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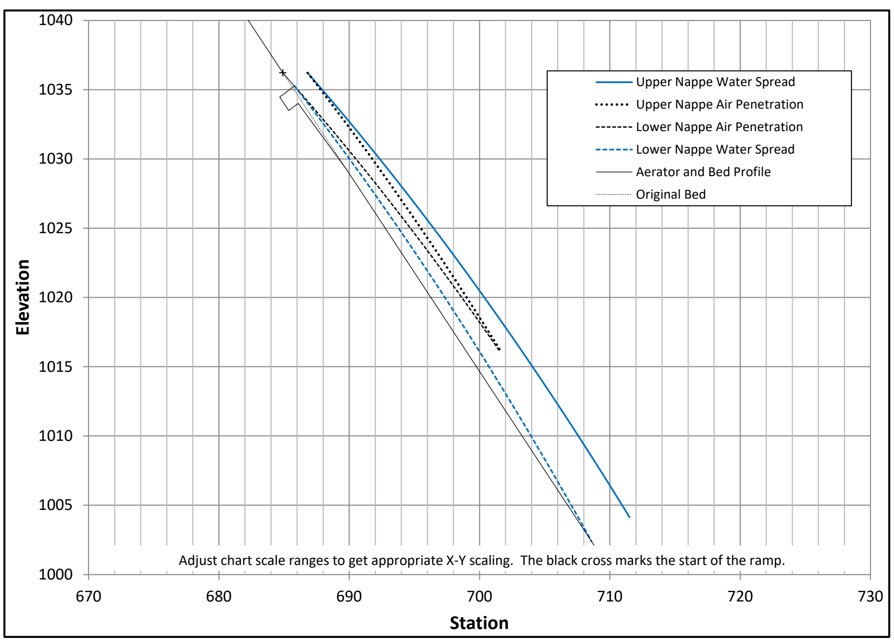
Hydraulic Laboratory Report HL-2019-03

SpillwayPro — Tools for Analysis of Spillway Cavitation and Design of Chute Aerators

A Supplement to Engineering Monograph 42 – *Cavitation in Chutes and Spillways*



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Hydraulic Investigations and Laboratory Services Group
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14. ABSTRACT
In April of 1990 the Bureau of Reclamation published Engineering Monograph No. 42, Cavitation in Chutes and Spillways. The monograph presented the state of the art for analyzing the potential for damaging cavitation in open channel spillways. The monograph was accompanied by a series of FORTRAN computer programs to compute water surface profiles, cavitation and aerated flow characteristics, optimized spillway profiles, spillway aerator ramp geometries and air flow characteristics, and damage indexes for spillway operations at varying flow rates over extended durations. Although the science and theory of these programs is still valid, computer technology advances have made it problematic to use the original programs. This report describes *SpillwayPro*, a new version of the suite of programs for cavitation analysis implemented on a Microsoft Excel spreadsheet platform. The Excel spreadsheets provide similar functionality as the original programs and include improvements inspired by applications of the software to real spillways.

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A Supplement to Engineering Monograph 42 – *Cavitation in Chutes and Spillways*

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

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Foreword

In April of 1990 the Bureau of Reclamation published Engineering Monograph No. 42, *Cavitation in Chutes and Spillways*. This comprehensive publication written by Dr. Henry T. Falvey, a Research Engineer with Reclamation's Hydraulic Laboratory, was a culmination (of sorts) of Falvey's career at Reclamation. Falvey had studied cavitation and its damaging effects on hydraulic structures throughout his 25+ years at Reclamation. He had become a world renowned expert on the subject and was a popular speaker, reviewer, and consultant on the topic when he retired in 1987. To accompany the Monograph, Dr. Falvey developed a series of computer programs coded in FORTRAN that were included with the document (on 5¼ inch floppy disks). The foundation of this suite of programs was HFWS (Henry Falvey Water Surface), a program that Dr. Falvey developed and improved throughout his career for use on problems of high-velocity flow, aerated flow, and cavitation. In fact, a printed code listing of one earlier version of HFWS was also provided in Engineering Monograph 41, Air-Water Flow in Hydraulic Structures. The other four programs included with Monograph 42 addressed Aerator Ramp Trajectory and Air-Flow Calculations, Constant Cavitation Number Spillway Design, Controlled Pressure Spillway Design, and Damage Index Calculation from Historical Data. Now, in 2019, as one might expect with the passage of almost 30 years, even though the science and theory behind these programs is still valid, it has become a challenge to run the programs in their original form.

Through Reclamation's Manuals & Standards Program (which originally funded the publication of Monograph 42), an effort to update the programs and restore them to utility in today's world was started in 2016. After Dr. Falvey's retirement from Reclamation, he had arranged in about 2001 for the FORTRAN codes to be converted to a series of Visual Basic routines running within a Microsoft Excel spreadsheet platform. Unfortunately, this conversion contained enough bugs that Reclamation staff still relied upon the original FORTRAN codes when needed, thus foregoing the advantages that a spreadsheet application could offer. To bring the programs into the modern era, the new project sought to debug the Visual Basic code in the spreadsheet application so that its results would match the old FORTRAN codes. A few bugs in the original programs were also detected and fixed in the process of rechecking the major algorithms used within the multiple programs, and some new features envisioned by Dr. Falvey and requested by users were also added. The result is *SpillwayPro*, an Excel spreadsheet that mirrors the original programs and adds improvements, operating in a user-friendly environment that allows maintenance for continued future use.

Monograph 42 and the accompanying programs were heavily influenced by Reclamation's experience with severe cavitation damage to the tunnel spillway at Glen Canyon Dam in 1983 and related experience designing spillway aerators for Glen Canyon, Hoover, Yellowtail, Flaming Gorge, Blue Mesa, and McPhee dams. The hydraulics laboratory responded to the Glen Canyon situation with emergency physical model studies and design efforts to develop spillway aerator ramps that would protect against future cavitation damage. The development of the computer programs was strongly influenced by the pressing need for analytical tools to accompany the physical modeling efforts. In early 2017 a new spillway emergency developed at Oroville Dam, a non-Reclamation facility designed and constructed by the California Department of Water Resources (DWR). Damage to the main spillway chute floor led to failure of multiple spillway chute panels and rapid erosion of a large scour hole and new channel outside of the constructed chute alignment. The water surface profile and aerator trajectory programs proved useful for the evaluation of proposed designs for retrofit ramps that might flip the spillway discharge further downstream to reduce the hydraulic attack upon the upstream portion of the scour hole. This application led to the addition of several new capabilities and outputs in the water surface profile and trajectory programs, most notably new calculations of the thrust forces applied to the ramp and the stream power along the chute and at jet impact locations. Finally, recent application of the water surface profile program to potential redesign of the Shasta Dam spillway led to improvements in the calculation of streamline curvature effects.

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Henry T. Falvey

March 2019 — Denver, Colorado

Introduction

Cavitation can cause devastating damage to spillway channels associated with high dams. *SpillwayPro*, the cavitation analysis spreadsheet described here, provides access to a suite of programs based on the FORTRAN programs originally presented in Engineering Monograph No. 42 (EM42), *Cavitation in Chutes and Spillways* (Falvey 1990). The original FORTRAN programs and the new Visual Basic for Applications (VBA) routines in the spreadsheet carry out the following analyses:

1. Water surface profile computation to determine hydraulic characteristics of flow, including cavitation and aerated flow parameters (program HFWS, described in Appendix A of EM42);
2. Spillway aerator ramp trajectory and air flow calculations (program HFTRAJ, Appendix D of EM42);
3. Design of "equal cavitation number" spillway profiles (program HFECN, Appendix C of EM42);
4. Design of "controlled pressure" spillway profiles (program HFCONP, Appendix C of EM42); and
5. Calculation of damage index values based on spillway operational history records (program DINDX, Appendix E of EM42).

The spreadsheet interface simplifies the assembly, organization, and presentation of both input and output data. With a few exceptions, the mathematical algorithms utilized in the code are the same as those described in EM-42. Changes and additions are described in this user's guide, but otherwise this guide describes only the functional use of the spreadsheets, with limited discussion of the concepts and principles of cavitation analysis. Engineering Monograph 42 remains the definitive reference and resource for understanding how to apply these computational tools to a cavitation design or analysis problem. The monograph is available at this time in PDF format from the Bureau of Reclamation Hydraulics Laboratory at:

- http://www.usbr.gov/tsc/techreferences/computer software/software/EM42/

Verification of Codes

The *SpillwayPro* computational routines written in Visual Basic for Applications were verified through a systematic process:

1. Recompile the original FORTRAN programs using the open-source GNU FORTRAN 77 (g77) compiler.

2. Build equivalent input data sets for the Excel spreadsheet application and the FORTRAN programs to represent the Glen Canyon Dam tunnel spillway example from EM42.
3. Execute both sets of programs (Excel and FORTRAN), compare results to the printed example results in EM42, and resolve differences between them.

This verification process revealed one significant problem in the original water surface profile program, which was the inclusion of a transition loss factor even at stations where the cross section shape and size were constant (see Differences from EM42 Programs). This problem was corrected in the *SpillwayPro* water surface profile program. Two factors affecting the pressure beneath the aerator nappe were also reevaluated during testing of the trajectory program, leading to changes in that program from the versions originally published in EM42. Several problems were also found and fixed in the program that computes controlled-pressure spillway profiles.

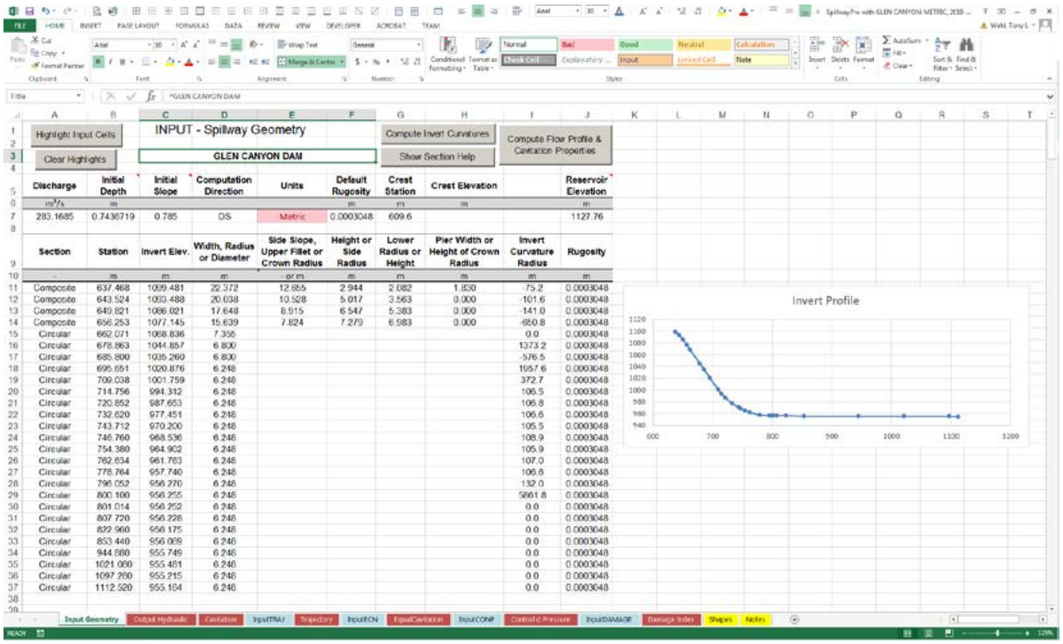
With input from Dr. Falvey, new features were added to the water surface profile programs, including roll wave detection and calculations of Froude number and stream power. Several additional outputs were also added to the trajectory program, many inspired by its recent use on Oroville Dam. Finally, new example applications were developed for the user's guide that follows.

The Structure of *SpillwayPro*

The Spreadsheet Pages

Unlike traditional computer programs that separate the computational instructions and logic (the compiled "code") from the input and output data files, the *SpillwayPro* cavitation spreadsheet workbook integrates the program code and input/output data into a single file. After opening the workbook file, the user will see a set of spreadsheet pages organized as shown in Figure 1. Light-blue colored spreadsheet tabs contain input data, and dark-red spreadsheet tabs contain tabular and graphical output. The tabs are arranged from left-to-right so that each input page precedes its corresponding output page(s). The **Input Geometry** page provides input for the water surface profile program that computes both basic hydraulic output ("**Output Hydraulic**") and cavitation characteristics ("**Cavitation**") during a single program execution. The **Input Geometry** page also provides basic chute profile information (stations and elevations) used by the trajectory program, although the trajectory program also has its own separate input page for parameters that are specific to the design and analysis of spillway aerators. At the far right side, the yellow **Notes** tab is provided as a convenient place for saving notes that describe specific scenarios being modeled.

Near the top of each spreadsheet page a title block is available, and the title blocks are initially set through cell formulas to copy the title entry from the **Input Geometry** page to the other pages (except the **Damage Index** pages which operate independently from the other pages). If desired, the user can choose to override the cell formulas and instead enter separate titles on the subsequent input pages for the trajectory, equal cavitation number, and controlled pressure profile programs.



Discharge	Initial Depth	Initial Slope	Computation Direction	Units	Default Rugosity	Crest Station	Crest Elevation		Reservoir Elevation
m³/s	m				m	m	m		m
283.1685	0.7436719	0.785	DS	Metric	0.0003048	609.6			1127.76

Section	Station	Invert Elev.	Width, Radius or Diameter	Side Slope, Upper Fillet or Crown Radius	Height or Side Radius	Lower Radius or Height	Pier Width or Height of Crown Radius	Invert Curvature Radius	Rugosity
-	m	m	m	- or m	m	m	m	m	m
Composite	637.468	1099.481	22.372	12.655	2.944	2.082	1.830	-75.2	0.0003048
Composite	643.524	1093.488	20.038	10.528	5.017	3.563	0.000	-101.6	0.0003048
Composite	649.821	1086.021	17.648	8.915	6.547	5.383	0.000	-141.0	0.0003048
Composite	656.253	1077.145	15.639	7.824	7.279	6.983	0.000	-650.8	0.0003048
Circular	662.071	1068.836	7.356					0.0	0.0003048
Circular	678.863	1044.857	6.800					1373.2	0.0003048
Circular	685.800	1035.260	6.800					-576.5	0.0003048
Circular	695.651	1020.876	6.248					1957.6	0.0003048
Circular	709.038	1001.759	6.248					372.7	0.0003048
Circular	714.756	994.312	6.248					106.5	0.0003048
Circular	720.852	987.653	6.248					106.8	0.0003048
Circular	732.620	977.451	6.248					106.6	0.0003048
Circular	743.712	970.200	6.248					105.5	0.0003048
Circular	746.760	968.536	6.248					108.9	0.0003048
Circular	754.380	964.902	6.248					105.9	0.0003048
Circular	762.634	961.783	6.248					107.0	0.0003048
Circular	778.764	957.740	6.248					106.6	0.0003048
Circular	796.052	956.270	6.248					132.0	0.0003048
Circular	800.100	956.255	6.248					5861.8	0.0003048
Circular	801.014	956.252	6.248					0.0	0.0003048
Circular	807.720	956.228	6.248					0.0	0.0003048
Circular	822.960	956.175	6.248					0.0	0.0003048
Circular	853.440	956.069	6.248					0.0	0.0003048
Circular	944.880	955.749	6.248					0.0	0.0003048
Circular	1021.080	955.481	6.248					0.0	0.0003048
Circular	1097.280	955.215	6.248					0.0	0.0003048
Circular	1112.520	955.104	6.248					0.0	0.0003048

Figure 1. — Input Geometry page.

Each input page is organized with general input data located across the top of the sheet. In the case of the **Input Geometry** sheet more detailed cross section information is provided in a table below the general input area. Key cells in the general input area (such as cell J7 highlighted in Figure 1) have been designated as Named Ranges within the spreadsheet. Cell J7 is named RESWSE (see upper left corner of Figure 1). This name is referred to in the VBA code, so it must be preserved. Normally these names are difficult to inadvertently modify, but moving data from other spreadsheets into the input cells can erase these names. If any names are accidentally erased, a record of the original definition of the named cells is provided on the **Notes** page.

VBA Computational Routines

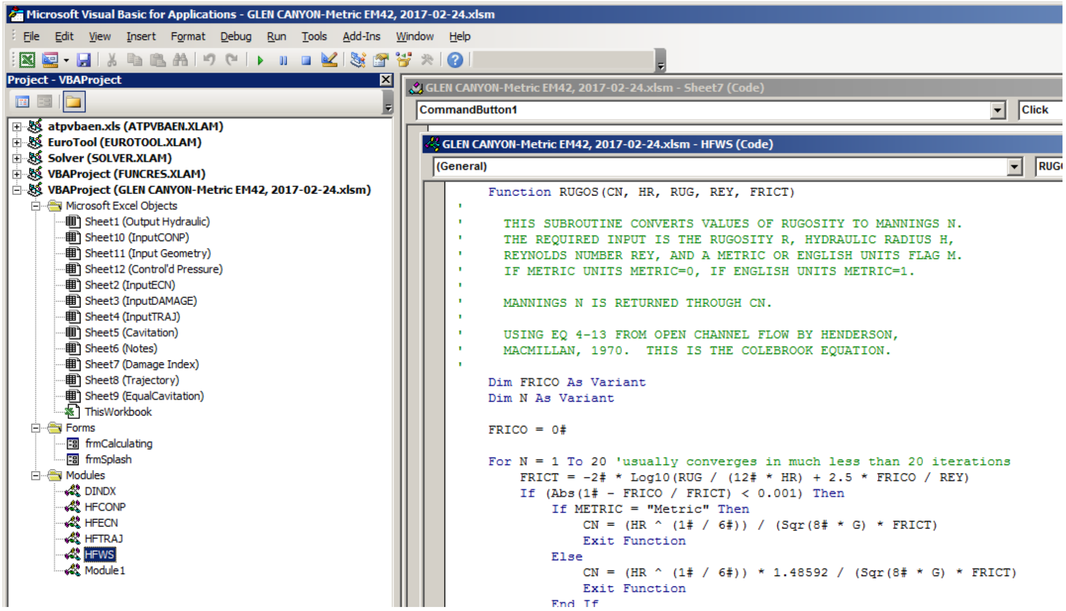


Figure 2. — Visual Basic for Application editor showing the program modules (left) and a snippet of the water surface profile program code (right).

Although the typical user of the spreadsheet will not need access to the actual program code, those who wish to customize the code or debug problems will be interested in viewing the code. The Visual Basic for Applications editor can be accessed from within Excel by pressing Alt-F11 (The “Alt” and “F11” keys pressed simultaneously). The VBA Project Editor will show the various components of the workbook. Double-clicking on any component in the list will provide access to the associated forms and code. Most of the spreadsheet pages have very minimal program code associated with them, primarily just that needed to execute the various programs when buttons on each page are clicked. The two forms in the application are used only to provide basic information about the spreadsheet upon first opening it, and to provide visual feedback during extended calculation periods. Module1 is relatively small and contains only the code needed to provide visual highlighting of input cells, described later in this report. The bulk of the computational code is contained in the five other Modules listed in the project editor. These correspond to the separate programs listed in the Introduction section of this report.

A detailed listing of the various computational routines is not necessary here. Most modules contain only a main routine and one associated subroutine to clean up the areas of the workbook used for program output. The HFWS and HFTRAJ modules are more complex and contain many computational subroutines and functions. One of the most important of these is the RADIUS function in module HFWS that computes the radius of curvature at each station of the spillway profile. This routine is separately executed by a button on the Input Geometry page. All other subroutines and functions are called by the respective main module programs that have their execution initiated from buttons located on the spreadsheet pages.

The Water Surface Profile Program

When the spreadsheet is first opened you may see a warning regarding the execution of macros. To use the computational routines you must choose to Enable Macros. This activates the Visual Basic code that is running in the background of the Excel spreadsheet. **The computational routines will execute very rapidly if the cavitation spreadsheet is the only open Excel workbook, but execution is often slowed remarkably if other workbooks are also open. This is apparently caused by Excel repeatedly shifting its focus from one workbook to the other in an attempt to recalculate all workbooks following each change of data within the cavitation spreadsheet. For best performance, unload other Excel workbooks when using the cavitation spreadsheet.**

After the program loads, you will see the startup message shown in Figure 3. Click on OK to start entering data for your spillway.

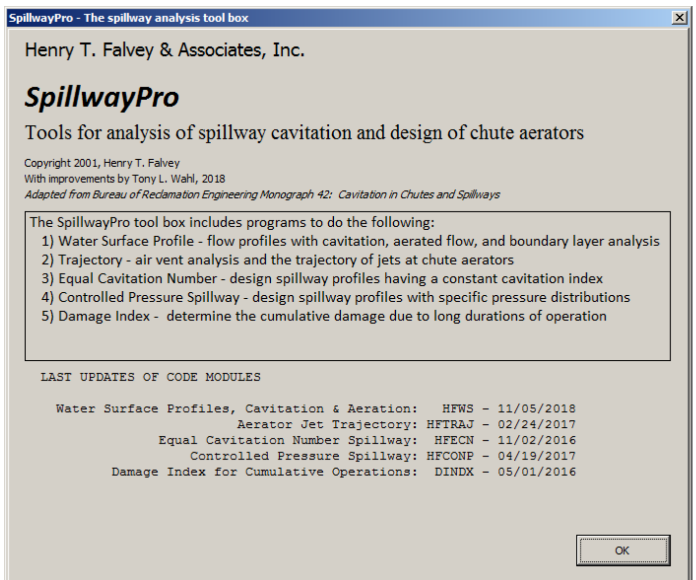
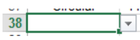


Figure 3. — Program startup screen.

Input of Geometry Data

The geometry data for the spillway is entered into the main data table that begins at row 11. The table shows the station, elevation, section shape and dimensions, invert curvature, and rugosity (roughness) for each cross section. For a typical spillway chute operating with supercritical flow, it is advisable to establish the first cross section at least a short distance downstream from the apex of the crest. This will start the water surface profile calculations in a region that is definitely supercritical and will avoid the need to calculate the flow profile in a region where there is extreme curvature of the spillway invert. Too much curvature can prevent the successful solution of the energy equation needed to compute the flow profile. A basic requirement to satisfy the one-dimensional gradually varied flow assumption is that the flow depth should never exceed 5% of the radius of curvature, although the depth solver may fail in some cases even if this requirement is met.

The required spacing and number of cross sections will depend on the calculated flow depths. The program will interactively warn the user if the estimated depth calculation error is going to exceed 1% and suggest that more cross sections be added (i.e., that a tighter spacing is needed). If more cross sections are needed, blank or filled rows of the table should be copied down the page and new sections can then be added. There is a ‘Data Validation’ input list for column A that must be duplicated to enable the selection of the cross section shape so it is important that the user does not just type additional data into blank rows at the bottom of the sheet. When column A is properly configured, the user should see the downward arrow indicative of a drop-down list when the cursor is positioned in column A: . There is no upper limit to the number of stations that can be included in the profile. Below the end of the defined profile the remainder of columns A-J should be empty. ***When adding more sections, it is important that elevations for new sections not be just linearly interpolated between existing sections, because this will cause the routine that calculates the curvature radius values to determine that the spillway profile is made up of a series of straight-line segments, with an extreme curvature calculated at each break in slope.***

The data for Glen Canyon Dam is entered in the example data file, and you may find it convenient to follow this example and overwrite the example data as you go, or you may start with an empty file. Be sure to set proper units and keep the units of the input data consistent. For example, in the metric system the discharges should be m^3/sec and depths, rugosity, stations, and elevations should all be in meters. In the English system, units are ft^3/s and ft.

At each cross section the following information is required:

- shape (column A)
- station (column B) - horizontal position in meters or feet
- invert elevation (column C)
- An entry in column D to define the width, radius, or diameter of the cross section. Some shapes require additional dimensions to fully define the shape. Table 1 summarizes the required dimensional inputs.
- Additional dimensional properties for complex shapes (columns E-H)
- Invert curvature (column I) – required for first cross section. Invert curvatures for subsequent cross sections will be calculated by the program.
- Rugosity (column J) – only required if it is different from the default rugosity specified at the top of the page (cell F7).

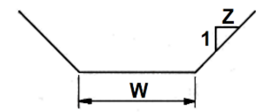
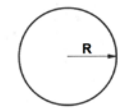
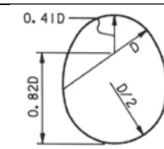
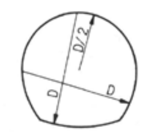
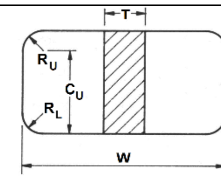
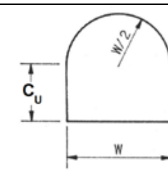
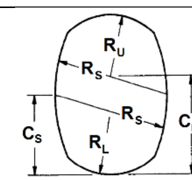
Six section types are available, illustrated in Table 1. To select the section type, click on a cell in column A and use the drop-down menu to select the appropriate type. If you find that there is no drop-down menu appearing, then you need to add to the number of stations in the table by copying additional rows (empty or filled with data), as explained above. To assist the user, a copy of Table 1 is stored on a separate **Shapes** page of the Excel workbook, and a **Show Section Help** button is also available on the **Input Geometry** page.

Two of the cross section shapes serve double-duty. Specifically, the rectangular option is used to also define trapezoidal channels, and the composite shape is used to define the modified (flat-bottomed) horseshoe shape. The composite shape should be used if there are internal piers in the cross section. The rectangular shape does not contain piers (even if pier widths are entered into the **Input Geometry** page). All of the cross section shapes are the same as the options that were offered in the original FORTRAN programs, but some of the variables have been renamed here to clarify the associations between the various fillet and radius dimensions and the centerline elevations of those curves.

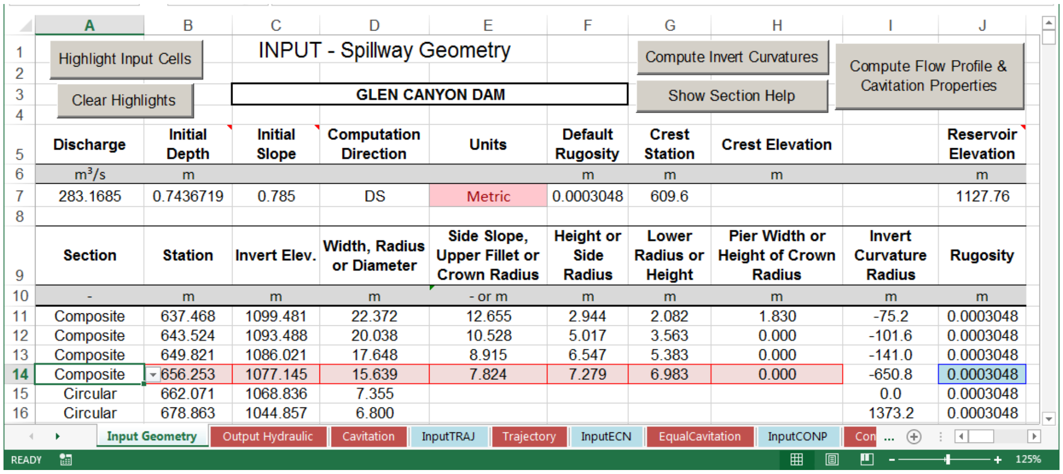
The original FORTRAN programs offered an option to define cross section dimensions in a vertical plane or in a plane that is normal to the bed slope at each station. In the new spreadsheet version of the programs the cross sections must be defined normal to the bed slope.

The remainder of this page is intentionally blank

Table 1. — Channel cross section shapes and associated dimensions.

Column A	Column D	Column E	Column F	Column G	Column H	
Shape	Width, Radius or Diameter	Side Slope or Upper Fillet or Crown Radius	Height or Side Radius	Lower Radius or Height	Pier Width or Height of Crown Radius	
Rectangular	Width W	Side Slope Factor Z	—	—	—	
Circular	Radius R (not diameter!)	—	—	—	—	
Egg Shape	Diameter D	—	—	—	—	
Horseshoe	Diameter D	—	—	—	—	
Composite	Width W	Upper Fillet Radius R_U	Height of Center of Upper Fillet C_U	Lower Fillet Radius R_L	Thickness of Center Wall T	
Modified Horseshoe (Use "Composite")	Width W	Crown Radius $R_U = W/2$	Height of Sidewall C_U	$R_L = 0$	T = 0	
User Defined (User must ensure that arcs will intersect)	Invert Radius R_L	Crown Radius R_U	Side Radius R_S	Height of Center of Side Radius C_S	Height of Center of Crown Radius C_U	

After a cross section shape is selected, the cells that must be filled in to define the cross section are highlighted as shown by the example in Figure 4. These highlights will remain on until the user clicks the **Clear Highlights** button in the top-left portion of the input sheet. To highlight the input cells for all stations at once, click the **Highlight Input Cells** button.



Discharge	Initial Depth	Initial Slope	Computation Direction	Units	Default Rugosity	Crest Station	Crest Elevation		Reservoir Elevation
m³/s	m				m	m	m		m
283.1685	0.7436719	0.785	DS	Metric	0.0003048	609.6			1127.76

Section	Station	Invert Elev.	Width, Radius or Diameter	Side Slope, Upper Fillet or Crown Radius	Height or Side Radius	Lower Radius or Height	Pier Width or Height of Crown Radius	Invert Curvature Radius	Rugosity
-	m	m	m	- or m	m	m	m	m	m
Composite	637.468	1099.481	22.372	12.655	2.944	2.082	1.830	-75.2	0.0003048
Composite	643.524	1093.488	20.038	10.528	5.017	3.563	0.000	-101.6	0.0003048
Composite	649.821	1086.021	17.648	8.915	6.547	5.383	0.000	-141.0	0.0003048
Composite	656.253	1077.145	15.639	7.824	7.279	6.983	0.000	-650.8	0.0003048
Circular	662.071	1068.836	7.355					0.0	0.0003048
Circular	678.863	1044.857	6.800					1373.2	0.0003048

Figure 4. — Highlighted input cells for the "Composite" cross section shape.

As mentioned earlier, a value of the radius of curvature must be entered by the user for the first station in the spillway profile. This can be determined by plotting the spillway profile independently and determining the curvature of circular arcs that will approximately match the bed profile between the first two stations. If the invert is falling away from the flow (concave-down) the radius of curvature should be negative. If the invert is rising up into the flow (concave-up) the curvature should be positive. If the invert profile between adjacent stations is straight, the invert curvature is infinite but should be entered into the spreadsheet as a zero.

When all of the required data have been input, click on **Compute Invert Curvatures**. This will compute the radius of curvature for the second and succeeding stations and will fill in those values of rugosity that were omitted. The radius of curvature and the rugosity are needed to calculate the hydraulic properties in the next step. When the computations are complete, you will see a confirmation message. You may edit the curvature results if desired. If you see anomalies in the rugosity or curvature values, correct the original input data and recompute the invert curvatures. If the results of the curvature computations look ok, then you are ready to click on **Compute Flow Profile & Cavitation Output.** This will run the water surface profile program to determine the hydraulic properties and cavitation properties for the flow.

Hydraulic and Cavitation Properties Output

The water surface profile program begins by calculating the flow profile for the first two stations, with the depth at the first station specified in the **Initial Depth** input cell and the depth at the second station calculated using the program's depth-solver subroutine. The energy grade line elevation is also calculated for these first two stations, and the results are used to linearly extrapolate the energy grade line elevation at the crest station. Assuming minimal losses from the reservoir to the spillway crest, this should match the reservoir water surface elevation. If the computed reservoir elevation does not closely match the reservoir elevation specified on the input sheet then it is an indication that the starting depth needs to be adjusted. The program will then compute a new estimate of the initial depth using the Newton-Raphson method as described on pg. 94-95 of EM42. The user is prompted to allow the program to adjust the initial depth estimate and the process is repeated until the computed energy grade line elevation at the crest matches the reservoir water surface elevation. When a match is achieved the program proceeds with the water surface profile calculation. Alternately, the user can choose to force the water surface profile to be calculated using the specified starting depth even though the crest energy grade line and reservoir level do not match. This effectively ignores the reservoir elevation setting and lets the program determine the reservoir level that would correspond to the specified initial depth at the first station.

The hydraulic and cavitation properties of the flow are displayed on two spreadsheets.

- **Output Hydraulic** presents the essential hydraulic properties such as flow depth, velocity, piezometric pressure, energy grade line elevation, air/water flow fraction, the flow profile designation, critical and normal depths, the Froude Number and the thickness of the boundary layer. In addition, the equivalent value of Manning's *n* is determined and provided as output at the top of the page, and a roll-wave check (new feature) is performed at each cross section.

  The Manning's n value shown in the output is calculated for the first station only. Since the Manning's and Darcy friction models are not equivalent, the effective Manning's n will vary down the length of the spillway.

- **Cavitation** presents essential cavitation properties such as the cavitation index of the flow, the cavitation index of the surface, the chamfers required to stop cavitation, damage potentials for three sizes of circular arc and three sizes of 90-degree offsets (calculated using the factors for triangular irregularities given in Table 2-1, EM42), the turbulence intensity of the flow, and the computed stream power applied to the spillway surface (new feature).

EM42 should be consulted for a detailed discussion of interpretation of the cavitation output table. The key factors are generally:

- The cavitation index (flow sigma column) — Values less than about 0.2 generally indicate a high potential for cavitation damage. For spillways with design cavitation index values in the range of 0.1 to 0.2, cavitation damage has traditionally been mitigated through surface tolerance specifications and maintenance programs designed to ensure a smooth surface free of offsets and other anomalies. When cavitation index values drop below 0.1, Reclamation has typically employed aerators to add air to the flow and protect the spillway surface from damaging cavitation. Aerators are typically located just upstream from the station at which the cavitation index drops below 0.2.

- Sigma of Uniform Roughness — When cavitation index (flow sigma) values drop to or below the values of "Sigma of Uniform Roughness" this is also an indicator of high potential for cavitation damage.
- Damage Potential — The damage potential column incorporates the influence of the size and shape of surface anomalies, the relative cavitation indices of the anomalies compared to the flow sigma, and the flow velocity. If a spillway is expected to operate for long periods, damage potential values give a direct indication of the severity of damage that can be expected, with 500 indicating incipient damage, 1000 indicating major damage, and 2000 or more indicating catastrophic damage (see Table 3-4 in EM42 for details). If the spillway will operate or has operated for only short periods of time, then the severity of accumulated damage after different operating durations can be evaluated using the Damage Index computer program (see EM42 pg. 38-39 and Appendix E for details).

The Trajectory Program

The trajectory program supports the design of aeration ramps to mitigate against cavitation damage. The program computes the trajectory of the flow off of the ramp which allows its flight distance, jet spread, and air uptake to be estimated. The program also computes pressure losses through the vent system that supplies air to the underside of the nappe and adjusts the jet trajectory for the resulting differential pressure forces that exist across the nappe.

The Trajectory program has its own input data, but also relies upon the spillway profile data and water surface profile computation discussed in the previous section. This water surface profile will typically be computed for the chute profile as it exists without a ramp in place. In most of the discussion that follows, it will be assumed that the ramp is to be constructed as an addition to an existing structure, with the ramp slope raised above the chute slope to lift the jet off of the chute floor. At the end of this section there is a short discussion of how to run the analysis for an "offset aerator" in which the upstream and downstream floor slopes are the same, but the chute floor alignment is offset at the aerator location.

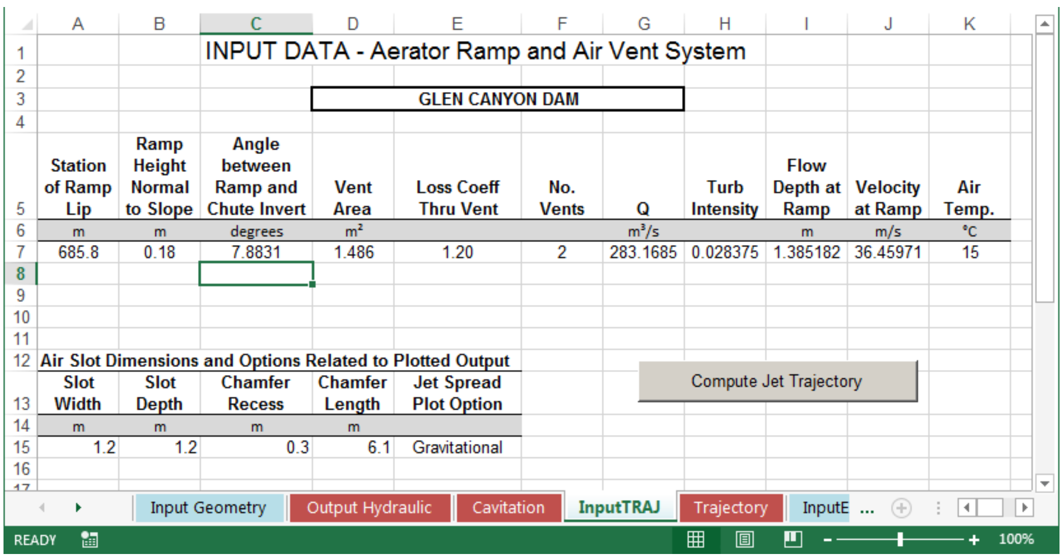
The input data that define the ramp geometry and air vent system characteristics are provided on the **InputTRAJ** spreadsheet (Figure 5). In addition, the basic spillway profile information (station and elevation) from the **Input Geometry** page are used by the program, and the flow depth, flow velocity, and turbulence intensity results from the water surface profile calculation are also needed at the station of the proposed ramp. Lookup functions in the spreadsheet input cells are provided to grab these results from the appropriate output pages, or the user can transfer results manually by typing values into the input cells. The title can be input again on this sheet because you may want to identify where the aerator is located. The aerator design parameters are the ramp height, the angle between the ramp and the invert, the vent area, the vent width, the loss coefficient through the vent, and the number of vents. The user can readily modify spillway geometry, ramp geometry, air vent geometry, the discharge, and the flow characteristics.

For a ramp that is to be elevated above the pre-existing slope of the spillway chute, the calculations of flow depth, velocity, and turbulence intensity at the ramp station for the original spillway profile will not have utilized the actual elevation of the ramp lip. If it is desired to have the most accurate estimates of these parameters, a separate water surface profile can be performed with the ramp lip elevation entering into the spillway chute profile, and the results then saved for manual entry in the trajectory program input cells. However, when the trajectory program is run, the spillway chute profile should be returned back to the condition without the ramp in place, since the ramp height and angle will be computed from this basis. (In most applications, the effect of refining the water surface profile analysis in this way is negligible, less than a fraction of 1% of the values computed for the unmodified chute profile.)

Some new input parameters and differences from the original FORTRAN trajectory program will be discussed here. The original program asked the user to provide the elevation of the ramp lip, which when compared to the original elevation of that station in the spillway profile would yield a vertical offset of the ramp lip above the original chute floor. The angle of the ramp flow surface was specified relative to horizontal. The new program instead asks the user to enter the ramp height in terms of its thickness at the lip measured <u>perpendicular to</u> the prevailing slope of the chute at the ramp station, and the angle of the ramp is specified as its deviation above the angle of the chute. This is the manner in which most ramp designs have been detailed on design drawings and in articles describing ramp design and performance.

An improvement made to the program is the automatic adjustment of the jet trajectory calculation to incorporate the effects of the relative ramp height. The procedures are described on pg. 62 of EM42 (Figure 5-3 and Eq. 5.3). The figure shows how a ramp of relatively small height compared to the flow depth is unable to fully deflect the jet, especially as the ramp deviation angle increases. The original program expected the user to determine this adjustment manually and enter the adjusted takeoff angle in place of the ramp surface angle. The new program contains equations that replicate the curves on Figure 5-3 so that the correction can be calculated in the program. The impact of this adjustment can be seen on the output page where the ramp angle and actual takeoff angle of the jet are both displayed.

Cell E15 offers the user an option to plot the jet spread using either a gravitational or empirical approach. The gravitational option is the same method used by the original program and is appropriate when the program is being used to simulate spillway aerators with slight ramp angles and short throw distances. The empirical option will provide more realistic output if the program is being used to simulate a ramp that functions like a flip bucket, throwing the water high into the air and causing it to land in a plunge pool well below the ramp elevation. (The program was used for this purpose in recent studies related to Oroville Dam.) The empirical option calculations are based on the work of Ervine et al. (1997).


INPUT DATA - Aerator Ramp and Air Vent System

GLEN CANYON DAM

Station of Ramp Lip	Ramp Height Normal to Slope	Angle between Ramp and Chute Invert	Vent Area	Loss Coeff Thru Vent	No. Vents	Q	Turb Intensity	Flow Depth at Ramp	Velocity at Ramp	Air Temp.
m	m	degrees	m²			m³/s		m	m/s	°C
685.8	0.18	7.8831	1.486	1.20	2	283.1685	0.028375	1.385182	36.45971	15

Air Slot Dimensions and Options Related to Plotted Output

Slot Width	Slot Depth	Chamfer Recess	Chamfer Length	Jet Spread Plot Option
m	m	m	m	
1.2	1.2	0.3	6.1	Gravitational

Figure 5. — Input data for the aerator design and trajectory program. The example data shown describes the aerator ramp and vent system constructed at Glen Canyon Dam, which is different from the example that was originally shown in EM42.

Other additional input parameters are provided in the spreadsheet version of the trajectory program to facilitate showing details of the air slot geometry on the flow trajectory plot. These are illustrated in Figure 6. This air slot geometry is typical of that used on several Reclamation spillways, but other slot details are also possible. Finally, an air temperature input allows the air vent calculations to be adjusted for changes in air density due to temperature and elevation (elevation determined from the **Input Geometry** page).

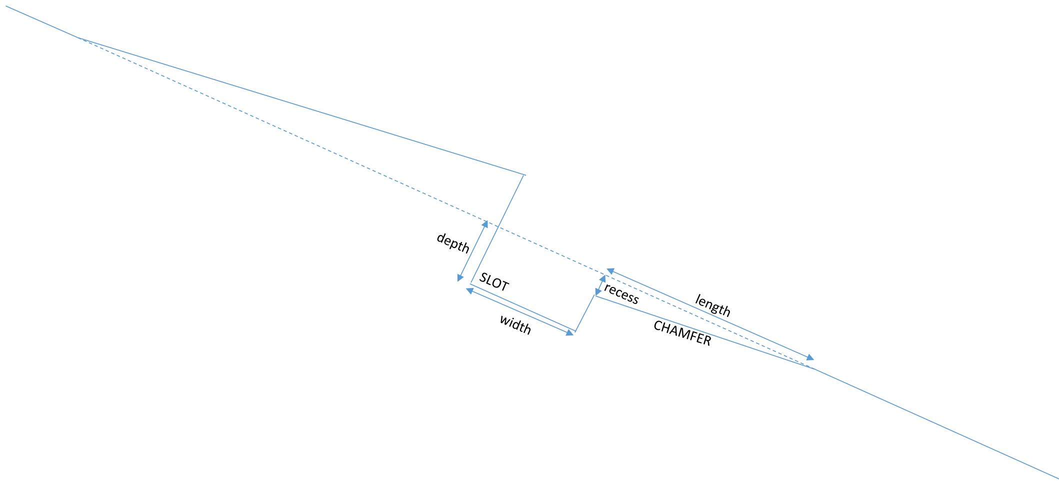


Figure 6. — Schematic view of air slot geometry

After the appropriate values are input, click on Compute Jet Trajectory. This will run the program and the results will be placed on the **Trajectory** spreadsheet. Four trajectories are output, two for the lower nappe and two for the upper nappe. The two lower nappe trajectories correspond to the maximum air penetration into the jet and the maximum dispersion of water caused by turbulence. The upper nappe profiles similarly correspond to the maximum dispersion of the water above the jet and the limits of penetration of air into the jet. These jet dispersion values can help the designer estimate where the jet first strikes the invert and the required height for chute training walls to contain the jet. They also support the calculation of the air flow rate entrained by the bottom side of the jet. Other important outputs related to aerator design are the air velocity at the inlet and the pressure difference developed through the vent system.

Several new outputs have been added to the trajectory program. The stream power intensity (kW/m^2) at the point of impact on the existing spillway chute is calculated as:

$$\frac{\rho V^3}{2t'} \sin\theta$$

Where V is the impact velocity of the jet, θ is the angle of inclination between the jet and the chute surface (90° for perpendicular impingement), t' is the fractional spread of the jet compared to its fully intact, non-aerated thickness (t = 1.5 indicates a jet whose thickness has increased 50%), and ρ is the water density.

Additional output information includes the thrust forces that will be applied to the ramp due to the change in flow direction of the jet and the total horizontal throw distance of the jet. The latter information could be determined from the trajectory coordinates, but is now more conveniently presented.

Compute Jet Trajectory

JET TRAJECTORY AND AERATOR RESULTS

GLEN CANYON DAM

RAMP GEOMETRY:	WIDTH		STATION		HEIGHT		ANGLE	
	5.61	m	685.8	m	0.18	m	7.8831	degrees
AIR DUCT:	AREA		LOSS COEFF		VENT WIDTH		NUMBER OF VENTS	
	1.49	m²	1.00		1.20	m	2	
FLOWS:	WATER		AIR FLOW		AIR VELOCITY		Δ PRESSURE	
	283.1685	m³/s	195.03	m³/s	65.6	m/s	3.174	kPa
RAMP HYDRAULICS:	TURBULENCE INTENSITY		FLOW DEPTH AT RAMP		MEAN VELOCITY		TAKEOFF ANGLE	
	0.028375		1.385182	m	36.46	m/s	6.341913	degrees
	STREAM POWER AT IMPACT		RAMP THRUST (NORMAL)		RAMP THRUST (LONGITUDINAL)		JET THROW DISTANCE (HORIZ.)	
	920.4	kW/m²	203193	N/m	11257	N/m	17.94	m

J E T   T R A J E C T O R Y

LOWER NAPPE				UPPER NAPPE			
Max Water Spread		Air Penetration Limit		Max Water Spread		Air Penetration Limit	
STATION	ELEV	STATION	ELEV	STATION	ELEV	STATION	ELEV
m	m	m	m	m	m	m	m
685.80	1035.26	685.80	1035.26	686.82	1036.20	686.82	1036.20
686.21	1034.76	686.24	1034.78	687.25	1035.73	687.28	1035.64
686.63	1034.26	686.68	1034.30	687.70	1035.25	687.69	1035.14
687.04	1033.75	687.12	1033.82	688.14	1034.77	688.10	1034.63
687.45	1033.24	687.56	1033.34	688.57	1034.28	688.52	1034.12
687.86	1032.72	688.00	1032.85	689.01	1033.79	688.93	1033.61
688.27	1032.21	688.44	1032.35	689.45	1033.30	689.34	1033.09
688.68	1031.68	688.88	1031.85	689.89	1032.80	689.75	1032.57
689.09	1031.16	689.31	1031.35	690.33	1032.30	690.16	1032.04
689.50	1030.63	689.75	1030.85	690.76	1031.79	690.57	1031.52
689.91	1030.10	690.19	1030.34	691.20	1031.29	690.98	1030.98
690.32	1029.56	690.62	1029.83	691.63	1030.77	691.38	1030.45
690.72	1029.02	691.06	1029.32	692.07	1030.26	691.79	1029.91
691.13	1028.48	691.49	1028.80	692.50	1029.74	692.20	1029.37

Figure 7. — Output from the trajectory program. The nappe trajectory output tables are truncated here to conserve space.

Offset Aerators

With an offset aerator there is no ramp per se, but instead an offset of the floor is provided (typically perpendicular to the floor slope), with identical floor slopes upstream and downstream from the aerator. To model this design in the trajectory program, the water surface profile analysis should be run with the actual floor profile elevations provided, including the aerator offset. The ramp height and ramp angle should both be specified as zero, since there is no elevated ramp raised above the slope of the incoming chute. When this analysis is run, the output screen will show ramp and jet takeoff angles of zero, with no adjustment for relative ramp height. The actual jet takeoff angle will be equal to the slope of the chute floor upstream from the aerator. For a realistic display of the offset geometry, the slot depth input parameter should be set equal to the offset distance perpendicular to the chute floor.

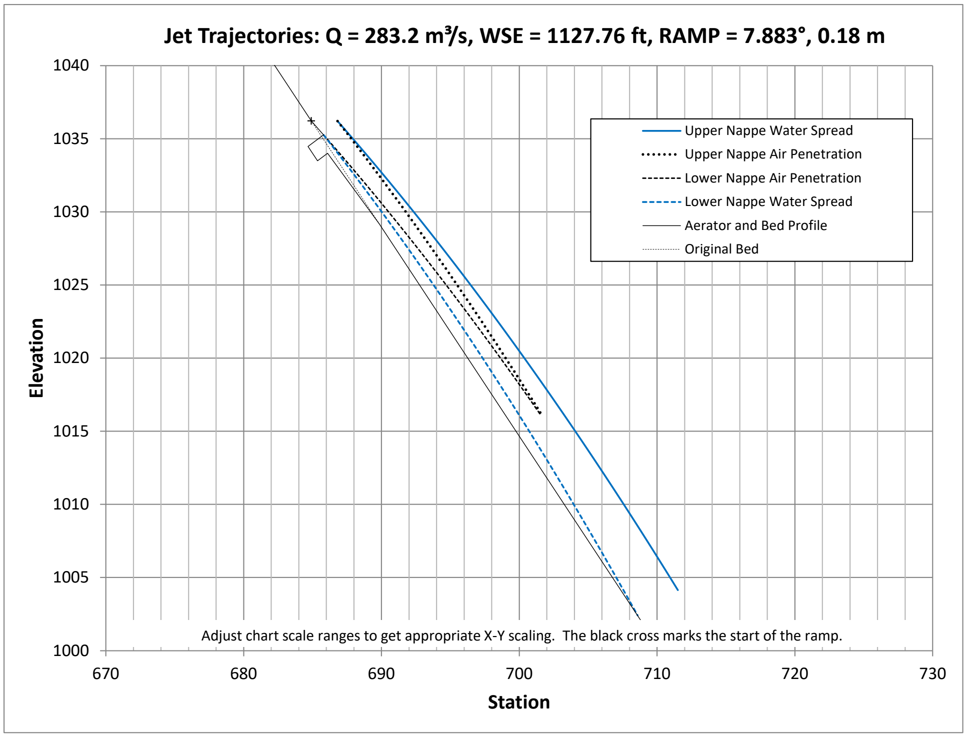


Figure 8. — Example jet trajectory output plot for the Glen Canyon Dam tunnel spillway aeration ramp.

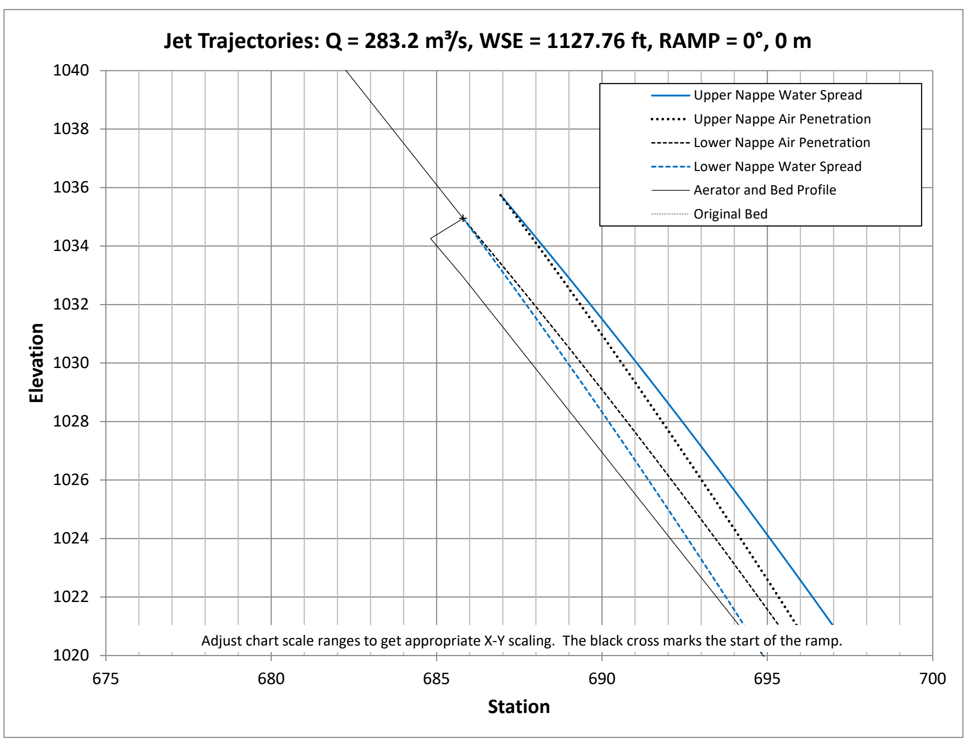


Figure 9. — Example jet trajectory output for an offset aerator. Chute floor slopes are equal upstream and downstream from the aerator, with zero ramp height and angle.

The Geometry Programs

The spreadsheet includes two programs that calculate specialized profiles designed to prevent cavitation in the vertical curve portion of the spillway. These programs can be useful in situations where there is freedom to vary the profile (either tunnel spillways or spillways constructed on the downstream face of concrete dams). They may be less useful when the spillway profile is dictated by site topography and cannot be varied significantly without great expense.

Constant Cavitation Number Profile

In this program, the vertical radius of curvature is varied along the length of the chute to produce a constant cavitation index value over the entire length of the vertical bend. The method can also account for the effects of convergence of the sidewalls. The resulting profile has a gradually increasing pressure distribution through the vertical curve. If the curve terminates in a chute or a tunnel, a large pressure gradient occurs at the point of tangency (PT), which can have an adverse effect on the flow conditions at this point. However, if the vertical curve terminates in a flip bucket, a spillway profile is produced that has the minimum potential for cavitation damage.

The **InputECN** sheet is used to provide the input data. In addition, this program also relies upon the geometry data (stations, elevations, cross sections) provided for the water surface profile program. The project title on the input page is set to use the project title from the Input Geometry page, or you may enter a custom title. You also must select whether to use a rotational (real fluid) or irrotational (ideal fluid) flow assumption, and you must specify several items that describe the geometry and initial conditions. These include the slope at the start of the vertical curve (point of curvature, PC), the station at the point of curvature, head from reservoir to point of curvature, unit discharge, a dimensionless convergence ratio (see EM42, pg. 113), atmospheric pressure above the vapor pressure of water, integration interval (Δ Head), and the reservoir elevation. The original FORTRAN program expected the user to enter the cosine of the slope, but the new spreadsheet takes the actual slope as the input variable. Once the inputs are completed, press the Compute Equal Cavitation Number Profile button and go to the **EqualCavitation** spreadsheet to see coordinates and a graph of the profile. The program always computes the profile until it reaches the station at which the slope becomes horizontal. Beyond that point the spillway could be provided with a flip bucket terminal structure.

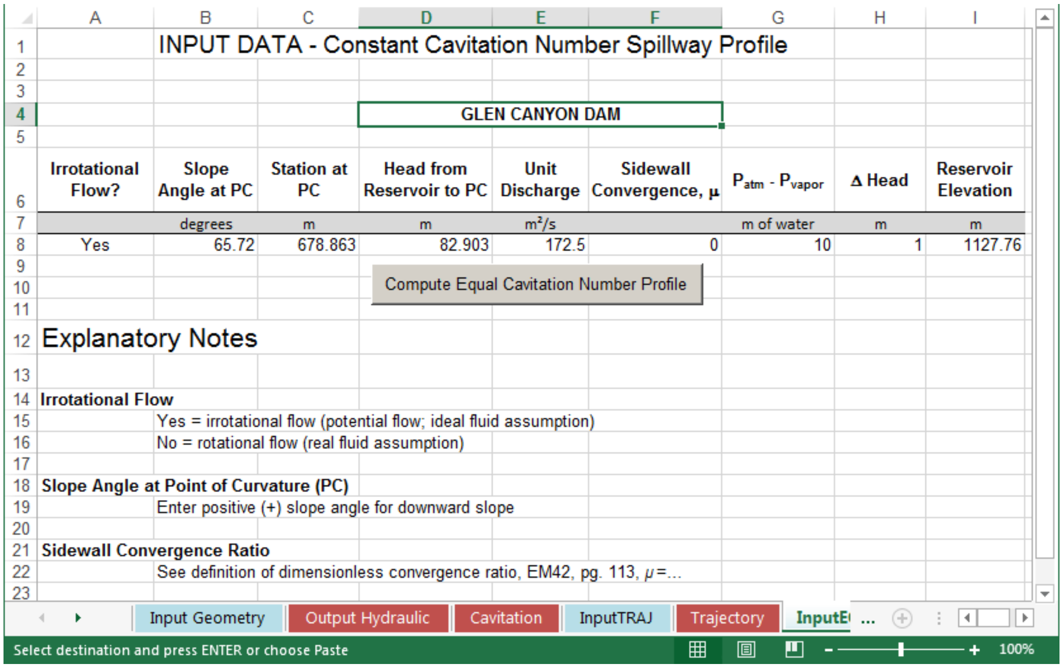


Figure 10. — Input data screen for computing a vertical curve profile for a constant cavitation number spillway.

A few additional notes about the application of the program and the example run shown in EM42 are in order. The program operates on the basis of unit discharge and the unit discharge supplied as input should be calculated as the product of the depth and velocity at the start of the vertical curve. The program should typically be run for a flow condition representing the maximum discharge through the spillway. However, for the example application that was provided in EM42 the unit discharge was set to 172.5 m^2/s. The proposed PC for the example run was station 678.863 m (the PC for the real spillway is at station 709.038 m), and this unit discharge occurs at the proposed PC for a flow rate of 1635 m^3/s, or about 56% of the rated capacity of each tunnel spillway at Glen Canyon Dam (2945 m^3/s at reservoir elevation 1127.76 m). In addition, the head from the reservoir to the PC was entered for the example run in EM42 as 92.627 m, which does not match the actual spillway profile. The proper input value for this head difference to match the field condition should be 1127.76 – 1044.857 = 82.903 m. Finally, the slope of the channel at the PC is also required as input, and the value used in the EM42 example was $\cos(\theta) = 0.4112$ ($\theta = 65.7°$; $S = \tan(\theta) = 2.217$). However the correct slope at this station for the actual Glen Canyon Dam tunnels is $S = 1.428$, $\theta = 55.00°$. Input values matching the actual spillway profile have been used for the example that is provided here, so the results differ from the equal cavitation number profile produced by the original example in EM42.

Equal Cavitation Number Profile

Compute Equal Cavitation Number Profile

GLEN CANYON DAM

IRROTATIONAL (POTENTIAL) FLOW ASSUMPTION

Unit Discharge	Sigma
m²/s	
172.5	0.145185

Station	Elevation	Radius	Slope	Depth	Piez
m	m	m	degrees	m	m
678.86	1044.86	10000000000.0	65.72	4.324	1.778
679.31	1043.86	5169.5	65.71	4.299	1.905
679.77	1042.86	2609.9	65.70	4.275	2.032
680.22	1041.86	1756.6	65.67	4.251	2.158
680.67	1040.86	1330.0	65.62	4.227	2.285
681.12	1039.86	1073.9	65.57	4.204	2.412
681.58	1038.86	903.2	65.51	4.181	2.539
682.03	1037.86	781.2	65.43	4.159	2.666
682.49	1036.86	689.6	65.35	4.137	2.792
682.95	1035.86	618.4	65.25	4.115	2.919
683.42	1034.86	561.4	65.14	4.094	3.046
683.88	1033.86	514.7	65.02	4.073	3.173
684.35	1032.86	475.8	64.90	4.052	3.299
684.82	1031.86	442.9	64.76	4.032	3.426
685.29	1030.86	414.6	64.61	4.012	3.553
685.77	1029.86	390.1	64.45	3.992	3.680
686.25	1028.86	368.7	64.28	3.972	3.807
686.73	1027.86	349.7	64.11	3.953	3.933
687.22	1026.86	332.9	63.92	3.934	4.060
687.71	1025.86	317.8	63.72	3.916	4.187
788.73	949.34	94.7	1.16	2.988	13.888
789.31	949.33	94.7	0.81	2.988	13.889
790.65	949.32	94.7	0.00	2.988	13.890

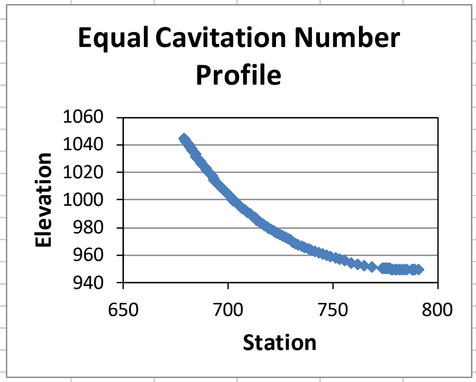


Figure 11. — Results of calculating a spillway profile with a constant cavitation number. Some rows of output are not displayed to condense the figure.

Controlled Pressure Profile

The **Controlled Pressure** program determines a vertical curve whose radius of curvature at the boundary follows either a triangular function or a sinusoidal function, increasing from zero at the start of the curve, reaching a maximum at the midpoint of the curve, and dropping back to zero at the end of the curve. This eliminates large pressure gradients at the start and end of the vertical curve. The radii of curvature upstream from the PC (start of the curve) and downstream from the PT (end of the curve) are infinite (inverse of radius of curvature = zero), so the use of either of these functions eliminates discontinuities in the radius of curvature. The sinusoidal function also eliminates discontinuities in the derivative of the radius of curvature, yielding an even smoother variation of the pressure profile. This design approach typically yields a longer profile than the equal cavitation number method.

The original FORTRAN program misreported the computed arc distance and radius of curvature values. The vertical curve geometry is computed internally in a dimensionless way, and results are then scaled up when they are output. The arc distances were not being scaled, and this problem was corrected. An error was also found in the programming of the equations used internally to integrate the curves using Simpson's rule (see EM42 Appendix C for details). Correcting this problem fixed the scaling of the radius of curvature values.

Problems were also found with the computation of the profile for the sinusoidal pressure option. Several erroneous equations were found in Chapter 4 and Appendix C of EM42 and these errors were embedded in the original constant pressure program. These errors caused the sinusoidal option to compute a skewed sinusoidal distribution rather than a symmetric distribution that reaches the minimum radius of curvature at the midpoint of the vertical curve. The corrected equations are shown in Table 2.

Table 2. — Correct equations for controlled pressure profiles.

EM42 Equation No.	Corrected equation
4.46	$k_r = \frac{1}{R^2 \theta_d}$
4.48	$s_m = \frac{\theta_d}{k_r}$
4.49	$k_r = \frac{1}{2R}$
C.12	$\theta = \theta_o + k\left[s - \frac{s_m}{2\pi}\sin\left(\frac{2\pi s}{s_m}\right)\right]$
C.14	$s_m = \frac{\theta_d}{k}$
C.15	$R_m = \frac{1}{\sqrt{k\theta_d}}$ (triangular) $R_m = \frac{1}{2k}$ (sinusoidal)
Not numbered, pg. 52-53, 113-114	q_i and $q_n = \frac{q}{(2gH_i^3)}$

As mentioned above, the program computes the vertical curves in a dimensionless manner and then scales them up for output. One of the program inputs discussed in EM42 is the radius factor (k_r in EM42 Chapter 4; k in Appendix C). Experimentation with the program and investigation of the curve equations during the debugging of the new spreadsheet proved that the k factor has no effect on the final output; the scaling of the curve to prototype size causes k to cancel out. As a result, this input parameter was removed from the spreadsheet. Required input data are shown in Figure 12.

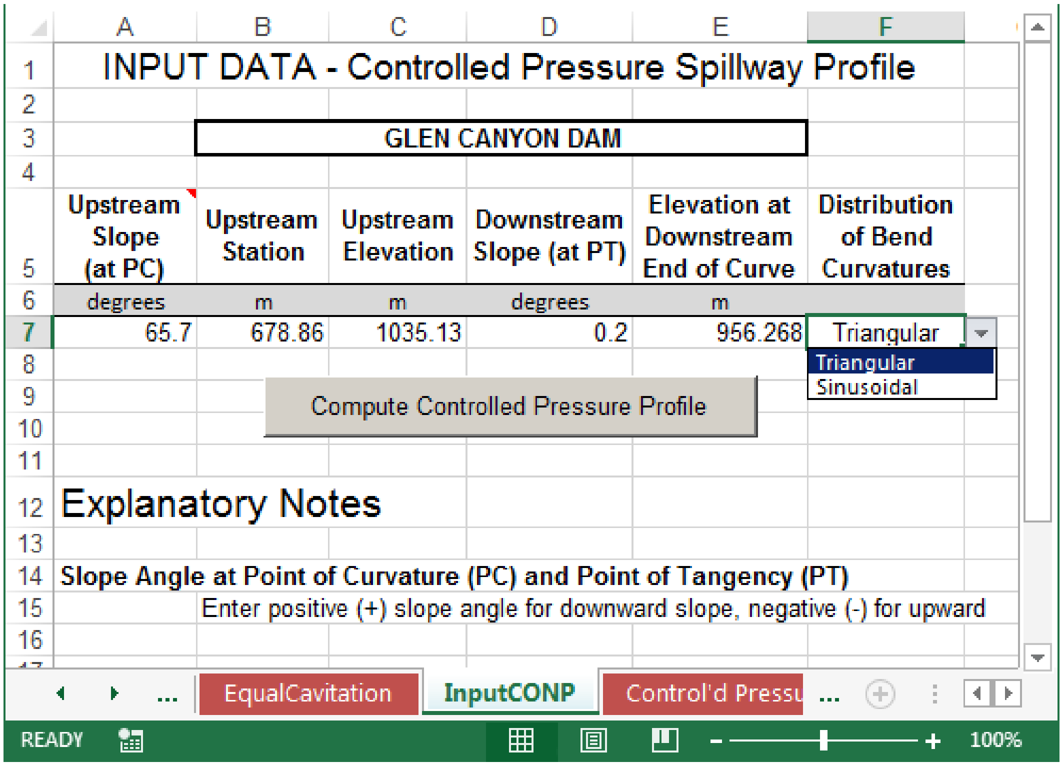


Figure 12. — Input data screen for computing a vertical curve profile for a controlled pressure spillway.

The example program runs that are shown in EM42 for the controlled pressure profile program used the same PC location as the constant cavitation number example. Again, this does not match the actual coordinates of this station for the Glen Canyon Dam spillways. The examples included in this document have been changed to use the correct elevation for a PC located at station 678.863 m on the existing spillway profile. The input data requirements for the controlled pressure program have also been changed so that the slope at the PC and at the PT are entered as positive numbers when the channel is downward sloping. This sign convention is consistent with the constant cavitation number program and the water surface profile program. (The original FORTRAN program required negative values when the channel was sloped down in the flow direction.)

Controlled Pressure Spillway Profile

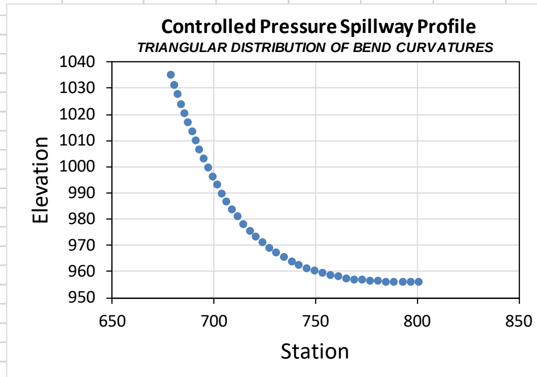
GLEN CANYON DAM

TRIANGULAR DISTRIBUTION OF BEND CURVATURES

Compute Controlled Pressure Profile

	Theta	Deflection Angle
	degrees	degrees
	65.7	65.5

X coordinate	Y coordinate	Radius of Curvature	Inverse of Radius, 1/R	Arc Distance
m	m	m	1/m	m
678.86	1035.13	############	1.34899E-12	0.000
680.49	1031.52	1386.6	0.00072117	3.963
682.14	1027.91	693.3	0.00144234	7.926
683.80	1024.32	462.2	0.00216351	11.889
685.49	1020.73	346.7	0.00288468	15.852
687.23	1017.17	277.3	0.00360585	19.815
689.01	1013.63	231.1	0.00432702	23.778
690.86	1010.13	198.1	0.00504819	27.741
692.78	1006.66	173.3	0.005769359	31.704
694.77	1003.23	154.1	0.006490529	35.667
696.85	999.86	138.7	0.007211699	39.630
699.03	996.55	126.1	0.007932869	43.593
701.31	993.31	115.6	0.008654039	47.556
703.70	990.15	106.7	0.009375209	51.519
706.21	987.08	99.0	0.010096379	55.482
708.84	984.11	92.4	0.010817549	59.445
711.59	981.26	86.7	0.011538719	63.408
714.47	978.54	81.6	0.012259889	67.371
717.47	975.96	77.0	0.012981059	71.334
720.61	973.54	73.0	0.013702229	75.296
723.87	971.29	69.3	0.014423399	79.259
727.26	969.23	73.0	0.013702229	83.222
730.75	967.35	77.0	0.012981059	87.185
734.33	965.66	81.6	0.012259889	91.148
737.99	964.14	86.7	0.011538719	95.111
741.72	962.80	92.4	0.010817549	99.074
745.50	961.61	99.0	0.010096379	103.037
749.33	960.58	106.7	0.009375209	107.000
753.19	959.69	115.6	0.008654039	110.963
757.08	958.93	126.1	0.007932869	114.926
760.99	958.29	138.7	0.007211699	118.889
764.92	957.77	154.1	0.006490529	122.852
768.86	957.34	173.3	0.005769359	126.815
772.81	957.01	198.1	0.00504819	130.778
776.76	956.76	231.1	0.00432702	134.741
780.72	956.57	277.3	0.00360585	138.704
784.68	956.44	346.7	0.00288468	142.667
788.64	956.36	462.2	0.00216351	146.630
792.60	956.31	693.3	0.00144234	150.593
796.57	956.28	1386.6	0.00072117	154.556
800.53	956.27	############	1.19814E-17	158.519



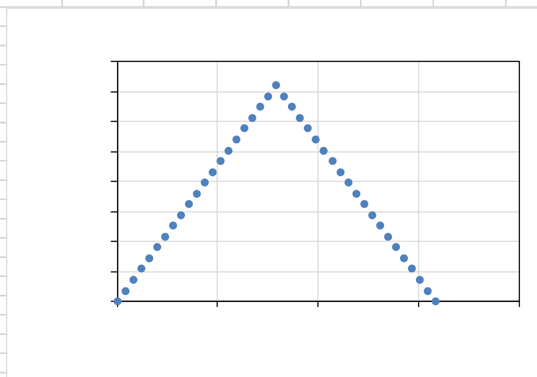


Figure 13. — Controlled pressure spillway profile calculated for a triangular distribution of the inverse of the radius of curvature.

Controlled Pressure Spillway Profile

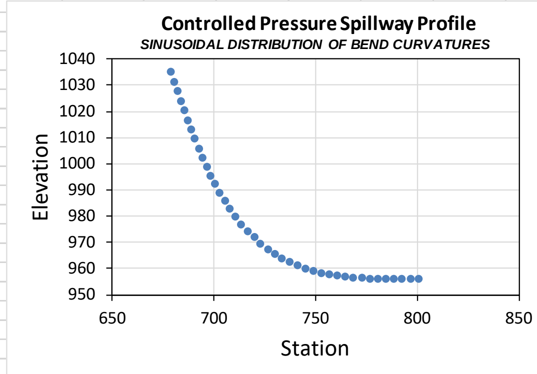
GLEN CANYON DAM

SINUSOIDAL DISTRIBUTION OF BEND CURVATURES

Compute Controlled Pressure Profile

Theta	Deflection Angle
degrees	degrees
65.7	65.5

X coordinate	Y coordinate	Radius of Curvature	Inverse of Radius, 1/R	Arc Distance
m	m	m	1/m	m
678.86	1035.13	############	7.14546E-13	0.000
680.51	1031.48	11367.2	8.79725E-05	4.000
682.15	1027.84	2859.4	0.000349724	7.999
683.81	1024.20	1284.0	0.000778808	11.999
685.47	1020.56	732.8	0.001364661	15.999
687.16	1016.93	477.8	0.002092857	19.999
688.87	1013.32	339.5	0.002945464	23.998
690.63	1009.73	256.3	0.003901489	27.998
692.44	1006.16	202.5	0.004937391	31.998
694.32	1002.63	165.9	0.006027663	35.997
696.29	999.15	139.9	0.007145459	39.997
698.36	995.73	121.0	0.008263255	43.997
700.54	992.37	106.9	0.009353528	47.997
702.84	989.10	96.3	0.01038943	51.996
705.28	985.93	88.1	0.011345455	55.996
707.85	982.87	82.0	0.012198062	59.996
710.58	979.94	77.4	0.012926257	63.995
713.45	977.16	74.0	0.01351211	67.995
716.46	974.53	71.7	0.013941195	71.995
719.62	972.08	70.4	0.014202946	75.994
722.92	969.81	70.0	0.014290918	79.994
726.33	967.73	70.4	0.014202946	83.994
729.86	965.85	71.7	0.013941195	87.994
733.49	964.17	74.0	0.01351211	91.993
737.20	962.69	77.4	0.012926257	95.993
740.99	961.40	82.0	0.012198062	99.993
744.83	960.29	88.1	0.011345455	103.992
748.72	959.36	96.3	0.01038943	107.992
752.65	958.60	106.9	0.009353528	111.992
756.60	957.98	121.0	0.008263255	115.992
760.57	957.49	139.9	0.007145459	119.991
764.55	957.11	165.9	0.006027663	123.991
768.54	956.84	202.5	0.004937391	127.991
772.54	956.64	256.3	0.003901489	131.990
776.53	956.50	339.5	0.002945464	135.990
780.53	956.41	477.8	0.002092857	139.990
784.53	956.35	732.8	0.001364661	143.990
788.53	956.32	1284.0	0.000778808	147.989
792.53	956.30	2859.4	0.000349724	151.989
796.53	956.28	11367.2	8.79725E-05	155.989
800.53	956.27	############	7.14546E-13	159.988



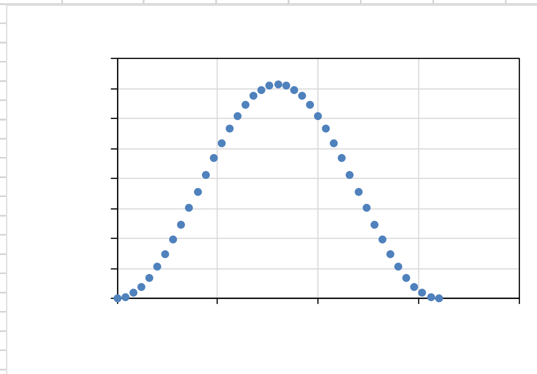


Figure 14. — Controlled pressure spillway profile with a sinusoidal distribution of the inverse of the radius of curvature.

The Damage Index Program

The **Damage Index** program can be used to assess damage observed in the field as a function of historical flow records or to estimate the damage that may occur under future operational scenarios.

Prediction of cavitation damage continues to be a challenging task. While the presence of cavitation can usually be predicted quite accurately, the damage that may occur depends on many site specific variables that are difficult to evaluate. The damage potential variable included in the cavitation output table is an indicator of the maximum damage that can be expected over a very long operational period. In EM42, Falvey (1990) also developed the related concept of the cavitation damage index to estimate the cumulative damage as a function of exposure time for shorter periods of operation at a given level of damage potential. Since most spillways will operate at a wide range of discharges over time, a computer program is helpful to determine the cumulative damage from a series of operations of varying duration at different flow rates.

The damage potential due to cavitation is related to the difference between the cavitation index of the surface irregularity or geometric feature when damage begins (the incipient cavitation index), and the cavitation index of the flow. In addition the damage rate has been found inversely proportional to the incipient cavitation index itself. Finally, the aggressiveness of the cavitation is a function of the relative velocity raised to the sixth power. These concepts related to long-term damage potential are discussed more fully in Chapter 3 of EM42.

In most hydraulic structures, the damage rate is also assumed to vary inversely with time. Accordingly, the depth of cavitation damage should be proportional to the logarithm of time. The damage index concept combines the damage potential and the exposure time to provide an indicator of the damage to be expected as a function of both discharge and time. The program performs the calculations needed to evaluate the cumulative effects of operation at varying levels and durations of discharge, with logarithmic accumulation of damage at rates that are dependent on the damage potential of each flow and the prior damage history. It should be noted these concepts are fairly abstract and their application to any given facility relies heavily on operational records, damage experience, and judgment.

The example application of the damage index program uses the historical operational data for the Glen Canyon Dam left tunnel spillway. This example is identical to the example shown in EM42, Appendix E. The only inputs that affect the calculations are the number of tunnels (cell A8) and the data entered in columns B, C, H, and I. The date information in columns E, F, and G is for identification purposes only. The damage potential values for specific discharges should be determined by running the cavitation analysis (water surface profile program) for each flow rate and selecting a damage potential corresponding to a presumed offset feature at a specific station in the chute. Any consistent units can be used for the flow rates in columns C and I. The example damage potential curve shown is identical to that used in the EM42 example, but the details of the associated offset feature and reservoir conditions that were originally used to generate the curve are unknown.

INPUT - Damage Index

GLEN CANYON DAM - LEFT TUNNEL SPILLWAY - Sta. 24+25 ft

Compute Accumulated Damage Index Values

of CFS.

Month, Day, and Year values are for identification purposes only and do not affect calculations. In this data set, the dates shown are the dates on which operation BEGAN at each specified flow rate. Operations may have continued into the next day or for multiple days.

Number of Tunnels	Damage Potential / 1000	Q / 1000	Month	Day	Year	Hours of Operation	Q / 1000
1	3.48	35	JUN	13	80	0.47	0.836
	3.30	25	JUN	13	80	0.48	1.254
	2.81	20	JUN	13	80	0.30	2.090
	2.73	15	JUN	13	80	0.07	8.358
	2.03	10	JUN	13	80	0.03	8.996
	9.97	5	JUN	13	80	0.38	10.492
	0.00	0	JUN	13	80	0.13	9.424
			JUN	13	80	0.07	8.996
			JUN	13	80	0.10	8.570
			JUN	13	80	0.10	8.146
			JUN	13	80	0.10	7.722
			JUN	13	80	0.05	7.300
			JUN	13	80	0.03	6.644
			JUN	13	80	0.07	5.956
			JUN	13	80	1.50	10.492
			JUN	13	80	0.13	9.424
			JUN	13	80	0.07	8.358
			JUN	13	80	0.10	7.722
			JUN	13	80	22.30	7.300
			JUN	22	80	0.17	1.080
			JUN	22	80	15.95	1.080
			JUN	22	80	14.00	1.512
			JUN	22	80	2.52	1.512
			JUN	23	80	0.35	10.872
			JUN	23	80	1.13	8.628
			JUN	23	80	0.53	10.872
			JUN	23	80	0.38	18.574
			JUN	23	80	0.27	25.058
			JUN	24	80	13.62	31.934
			JUN	24	80	16.00	2.164
			JUN	24	80	10.00	2.598
			JUN	25	80	7.00	3.030
			JUN	25	80	11.25	7.54
			JUN	26	80	21.5	8.662
			JUL	2	80	22.75	3.334
			JUL	3	80	24	1.732
			JUL	7	80	48	1.298
			OCT	31	81	0.13	6.168
			NOV	1	81	0.3	10.772
			APR	24	82	0.95	10.614
			APR	24	82	0.42	13.384
			APR	24	82	0.35	13.384
			JUN	2	83	23	10.064
			JUN	3	83	45	15.078
			JUN	5	83	24	20.176
			JUN	6	83	3	10.106
			JUN	6	83	0.15	7.894
			JUN	6	83	2.05	3.998
			JUN	7	83	73	4.014
			JUN	13	83	50	2.162
			JUN	15	83	64	11.84
			JUN	19	83	53	17.176
			JUN	21	83	45	20.07
			JUN	23	83	102	10.322
			JUN	27	83	1	25.016
			JUN	27	83	12	25.016
			JUN	28	83	0.75	32
			JUN	28	83	29.25	20.182
			JUN	29	83	46.55	15.044
			JUL	1	83	0.1	15.044
			JUL	1	83	44.07	20.006
			JUL	3	83	49.7	20.164
			JUL	5	83	6.58	18.83
			JUL	5	83	40	12.994
			JUL	7	83	5.7	11.011
			JUL	8	83	1	10.002
			JUL	8	83	6	10.002
			JUL	9	83	45	5.01
			JUL	11	83	141.03	7.458
			JUL	17	83	0.08	4.972
			JUL	17	83	21.92	4.972
			JUL	18	83	119.92	2.916

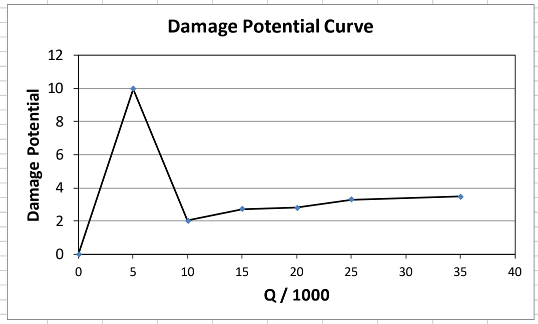


Figure 15. — Input data for computing damage index values.

DAMAGE INDEX REPORT

Compute Accumulated Damage Index Values

GLEN CANYON DAM - LEFT TUNNEL SPILLWAY - Sta. 24+25 ft

Date	Total Time	Q in 1000's	Damage Potential	Cumulative Damage Index
JUN 13 80	0.47	0.84	2914	1123
JUN 13 80	0.95	1.25	4183	2430
JUN 13 80	1.25	2.09	6346	3611
JUN 13 80	1.32	8.36	6613	3874
JUN 13 80	1.35	9.00	5061	3944
JUN 13 80	1.73	10.49	1716	4009
JUN 13 80	1.86	9.42	3857	4182
JUN 13 80	1.93	9.00	5061	4335
JUN 13 80	2.03	8.57	6129	4630
JUN 13 80	2.13	8.15	7063	4987
JUN 13 80	2.23	7.72	7869	5394
JUN 13 80	2.28	7.30	8542	5618
JUN 13 80	2.31	6.64	9336	5770
JUN 13 80	2.38	5.96	9837	6146
JUN 13 80	3.88	10.49	1716	6216
JUN 13 80	4.01	9.42	3857	6315
JUN 13 80	4.08	8.36	6613	6491
JUN 13 80	4.18	7.72	7869	6828
JUN 13 80	26.48	7.30	8542	27332
JUN 22 80	26.65	1.08	3670	27332
JUN 22 80	42.60	1.08	3670	27366
JUN 22 80	56.60	1.51	4904	27618
JUN 22 80	59.12	1.51	4904	27662
JUN 23 80	59.47	10.87	1530	27662
JUN 23 80	60.60	8.63	5992	27729
JUN 23 80	61.13	10.87	1530	27729
JUN 23 80	61.51	18.57	2850	27729
JUN 23 80	61.78	25.06	3304	27729
JUN 24 80	75.40	31.93	3538	27748
JUN 24 80	91.40	2.16	6513	29075
JUN 24 80	101.40	2.60	7416	30416
JUN 25 80	108.40	3.03	8180	31700
JUN 25 80	119.65	7.54	8175	33411
JUN 26 80	141.15	8.66	5910	33840
JUL 2 80	163.90	3.33	8638	37064
JUL 3 80	187.90	1.73	5481	37214
JUL 7 80	235.90	1.30	4309	37251
OCT 31 81	236.03	6.17	9718	37278

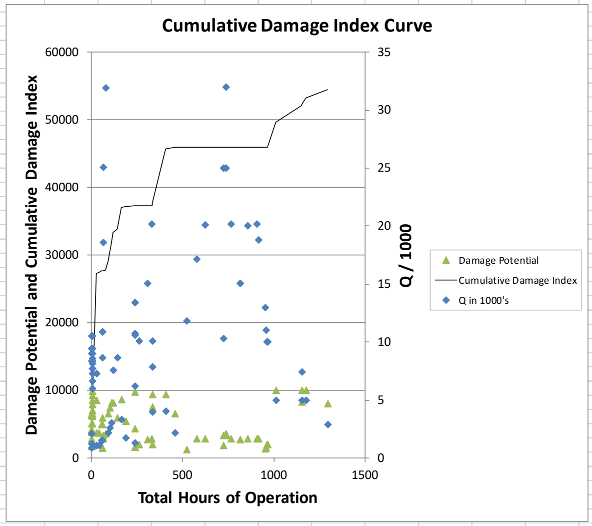


Figure 16. — Output from damage index program.

Differences from the EM42 FORTRAN Programs

The spreadsheet implementation of the cavitation analysis programs has several differences from the original FORTRAN programs, some of which have already been noted. A summary is provided here.

Water Surface Profile program

- The spreadsheet version of HFWS calculates a transition loss of $0.1|V_2^2-V_1^2|/(2g)$ only when the cross section shape or size varies from one station to the next. The original FORTRAN program assessed such a loss at every station, even when the cross section did not vary, because it was failing in many cases to reset the loss factor back to zero after it had been (validly) set to 0.1 at a location where the section geometry had changed. This was overestimating head losses down the chute, since transition losses were being assessed solely because the flow was accelerating under the influence of gravity.
- Cross section shapes are always entered with dimensions defined perpendicular (normal) to the bed slope. (The original FORTRAN programs offered an option to define sections in a vertical plane.)

- Added Froude number to hydraulic output table. Two Froude numbers are provided. One is adjusted for slope, curvature, and the energy correction factor, while the other is calculated as simply $Fr_{basic} = V/(gD)^{0.5}$, with D being the hydraulic depth (area divided by top width).
- Added calculations to detect possibility of roll waves. The method is described in *Design of Small Canal Structures*, p. 108-114.
- Added calculation of stream power applied to channel bottom, γDSV, where γ = unit weight of water, D = hydraulic depth (area / top width), S is the friction slope, and V is flow velocity.
- The turbulence intensity calculation in early versions of the spreadsheet did not match the calculation in the EM42 FORTRAN program. The proper calculation was restored. Turbulence intensity is calculated from $T_i = 0.25\sqrt{f}$ where f is Darcy's friction factor. The value of f is determined using the Colebrook-White equation as presented for open channel flow by Henderson (1966), with the boundary layer thickness replacing the usual hydraulic radius term, $\frac{1}{\sqrt{f}} = -2\log_{10}\left(\frac{k_s}{12\delta} + \frac{2.5}{Re\sqrt{f}}\right)$

  δ = boundary layer thickness
  k_s = rugosity
  $Re = 4R_hV/\nu$ = Reynolds number
  R_h = hydraulic radius, wetted flow area divided by wetted perimeter
  ν = kinematic viscosity
- Methods for computing the effects of streamline curvature on piezometric head were revised to also include the associated effects of channel slope and the variation of streamline curvature with distance from the channel bed.

Trajectory program

- The ramp angle is entered as the number of degrees deviation above the prevailing bed slope at the ramp station, as defined by the elevation and station values given in the geometric input. (The ramp angle was defined in the original FORTRAN program as the angle below horizontal.)
- The ramp height is entered as the distance between the existing channel bed and the ramp lip, measured perpendicular to the bed slope. (The original FORTRAN program asked the user to supply the elevation of the ramp lip.)
- Jet trajectory calculations automatically incorporate an adjustment for effect of relative ramp height, based on EM-42, Figure 5-3.
- Added calculation of stream power at point of jet impact
- The pressure factor, C_n, in Eqs. 5.1 and 5.2 that affects the jet trajectory was modified in the original FORTRAN program by two multipliers that

were not discussed in EM42. Both have been eliminated from the new trajectory program.

- The "PF" factor quadrupled the value of C_n when there was more than one air vent. The effect was backward from the correct adjustment, and the proper adjustment was determined to already be accounted for in the air vent velocity calculations.
- The "BV/B" factor reduced the effective pressure difference applied across the jet when the width of the air vent slot was small compared to the width of the spillway chute. This factor was an approximate empirical adjustment, but there is insufficient experimental evidence to validate its use at this time.

Controlled Pressure program

- Corrected formulas for sinusoidal distribution of invert curvatures
- Corrected scaling of output results, including arc distances and radii of curvature
- Corrected integration calculations by Simpson's rule

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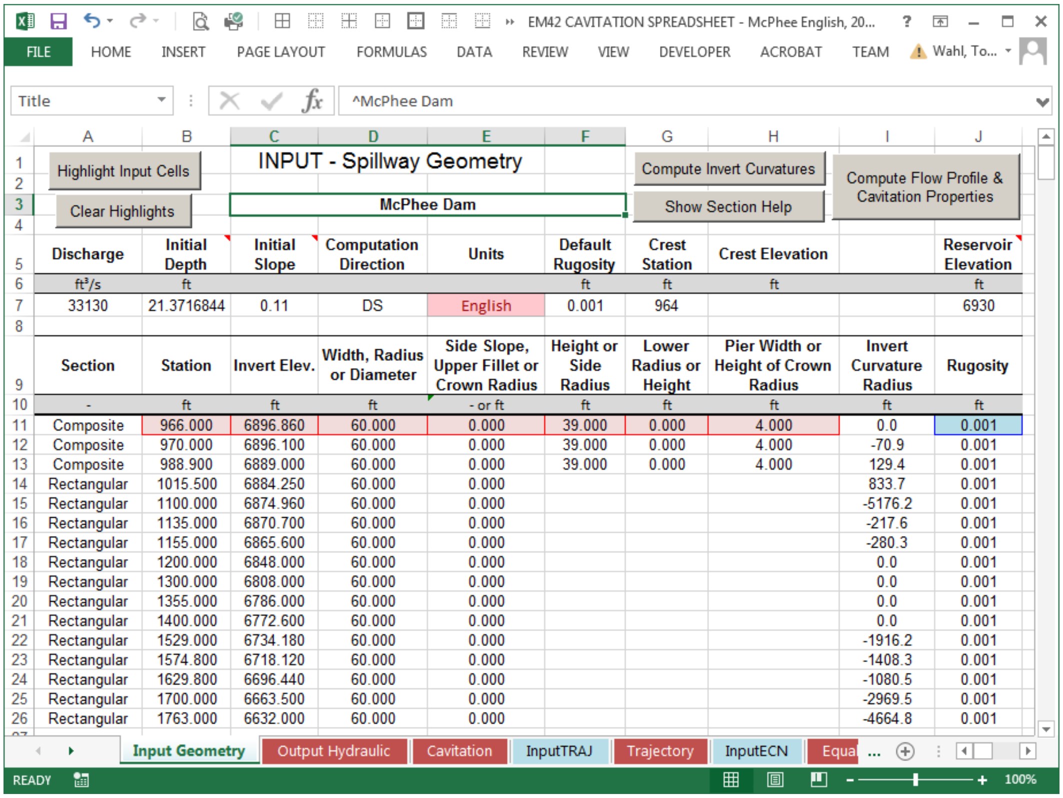
Appendix A: Example Application

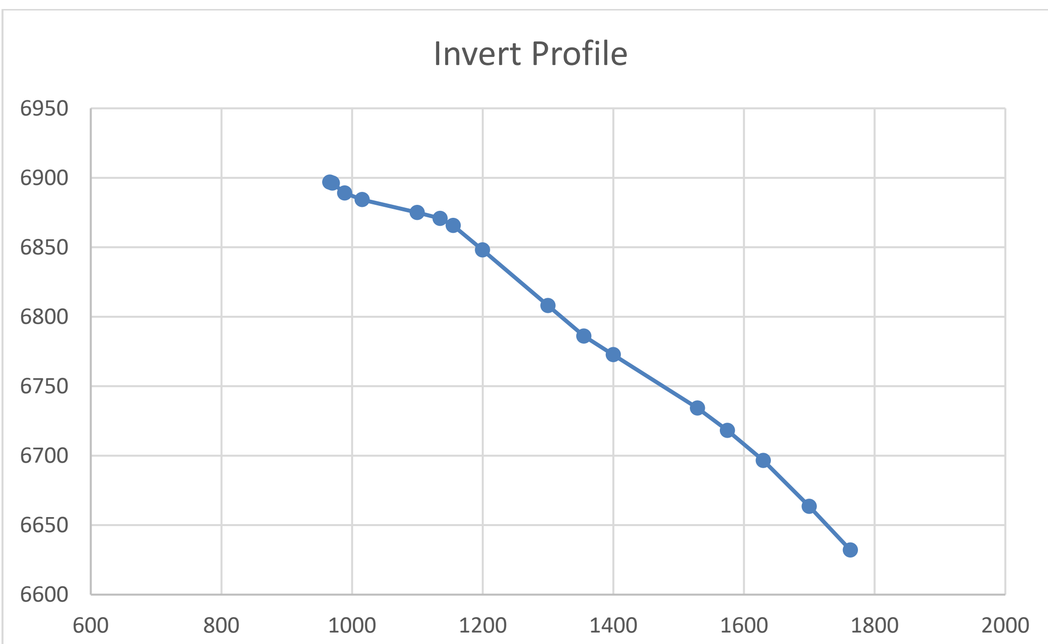
Tunnel spillways at Glen Canyon, Hoover, Yellowtail, Flaming Gorge, and Blue Mesa dams have all been retrofitted with aeration ramps. Yellowtail and Flaming Gorge were modified prior to 1983 and the others following the 1983 cavitation damage incident at Glen Canyon Dam. Example applications of the cavitation analysis programs for Glen Canyon Dam are provided in the main body of this report. Reclamation's other tunnel spillways at Kortes Dam and Seminoe Dam have not been modified, as their damage potentials were not deemed large enough to warrant aeration.

This appendix provides an example application of the water surface profile and aerator trajectory programs for McPhee Dam, a straight chute spillway that was newly constructed in 1983-84 with an aeration ramp included in the design.



Discharge	Initial Depth	Initial Slope	Computation Direction	Units	Default Rugosity	Crest Station	Crest Elevation		Reservoir Elevation
ft³/s	ft				ft	ft	ft		ft
33130	21.3716844	0.11	DS	English	0.001	964			6930

Section	Station	Invert Elev.	Width, Radius or Diameter	Side Slope, Upper Fillet or Crown Radius	Height or Side Radius	Lower Radius or Height	Pier Width or Height of Crown Radius	Invert Curvature Radius	Rugosity
-	ft	ft	ft	- or ft	ft	ft	ft	ft	ft
Composite	966.000	6896.860	60.000	0.000	39.000	0.000	4.000	0.0	0.001
Composite	970.000	6896.100	60.000	0.000	39.000	0.000	4.000	-70.9	0.001
Composite	988.900	6889.000	60.000	0.000	39.000	0.000	4.000	129.4	0.001
Rectangular	1015.500	6884.250	60.000	0.000				833.7	0.001
Rectangular	1100.000	6874.960	60.000	0.000				-5176.2	0.001
Rectangular	1135.000	6870.700	60.000	0.000				-217.6	0.001
Rectangular	1155.000	6865.600	60.000	0.000				-280.3	0.001
Rectangular	1200.000	6848.000	60.000	0.000				0.0	0.001
Rectangular	1300.000	6808.000	60.000	0.000				0.0	0.001
Rectangular	1355.000	6786.000	60.000	0.000				0.0	0.001
Rectangular	1400.000	6772.600	60.000	0.000				0.0	0.001
Rectangular	1529.000	6734.180	60.000	0.000				-1916.2	0.001
Rectangular	1574.800	6718.120	60.000	0.000				-1408.3	0.001
Rectangular	1629.800	6696.440	60.000	0.000				-1080.5	0.001
Rectangular	1700.000	6663.500	60.000	0.000				-2969.5	0.001
Rectangular	1763.000	6632.000	60.000	0.000				-4664.8	0.001



COMPUTED FLOW PROFILE - HYDRAULIC PROPERTIES

McPhee Dam

Q	Y_o	Rugosity	Manning's *n*	EGL at Crest
ft³/s	ft	ft		ft
33130	22	0.0010000	0.013254034	6929.965

Compute Flow Profile & Cavitation Properties

Station	Invert Elevation	Slope	Depth	Velocity	Water Surface Elev.	Piez	Energy Grade Line	Q Air/ Q Water	Profile	Normal Depth	Critical Depth	Froude Number	Thickness Boundary Layer	Roll Wave Check
ft	ft	-	ft	ft/s	ft	ft	ft	-	-	ft	ft	-	ft	-
966.000	6896.86	0.1100	22.0000	26.891	6918.993	21.868	6929.957	0.00	S2	5.850	22.194	1.01	0.037	No
970.000	6896.10	0.1900	18.8092	31.453	6915.246	18.479	6929.940	0.00	S2	4.851	22.283	1.29	0.095	No
988.900	6889.00	0.3757	16.3241	36.241	6906.438	20.426	6929.822	0.00	S2	3.901	23.956	1.73	0.303	No
1015.500	6884.25	0.1786	13.4629	41.014	6897.926	18.688	6929.062	0.00	S2	4.462	22.432	2.09	0.539	No
1100.000	6874.96	0.1099	10.6789	51.706	6885.703	11.680	6928.200	0.00	S2	5.223	21.383	2.82	1.124	No
1135.000	6870.70	0.1217	10.0226	55.092	6880.796	9.766	6927.682	0.00	S2	5.052	21.186	3.08	1.353	No
1155.000	6865.60	0.2550	9.0686	60.887	6874.959	3.976	6927.296	0.00	S2	3.989	20.697	3.55	1.482	No
1200.000	6848.00	0.3911	8.2171	67.197	6856.823	7.653	6926.092	0.00	S2	3.513	21.696	4.29	1.764	No
1300.000	6808.00	0.4000	6.6755	82.716	6815.189	6.198	6921.728	0.00	S2	3.491	21.773	5.89	2.325	No
1355.000	6786.00	0.4000	6.1730	89.449	6792.648	5.731	6918.209	0.00	S2	3.491	21.815	6.64	2.619	No
1400.000	6772.60	0.2978	5.9537	92.744	6778.812	5.706	6914.920	0.00	S2	3.805	21.620	6.92	2.846	No
1529.000	6734.18	0.2978	5.4762	100.830	6739.894	5.248	6903.571	0.00	S2	3.805	21.738	7.91	3.453	No
1574.800	6718.12	0.3507	5.2952	104.276	6723.731	3.666	6898.726	0.00	S2	3.625	21.794	8.40	3.667	No
1629.800	6696.44	0.3942	5.1051	108.160	6701.927	3.355	6892.167	0.00	S2	3.506	21.972	8.98	3.921	No
1700.000	6663.50	0.4692	4.8530	113.778	6668.861	2.450	6882.340	0.00	S2	3.342	22.253	9.90	4.244	No
1763.000	6632.00	0.5000	4.6771	118.058	6637.229	3.438	6872.168	0.00	S2	3.286	22.566	10.63	4.530	No

COMPUTED FLOW PROFILE - CAVITATION PROPERTIES

McPhee Dam

Compute Flow Profile & Cavitation Output

Q	Initial Depth	Rugosity	Manning's *n*
ft³/s	ft	ft	
33130	22	0.001	0.01325403

Station	Flow Sigma	Sigma of Uniform Roughness	Required Chamfer to Stop Cavitation	DAMAGE POTENTIAL: Circular Arc 1/4-in (5-mm)	Circular Arc 1/2-in (12.5-mm)	Circular Arc 1-in (25-mm)	90° Offset 1/4-in (5-mm)	90° Offset 1/2-in (12.5-mm)	90° Offset 1-in (25-mm)	Turbulence Intensity	Stream Power
ft	-	-	n : 1	-	-	-	-	-	-	-	kW/m2
966.00	4.251	0.040	1	0	0	0	0	0	0	0.047	1.79
970.00	2.887	0.040	1	0	0	0	0	0	0	0.041	2.63
988.90	2.270	0.041	1	0	0	0	0	0	0	0.035	3.76
1015.50	1.706	0.039	2	0	0	0	0	0	0	0.033	3.51
1100.00	0.904	0.041	3	0	0	0	0	0	1	0.030	6.77
1135.00	0.756	0.041	4	0	0	1	0	0	2	0.030	8.12
1155.00	0.518	0.041	6	1	2	7	1	4	12	0.029	10.85
1200.00	0.478	0.042	7	1	4	11	2	6	17	0.029	14.45
1300.00	0.302	0.043	13	18	43	99	23	57	133	0.028	26.64
1355.00	0.254	0.044	17	42	98	218	50	119	275	0.028	33.61
1400.00	0.236	0.044	19	60	136	302	68	161	369	0.028	37.44
1529.00	0.197	0.044	24	138	308	670	145	336	757	0.027	48.07
1574.80	0.175	0.045	29	237	521	1123	242	553	1237	0.027	53.17
1629.80	0.161	0.045	32	346	754	1618	344	779	1734	0.027	59.36
1700.00	0.141	0.045	39	626	1351	2878	601	1349	2981	0.027	69.14
1763.00	0.135	0.046	41	752	1620	3443	703	1574	3473	0.026	77.30

EM42 CAVITATION SPREADSHEET - McPhee English, 2017...

FILE HOME INSERT PAGE LAYOUT FORMULAS DATA REVIEW VIEW DEVELOPER ACROBAT Team Wahl, To...

STREAMPOWER | 1582.07560940785

Compute Jet Trajectory

JET TRAJECTORY AND AERATOR RESULTS

McPhee Dam

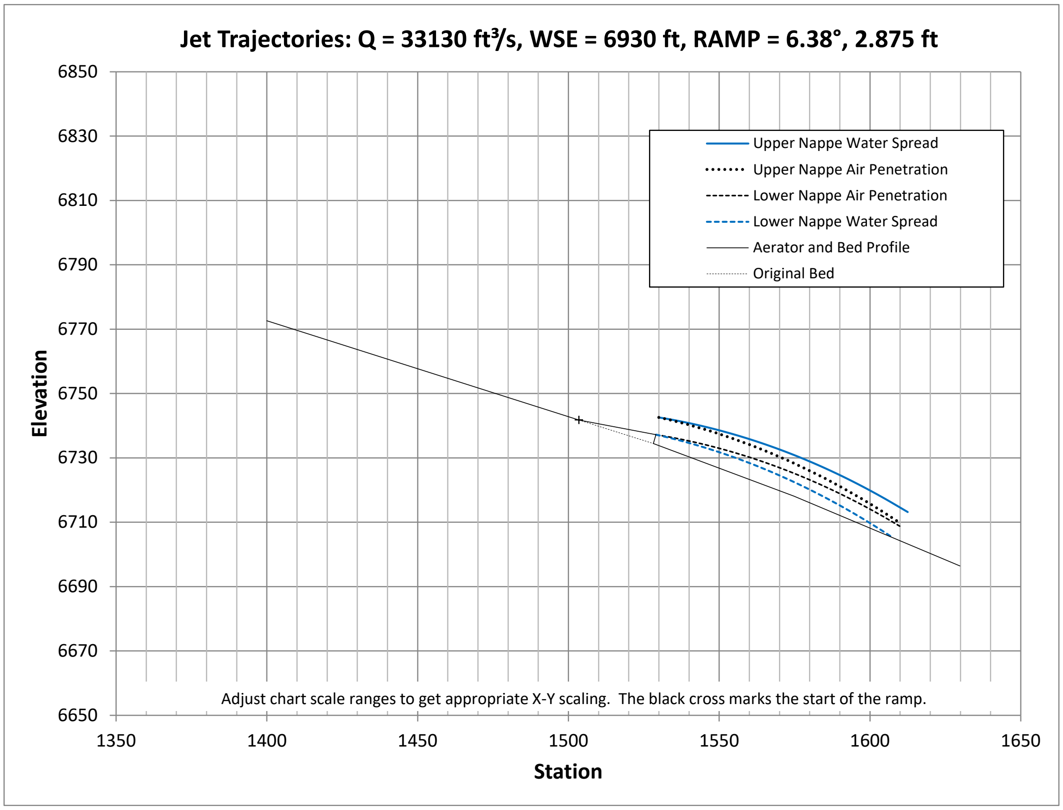
RAMP GEOMETRY:	**WIDTH**	**STATION**	**HEIGHT**	**ANGLE**
	60.00 ft	1529 ft	2.875 ft	6.3795 degrees
AIR DUCT:	**AREA**	**LOSS COEFF**	**VENT WIDTH**	**NUMBER OF VENTS**
	16.00 m²	1.00	0.00 ft	2
FLOWS:	**WATER**	**AIR FLOW**	**AIR VELOCITY**	**Δ PRESSURE**
	33130 ft³/s	13832.16 ft³/s	432.3 ft/s	1.060 psi
RAMP HYDRAULICS:	**TURBULENCE INTENSITY**	**FLOW DEPTH AT RAMP**	**MEAN VELOCITY**	**TAKEOFF ANGLE**
	0.02709	5.476236 ft	100.83 ft/s	6.3795 degrees
	STREAM POWER AT IMPACT	**RAMP THRUST (NORMAL)**	**RAMP THRUST (LONGITUDINAL)**	**JET THROW DISTANCE (HORIZ.)**
	1582.1 kW/m²	12001 lb/ft	669 lb/ft	78.61 ft

J E T   T R A J E C T O R Y

LOWER NAPPE				UPPER NAPPE			
Max Water Spread		Air Penetration Limit		Max Water Spread		Air Penetration Limit	
STATION	ELEV	STATION	ELEV	STATION	ELEV	STATION	ELEV
ft	ft	ft	ft	ft	ft	ft	ft
1529.00	6737.18	1529.00	6737.18	1529.97	6742.57	1529.97	6742.57
1532.10	6736.51	1532.13	6736.68	1532.96	6742.09	1533.22	6741.87
1535.20	6735.80	1535.26	6736.13	1536.08	6741.55	1536.31	6741.16
1538.29	6735.04	1538.39	6735.54	1539.21	6740.96	1539.41	6740.40
1541.38	6734.23	1541.51	6734.91	1542.33	6740.32	1542.50	6739.59
1544.47	6733.38	1544.62	6734.22	1545.45	6739.64	1545.59	6738.74
1547.56	6732.48	1547.74	6733.50	1548.56	6738.91	1548.67	6737.84
1550.64	6731.54	1550.85	6732.72	1551.67	6738.14	1551.75	6736.90
1553.71	6730.55	1553.95	6731.90	1554.78	6737.32	1554.83	6735.91
1556.78	6729.52	1557.05	6731.04	1557.88	6736.45	1557.90	6734.88
1559.85	6728.44	1560.15	6730.13	1560.97	6735.54	1560.96	6733.80
1562.91	6727.31	1563.24	6729.17	1564.07	6734.58	1564.02	6732.67
1565.96	6726.14	1566.33	6728.16	1567.15	6733.58	1567.08	6731.50
1569.01	6724.92	1569.41	6727.12	1570.23	6732.53	1570.13	6730.28
1572.06	6723.65	1572.48	6726.02	1573.31	6731.43	1573.17	6729.02
1575.10	6722.34	1575.55	6724.88	1576.38	6730.29	1576.21	6727.71
1578.13	6720.99	1578.62	6723.69	1579.44	6729.11	1579.25	6726.35
1581.16	6719.59	1581.67	6722.46	1582.50	6727.87	1582.27	6724.95
1584.18	6718.14	1584.73	6721.18	1585.55	6726.60	1585.29	6723.50
1587.19	6716.64	1587.77	6719.86	1588.59	6725.27	1588.31	6722.00
1590.20	6715.10	1590.81	6718.49	1591.63	6723.90	1591.32	6720.46
1593.20	6713.52	1593.84	6717.07	1594.66	6722.48	1594.32	6718.88
1596.19	6711.88	1596.86	6715.61	1597.69	6721.02	1597.31	6717.25
1599.18	6710.21	1599.88	6714.10	1600.70	6719.51	1600.30	6715.57
1602.16	6708.48	1602.89	6712.54	1603.71	6717.96	1603.27	6713.84
1605.13	6706.71	1605.89	6710.94	1606.71	6716.35	1606.24	6712.07
1607.61	6705.19	1609.82	6708.78	1612.51	6713.16	1610.31	6709.58

Input Geometry | Output Hydraulic | Cavitation | InputTRAJ | Trajectory | InputECI ...

READY 100%



Jet Trajectories: Q = 33130 ft³/s, WSE = 6930 ft, RAMP = 6.38°, 2.875 ft
Upper Nappe Water Spread
Upper Nappe Air Penetration
Lower Nappe Air Penetration
Lower Nappe Water Spread
Aerator and Bed Profile
Original Bed
Elevation
6850
6830
6810
6790
6770
6750
6730
6710
6690
6670
6650
Adjust chart scale ranges to get appropriate X-Y scaling. The black cross marks the start of the ramp.
1350
1400
1450
1500
1550
1600
1650
Station