average

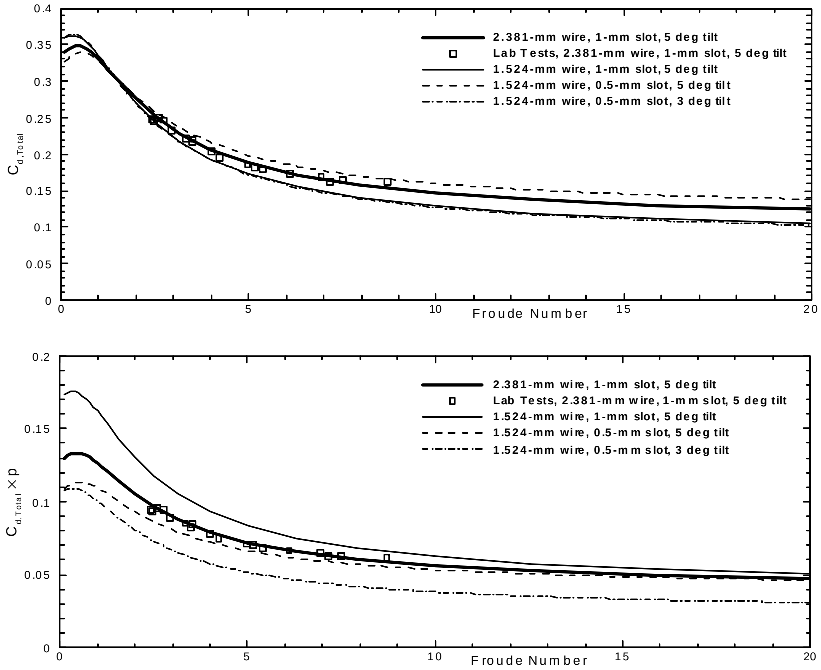

Figure 2. — Variation of the total discharge coefficient, $C_{d,Total}$ and the screen performance parameter, $C_{d,Total}\times(p)$, for several configurations of tilted-wire screens.

Froude number over the length of the screen will be reduced and flow through the screen will increase significantly and become more sensitive to the orifice porosity.

The complete numerical model for Coanda-effect screen structure performance has been applied to results from past (Wahl, 1995) and recent laboratory tests conducted by Reclamation on prototype Coanda-effect screen structures. When there is no bypass flow, the model predicts the wetted distance of screen required to capture all of the flow. When there is bypass flow, the model predicts the flow through the screen and the bypass flow. Performance of the model is tested by comparing the predictions of wetted screen length and screened flow to observed values from the laboratory tests. Figure 4 shows that with $C_{d,V}$ = 0.45 and $C_{d,D}$ = 0.43, the model effectively predicts the observed screen performance of about 100 tests on eight different Coanda-effect screen structures utilizing 1 mm or 0.5 mm slot widths, initial (top-of-screen) inclination angles of 45° to 60°, and screen arc lengths ranging from 0.46 m (18 inches) to 1.12 m (44 inches). The slight overprediction of wetted flow distance may be due to a bias in the visual observations of wetted flow distance, which is somewhat difficult to observe precisely; the predictions of discharge through the screen from the tests in which there was bypass flow are quite good.

Figure 5 shows the application of the numerical model to three hypothetical screen structures that are identical except for differences in the wire width and slot size. Differences in flow through the screen are significant, but the changes are not as great as the changes in nominal screen porosity, $t/(t+w)$ (i.e., the orifice porosity). For example, reducing the slot width from 1 mm to 0.5 mm reduces the porosity by 41%, from 0.307 to 0.181, but produces only a 15 to 20 percent reduction in flow through the screen for a given inflow to the structure.

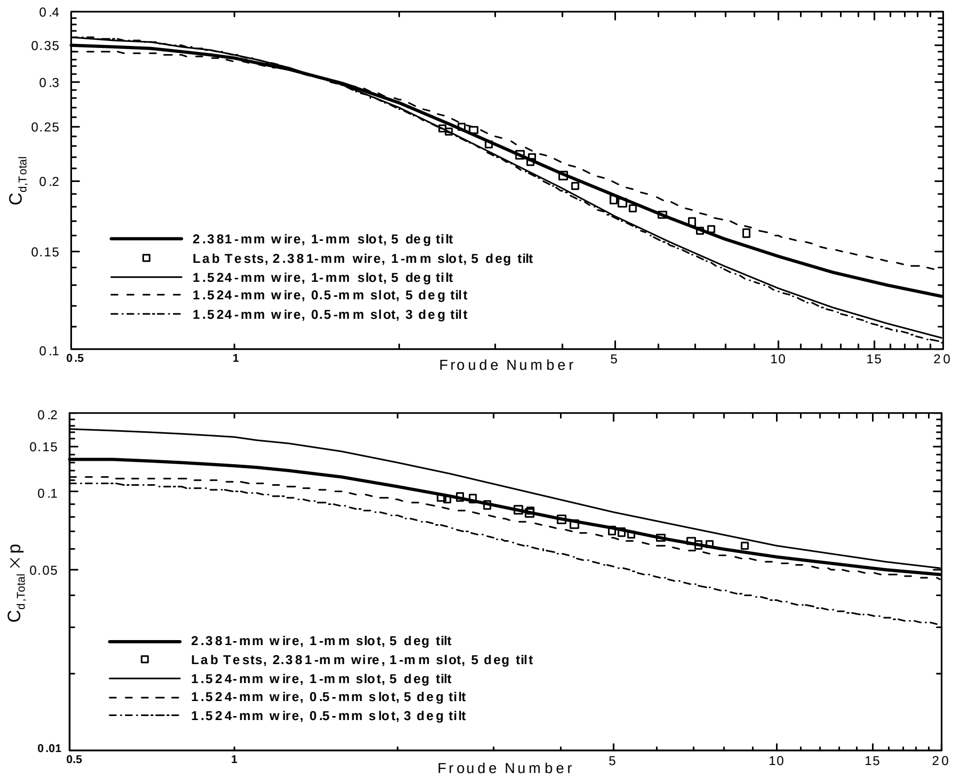

Figure 3. — Total discharge coefficients and screen performance parameters for several configurations of tilted-wire screens (log-log scales).

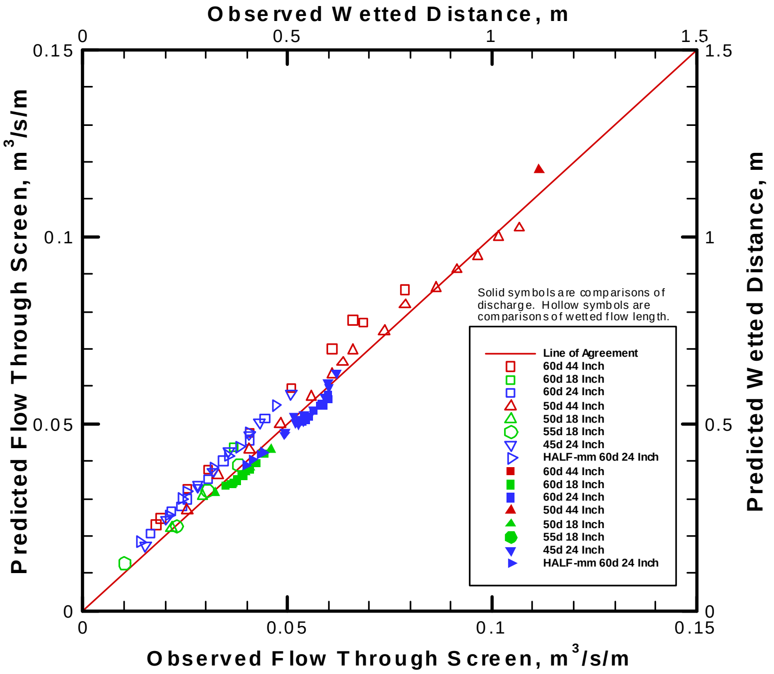

Figure 4. — Comparing predicted and observed screen performance to illustrate the ability of the numerical model to predict wetted flow distance and screened flow. The slight overprediction of wetted distance may be due to a bias in the observed wetted distances.

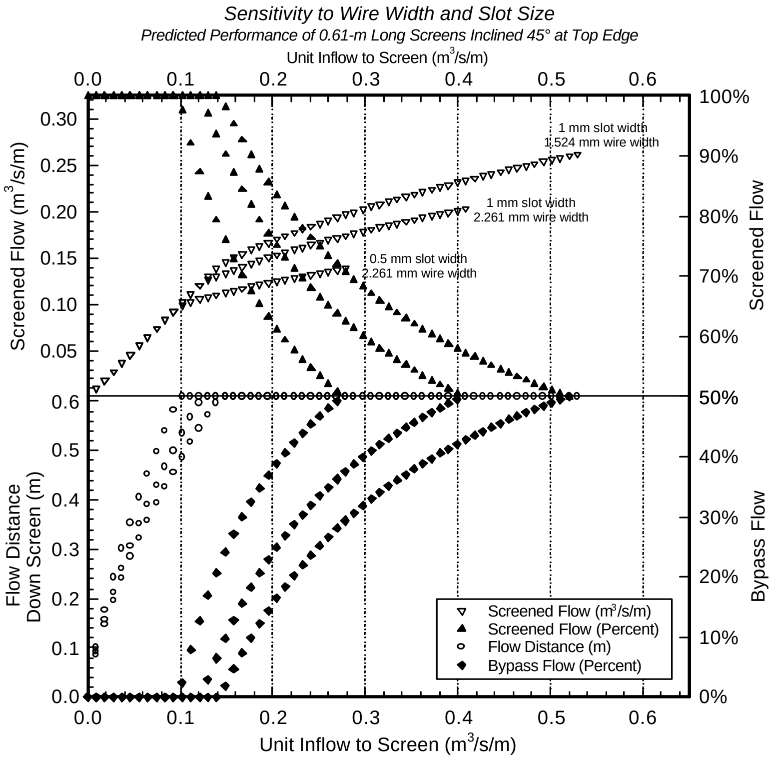

Figure 5. — Predicted hydraulic performance of three 45° inclined screens with varying wire widths and slot sizes.

Conclusions

A numerical model for hydraulic performance of Coanda-effect screens has been developed and has successfully predicted the performance of several laboratory-tested prototype-scale screen structures. The model incorporates a relation for the discharge coefficient of tilted wire screens that is shown to be a function of the Froude number of the flow passing over the screen surface. The model allows prediction of changes in screen performance caused by variation of screen design parameters including drop height, wire width, slot size, wire tilt angle, screen inclination angle, and screen arc radius.

Acknowledgments

The majority of the work described in this paper was funded by the Reclamation Research and Technology Transfer Program, projects NM022, ER.99.29 and ER.99.10. A portion of the test data used to calibrate the numerical model was collected under a cooperative agreement with the Metro Wastewater Reclamation District, Denver, Colorado.

References

Babb, A. F., and S. Schlenker (1999). “Flow Through Perforated Floor Plates on Supercritical Slopes.” *Proceedings*, 1999 International Water Resources Engineering Conference, Seattle, Washington, August 8-12, 1999.

Buell, J. (2000). “Biological Performance Tests of East Fork Irrigation District’s Sand Trap and Fish Screen Facility.” Buell & Associates, Inc., 2708 S.W. Bucharest Ct., Portland, OR 97225.

Chow, V. T. (1959). *Open-Channel Hydraulics*. McGraw-Hill Book Company, New York, NY.

Finch, H. E., and Strong, J. J. (1983). *Self-Cleaning Screen*. U.S. Patent 4,415,462. November 15, 1983.

Ott, R. F., Boersma, E., and Strong, J. (1987). "Innovative Intake Protects Both Aquatic Life and Turbine Equipment." *Waterpower '87*, Portland, Oregon, Aug. 19-21, 1987.

Strong, J. (1989). “Innovative Fish Barrier for Waterfowl Lake Restoration.” *Proceedings of the Twenty-Eighth Annual Conference of the Association of Conservation Engineers*, Lexington, KY, October 8-12, 1989.

Strong, J. J., and Ott, R. F. (1988). “Intake Screens for Small Hydro Plants.” *Hydro Review*, vol. VII, no. V, October 1988.

Wahl, T. L. (1995). "Hydraulic Testing of Static Self-Cleaning Inclined Screens." *Water Resources Engineering*, Proceedings of the First International Conference on Water Resources Engineering, ASCE, San Antonio, Texas, August 14-18, 1995.

Disclaimer

References to commercial products in this paper are for informational purposes only and do not constitute endorsement by the authors or the U.S. Bureau of Reclamation.