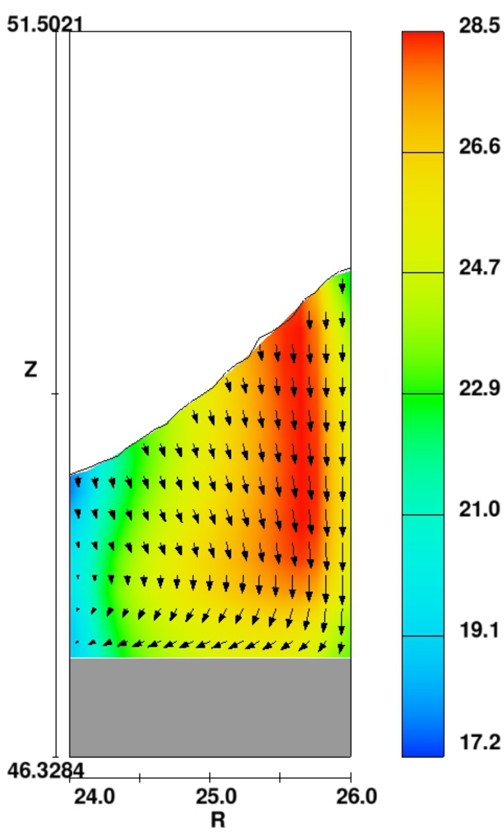
RECLAMATION

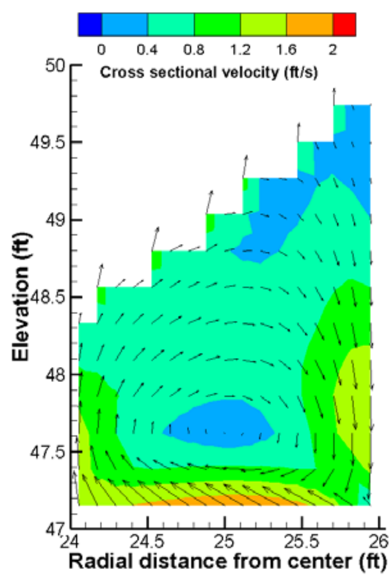
Managing Water in the West

Helix Downstream Fish Passage Design

Research and Development Office
Science and Technology Program
Final Report ST-2016-3437-01

HL-2016-10





U.S. Department of the Interior
Bureau of Reclamation
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Mission Statements

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14. ABSTRACT *(Maximum 200 words)*

Reclamation's work on downstream fish passage for Cle Elum Dam led to the initial development of a helix design that will allow self-guided passage from a reservoir where water surface fluctuations are greater than 50 ft in elevation. Successful and extensive physical and numerical modeling from the Cle Elum project was used as a starting point for developing a more general design that can be adapted for widespread application to dam sites throughout the United States.

Numerical analyses were made using FLOW-3D computational fluid dynamics software to apply the helix design to other sites where the discharge range, elevation drop, and velocity criteria requirements are different from those at Cle Elum Dam. Using the CFD modeling tools and a range of criteria, optimal helix geometry for each case study were determined.

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Executive Summary

Providing access to high value headwater spawning and rearing habit that has been cut off due to the construction of dams is a key component for the recovery of endangered fish species. Dams constructed without allowance for upstream and downstream fish passage have resulted in the extirpation of anadromous salmon and steelhead populations in many areas. Throughout the Pacific Northwest region there is a renewed effort to provide upstream and downstream passage at mainstem storage reservoirs to access this high value habitat previously accessible prior to dam construction. Storage reservoirs present many unique challenges to fish passage. The most obvious challenge is dam height, with many dams being from 100 ft to more than 500 ft high. Second, storage reservoirs are operated to store and release water seasonally, creating reservoir water surface fluctuations of 10s or 100s of feet in a year. To date, most high dams where downstream fish passage has been established are hydropower generation facilities with minimal fluctuation in pool elevation. Generally, fish passage structures at these facilities have consisted of trap and haul methods utilizing manned surface collectors, but these have very high operation and maintenance (O&M) costs.

The helix design now being constructed for downstream fish passage at Cle Elum Dam [1] has the potential to be adapted for downstream fish passage at other locations. To provide designers with a basis for adapting the concept to other locations, the helix fish passage channel was studied further, extending the work done to develop the Cle Elum Dam design. This research is needed to reduce the high cost of implementing passage on storage reservoirs.

This study investigated six configurations of helix chutes operating at 200 ft^3/s discharge. The objectives of the study were to optimize the designs to minimize injury and disorientation to fish during downstream passage. For the 11.75-ft loop height simulations, the 2.0 foot width appears to be optimal. For the 20.0-ft loop height simulations, the 2.0 foot width also appears to be optimal. In both cases these chute widths are approximately the same as the average flow depths.

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Introduction

Background

The U.S. Bureau of Reclamation (Reclamation) has completed the development of a downstream passage design for Cle Elum Dam that consists of a series of structures that will allow fish to self-guide into a structure that carries them around the dam and into the downstream river channel. Downstream fish passage at high head dams has always been difficult. Most high dams with downstream fish passage are hydropower generation facilities with minimal fluctuation in pool elevation. Generally, fish passage structures at high head facilities consist of manned surface collectors with trap and haul methods that require high operation and maintenance (O&M) costs. Cle Elum Dam is a storage reservoir that experiences seasonal swings in reservoir water surface elevation of about 100 feet. Surface collectors are not compatible with such large reservoir fluctuations, so new fish passage concepts were developed and evaluated for use at this site.

The final design includes an intake structure, helical free-surface fish passage channel (the helix), tunnel, and outfall. The helix is described in a 2015 report [1]. The study investigated 8 configurations in order to find an optimal shape. These configurations were:

1) 6 ft diameter round pipe, 52 ft helix diameter;
2) 6 ft diameter round pipe, 40 ft helix diameter;
3) 6 ft diameter round pipe, 80 ft helix diameter;
4) 4 ft wide chamfered rectangular box, 52 ft helix diameter;
5) 4 ft wide rectangular box, 52 ft helix diameter;
6) 4 ft wide rotated box, 52 ft helix diameter;
7) 5 ft wide rotated rectangular box, 52 ft helix diameter;
8) 5 ft wide rectangular box, 52 ft helix diameter.

The study found that the 4 ft wide rectangular box and 52 ft helix diameter (option 5) provided the least roll over of the flow and the greatest cross sectional area of flow that was less than 1 ft/s.

The Helix design now being constructed for downstream fish passage at Cle Elum Dam [1] has the potential to be adapted for downstream fish passage at other locations. This research study was conducted to provide designers with a basis for adapting the concept to other locations with a range of site conditions.

Goals for Project

Providing access to high value headwater spawning and rearing habit that has been cut off due to the construction of dams is a key component for the recovery of endangered fish species. Dams constructed without allowance for upstream and downstream fish passage have resulted in the extirpation of anadromous salmon and steelhead populations in many areas. Throughout the Pacific Northwest region there is a renewed effort to provide upstream and downstream passage at mainstem storage reservoirs to access this high value habitat previously accessible prior to dam construction. Storage reservoirs present many unique challenges to fish passage. The most obvious challenge is dam height, since many storage dams range from 100 ft to more than 500 ft high, and traditional fish passage solutions become infeasible or cost-prohibitive for such large heights. Second, storage reservoirs are operated to store and release water seasonally, creating reservoir water surface fluctuations of 10s or 100s of feet in a year.

On April 7, 2011 the NOAA (National Oceanic and Atmospheric Administration) Southwest Region transmitted a letter to Reclamation concerning the reasonable and prudent alternative (RPA) to comply with the recent Biological Opinion (BO), in part stating "The RPA includes a new year-round storage and temperature management program for Shasta Reservoir and the Upper Sacramento River, as well as long-term passage prescriptions at Shasta Dam and reintroduction of winter-run salmon into its native habitat in the McCloud and/or Upper Sacramento rivers."

This would require Reclamation to design and construct facilities for upstream and downstream fish passage at Shasta Dam (523 ft high), which is a storage reservoir with significant pool fluctuation. Similar fish passage facilities are being considered for other Central Valley Project dams including Folsom Dam (275 ft high).

In order to retrofit such existing facilities to accommodate downstream fish passage, the helix fish passage technology developed for Cle Elum Dam was studied further to allow the technology to be applied successfully at other sites. This research is needed to reduce the high cost of implementing fish passage at large storage reservoirs.

The goal of this study is to identify optimum flow conditions for three species of salmon (sockeye, coho and spring chinook) by comparing the velocity conditions at various cross sections of a helical fish passage channel.

Study Methods

CFD Modeling

This study used the commercially available Computational Fluid Dynamics program FLOW-3D Version 11.0.2.03 by Flow Science Inc. [1], which is a finite

[1] Flow Science Inc., Introduction to FLOW-3D, 1996.

difference, free surface, transient flow modeling system that was developed to solve the Navier-Stokes equations, using up to three spatial dimensions.

The finite difference equations are based on a fixed Eulerian mesh of non-uniform rectangular control volumes using the Fractional Area/Volume (FAVOR) method[2]. Free surfaces and material interfaces are defined by a fractional volume-of-fluid (VOF) function. FLOW-3D® uses an orthogonal coordinate system as opposed to a body-fitted system.

The results from FLOW-3D simulations were analyzed to identify, quantify, and qualify the key hydraulic characteristics.

CFD Parameters

The following assumptions were made and options selected for each simulation:

- One fluid (air simulated with void space)
- Free surface
- Turbulence model: Renormalized Group (RNG) model with Dynamically computed Maximum Turbulent Mixing Length
- Pressure Solver: Generalized Minimal Residual (GMRES)
- Water at 20° Celsius (68° degree Fahrenheit)
  - Water density of 1.9403 slugs/ft^3
  - Dynamic viscosity of 2.08855×10^{-5} lbf-s/ft^2
  - Incompressible
- Roughness height (rugosity) of 0.0042 ft for smooth concrete with minimal joint interference
- Volume of Fluid Advection: Automatic fluid convection
- Momentum Advection: First Order
- Convergence controls: Default values were used
- Gravity: -32.2 ft/s^2 in the vertical (Z) direction
- The cylindrical coordinate system was used. The outer helix wall was defined by the helix diameter of 52 ft (same diameter as the Cle Elum final design).

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[2] J.M. Sicilian, "A FAVOR Based Moving Obstacle Treatment for FLOW-3D," Flow Science, Inc. Technical Note #24, April 1990 (FSI-90-TN24).

Solids Model Development

The chute was defined using stereolithography files that were generated using commercially available AutoCAD 2015 and imported into FLOW-3D.

Solid walls, inner and outer, were defined by the cylindrical coordinate system. Six or more helix loops were simulated with the data extracted from the end of the fourth loop.

Computational Workstation

These simulations were performed on a Dell Precision T7600 which has a Dual Eight Core XEON E5-2687W, running at 3.1GHz.

Engineering Evaluation Parameters

Since there were no existing guidelines for evaluating cross sections extracted from the Cle Elum helix chute, several parameters were established for comparing designs and determining whether or not secondary flow currents would cause injury to fish. These key parameters were evaluated and compared among the designs in an effort to fulfill the following objectives:

- Minimizing impingement of flow and fish – This was evaluated based on magnitude of sweeping velocity that could potentially sweep fish into a sidewall.

- Smooth flow conditions – This was evaluated based on the percentage area within the cross section where velocity (relative to the fish and described in the next section) was 1.0 ft/s or less. This was determined as the ideal fish location within the body of flow.

- Minimizing flow rotation that can cause the body of flow to roll-over, potentially leading to injury or disorientation of fish – This was evaluated by subtracting the minimum (downward) velocity from the maximum (upward) velocity at a flow cross section after flow in the helix chute stabilized. This was designated as the Roll Over Potential (ROP) parameter.

- Reduced Secondary flow rotation that can cause fish to rollover - This was evaluated by observation, based on tightness of rotation.

This study focused on the percentage area within the cross section where velocity (relative to the fish) was 1.0 ft/s or less since the species of concern were considered to be able to maintain control under this condition.

Analysis of a Fish’s Point of View in the Chute

The Cle Elum helix studies [1] found that a fish’s helix transport experience was extremely difficult to determine from direct evaluation of the helix flow field. To illustrate this, one cross sectional velocity plot from FLOW-3D results is presented in Figure 1. Since the average downward velocity is greater than the flow circulation velocities within the channel cross section, plotting absolute (Eulerian) velocity vectors makes it very difficult to visualize flow features that fish would experience as they pass downstream with the flow. Key features like rotational flow were very difficult to visualize and analyze without adjusting velocities to the fish’s moving frame of reference.

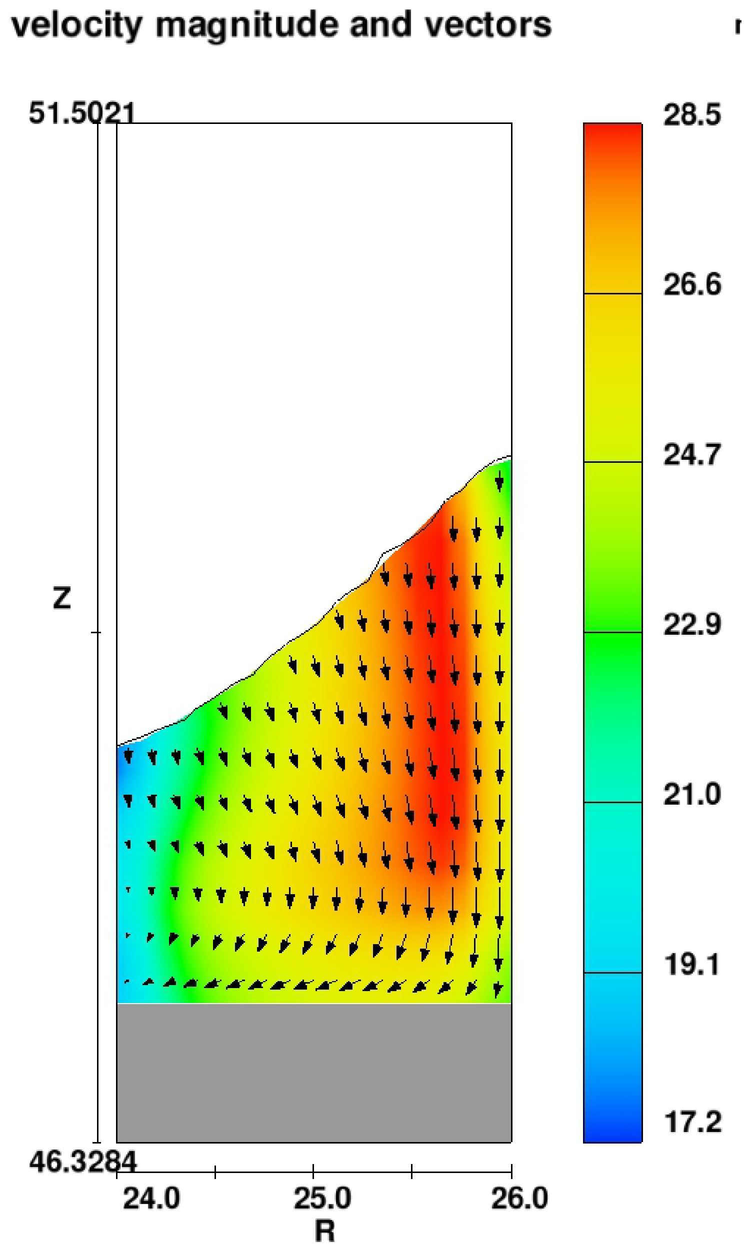

Figure 1. Cross section of flow from a FLOW-3D simulation.

For the data analysis of each flow field, the average vertical velocity was calculated and then subtracted from the flow field. This produced an adjusted secondary flow field that would be experienced by a fish moving down the chute at a similar average average vertical velocity (Figure 2). This is a Lagrangian view of the flow field. The Cle Elum Design and Core teams concluded that the species of interest would be able to negotiate secondary flows with a relative velocity less than 1 ft/s, and maximizing the area of the cross section that contained flows below this velocity level would minimize potential injury or disorientation of fish.

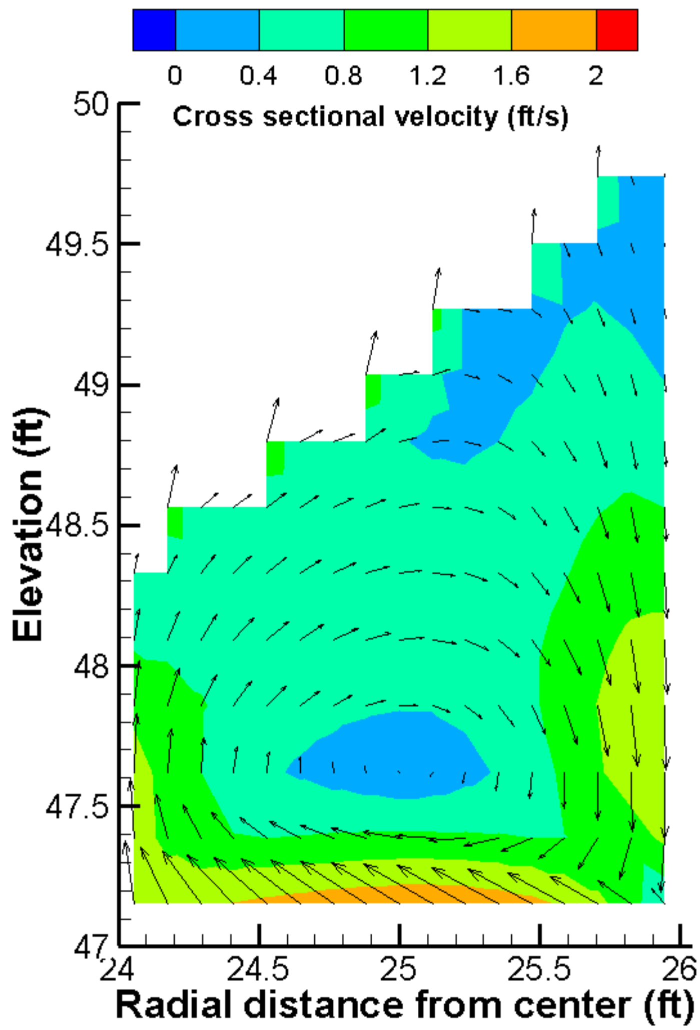

Figure 2. Lagrangian vector field.

Data Results and Conclusions

Seven configurations were simulated. Each used a discharge of 200 ft^3/s. Each simulation had a loop height of either 11.75 feet or 20 feet. One simulation result was discarded due to an incorrect input parameter. An overview of the simulations is given in Table 1.

The analysis of the data is shown in Table 2. For the 11.75 ft loop height simulations, the 2.0 foot width appears to be optimal. For the 20.0 ft loop height simulations, the 2.0 foot width also appears to be optimal.

Table 1. Overview of simulations.

HEIGHT (FT)	CHUTE WIDTH (FT)	CELL SIZE (FT XFT)	SIMULATION TIME (DAY)
11.75	1.0	0.11 x 0.11	31
11.75	1.5	0.17 x 0.17	18
11.75	2.0	0.12 x 0.24	23
11.75	4.0	0.24 x 0.24	7
20	2.0	0.12 x 0.24	30
20	2.5	0.15 x 0.15	33

Table 2. Data analysis

HEIGHT (FT)	CHUTE WIDTH (FT)	AVERAGE VERTICAL VELOCITY (FT/S)	FLOW AREA (FT^2)	AVERAGE FLOW DEPTH (FT)	AREA LESS THAN 1 FT/S (FT^2)	PERCENT OF AREA THAT IS LESS THAN 1 FT/S
11.75	1.0	-1.98	7.2	7.2	5.4	75.0
11.75	1.5	-2.07	5.8	3.9	4.2	72.0
11.75	2.0	-1.70	4.0	2.0	3.3	83.0
11.75	4.0	-1.96	7.1	1.8	5.7	81.0
20	2.0	-4.50	5.6	2.8	3.0	54.0
20	2.5	-4.30	5.8	2.3	3.2	55.0

Recommendations

The width of the rectangular helix chute appears to have a minor effect on the percent of the channel cross-sectional area that has a relative velocity less than 1 ft/s. A chute width approximately equal to the average flow depth appears to be optimal. Increasing the slope of the chute also appears to reduce the area that is 1 ft/s or less.

Further investigations could consider that the configurations studied herein had widely different height to width aspect ratios than those used for the fish passage at Cle Elum Dam. Accordingly, a fish near the top of tall and narrow chute may not experience similar flow conditions as a fish near the bottom (Figure 3).

Roll Over Potential (ROP) was used in the Cle Elum study to indicate a potential for rolling a fish over causing disorientation, and was calculated as the difference of the maximum and minimum vertical velocities. The parameter did not take into account the length between these velocities, which would indicate the maximum speed of revolution of the flow. Other parameters that may better describe local stresses on the fish could be velocity gradient[3], vorticity[4], relative helicity[5], circulation[6], or shear stress[7] using live fish studies with CFD or PIV (Particle image velocimetry). These values and vector fields can be computed in various post-processing tools such as Tecplot. As with the study for the Cle Elum helix, it seems that lower values for each parameter would promote safe fish passage, but the limits of what is acceptable are unknown, so this could also be a topic for further research.

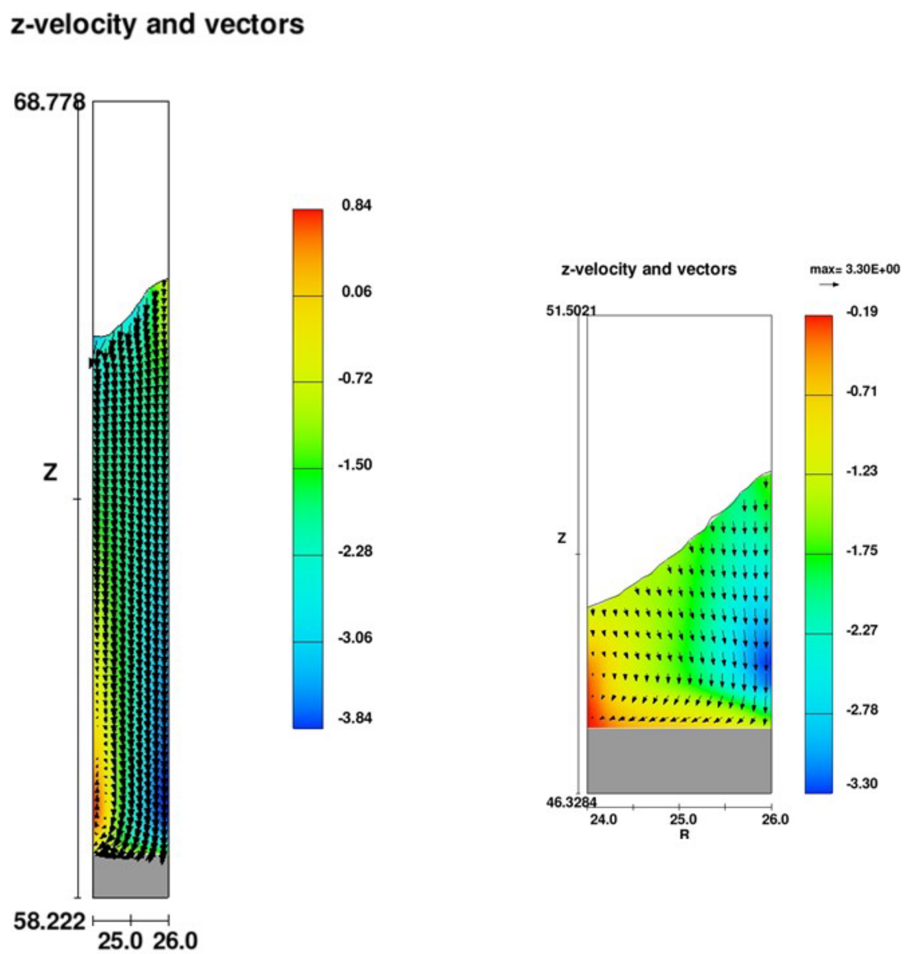

Figure 3. Vertical velocities for two simulations.

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[3] For a description of velocity gradient see https://en.wikipedia.org/wiki/Velocity_gradient (9/29/2016)
[4] For a description of vorticity see https://en.wikipedia.org/wiki/Vorticity (9/29/2016)
[5] For a description of helicity see https://en.wikipedia.org/wiki/Hydrodynamical_helicity (9/29/2016)
[6] For a description of circulation see https://en.wikipedia.org/wiki/Circulation_(fluid_dynamics) (9/29/2016)
[7] For a description of shear stress see https://en.wikipedia.org/wiki/Shear_stress (9/29/2016)

References

1. Hanna, Leslie J.; Higgs, Jim; Mefford, B.; Wagner, J., “Helix Design for Downstream Fish Passage at Cle Elum Dam”, U.S. Bureau of Reclamation, Hydraulic Laboratory Report, HL-2015-01