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HYDRAULIC FORCES ON SUBMERGED BRIDGE DECKS

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16 Abstract <p>Bridge decks can be subjected to large horizontal forces when overtopping occurs. These forces may result in the displacement of bridge decks from the bents. This paper reports on the results of a laboratory study of horizontal forces on bridge decks under submerged, steady flow conditions with tailwater elevations above the top of the bridge deck. Momentum analysis was used to determine the horizontal force on model bridge decks subjected to overtopping. Empirical equations were developed that expressed the dimensionless horizontal force per unit bridge width as functions of the approach flow Froude number and dimensionless geometric parameters. The empirical equation with the smallest standard error was used to determine the resultant horizontal force on a prototype bridge using the output from the Hydrologic Engineering Center's River Analysis System (HEC-RAS Version 3.1.3) one-dimensional, hydraulic model.</p>			
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ABSTRACT

Bridge decks can be subjected to large horizontal forces when overtopping occurs. These forces may result in the displacement of bridge decks from the bents. This paper reports on the results of a laboratory study of horizontal forces on bridge decks under submerged, steady flow conditions with tailwater elevations above the top of the bridge deck. Momentum analysis was used to determine the horizontal force on model bridge decks subjected to overtopping. Empirical equations were developed that expressed the dimensionless horizontal force per unit bridge width as functions of the approach flow Froude number and dimensionless geometric parameters. The empirical equation with the smallest standard error was used to determine the resultant horizontal force on a prototype bridge using the output from the Hydrologic Engineering Center's River Analysis System (HEC-RAS Version 3.1.3) one-dimensional, hydraulic model. An EXCEL spreadsheet was developed to carry out the computations.

(<http://www.hec.usace.army.mil/software/hecras/hecras-download.html>)

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CHAPTER 1 - INTRODUCTION

1.1 Background

This project was originally entitled Review of Menu Driven Program for Scour Analysis. Unfortunately, the menu driven WSPRO program was never completed by FHWA. The graduate students funded by the project were put to work in the lab while waiting for the program to be completed. Consequently, this report presents the results of those laboratory experiments. Essentially, a series of flume experiments were undertaken to study the forces exerted on bridge decks under submerged flow conditions. This topic is of particular interest today considering the many bridge decks pushed from their bents during Hurricane Katrina. The picture below showing the aftermath at one bridge is compliments of Dr. William C. Clawson of HNTB.



Figure 1.1: I-10 Bridge, New Orleans, August, 2005.

The results of the experimental work were summarized by 3 different empirical equations expressing the unit horizontal bridge deck force as functions of flow and geometry parameters. A spreadsheet was then developed to calculate the bridge deck force distribution for structures modeled in HEC-RAS 3.1.3. The empirical equation that showed the “best-fit” was used in the spreadsheet.

1.2 Objectives

The specific objectives of this study were:

1. To perform a series of flume experiments to investigate the horizontal, hydraulic force distribution on bridge decks under submerged conditions.
2. To develop empirical curves or equations summarizing the experimental data.
3. To develop an EXCEL spreadsheet that can be used to analyze horizontal, hydraulic forces on bridge decks using the empirical results and output from HEC-RAS hydraulic models.

CHAPTER 2 - EXPERIMENTAL PROCEDURES

2.1 Experimental Set-Up

Hydraulic tests of model bridge decks were performed in the glass-walled, 40-ft long, 1-ft wide tilting flume in the Hydraulics Laboratory at the University of Kansas. Water depths are controlled using sluice gates at the upstream and downstream ends of the 40-ft flume test section. The flume flow is supplied by the lab's constant-head tank system and controlled with a valve and venturi meter in the flume inflow line. The constant-head, recirculating water system pumps water from a sump pit in the basement up to a head box on the roof of the building. The head box is divided into a supply region and a return region that are separated by a weir. The supply pipes for the lab flume take water from the upstream side of the head box weir. The portion of the pump flow that exceeds the flume requirement flows over the weir and returns to the sump. Since the weir is relatively long, the water surface elevation in the head tank is relatively constant for a wide range of flume flows.

The bridge decks were modeled using 2-by dimension lumber with a constant thickness of 1.5 inches. Figure 2.1 shows a schematic of the set-up and defines flow and geometric parameters. The water depths upstream and downstream from the model bridge deck, y_1 and y_2 , were above the top of the deck.

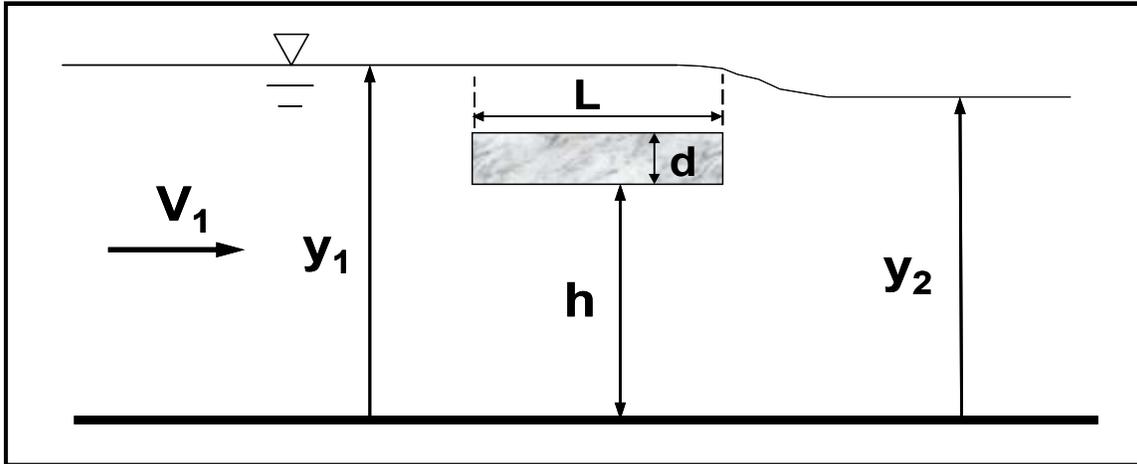


Figure 2.1: Flume Set-Up.

The depth y_1 was measured 0.5 feet upstream from the upstream face of the bridge deck using a point gauge. Section 2 was located 4 feet downstream from Section 1. Piezometers were placed at both sections and a Rouse micro manometer was used to measure the difference in piezometric head, Δy . Since the flume was horizontal, y_2 was determined by subtracting Δy from y_1 . This was necessary since a direct measurement of the downstream depth was difficult due to surface waves.

2.2 Test Procedures

Experiments were performed over a range of flows for L/d -values of 4, 6, 8 and 10 and h/d values of 2, 4, 6 and 8. The discharge and depths were varied over a wide range of conditions. A total of 382 experiments were performed. The approach Froude number, $V/(gy_1)^{1/2}$, ranged from 0.071 to 0.503 as shown in the APPENDIX.

The horizontal, hydraulic force on the water between Sections 1 and 2 for a rectangular channel of width b was determined from the momentum equation as shown below.

$$F = \gamma(M_1 + M_2) \quad \text{Equation 1}$$

Where $M = \frac{by^2}{2} + \frac{(Vby)^2}{gby}$ and γ = specific weight of water. Using the flume

discharge and the depths y_1 and y_2 , the F-value can be determined. This force, F, consists of the force on the bridge deck, F_d , and the friction force on the flume bottom and sidewalls between Sections 1 and 2, F_f .

The friction force is given by

$$\begin{aligned} F_f &= \tau P_w L = (\gamma R S_f) P_w L = (\gamma (A / P_w) S_f) P_w L \\ &= \gamma A S_f L \end{aligned} \quad \text{Equation 2}$$

Where the friction slope is given by the following form of Manning's equation

$$S_f = \left(\frac{nV}{1.49} \right)^2 \left(\frac{P_w}{A} \right)^{4/3} \quad \text{Equation 3}$$

Substituting Equation 3 into Equation 2 gives

$$F_f = \gamma A L \left(\frac{nV}{1.49} \right)^2 \left(\frac{P_w}{A} \right)^{4/3} = \gamma L \left(\frac{nV}{1.49} \right)^2 \left(\frac{(b + 2y)^{4/3}}{(by)^{1/3}} \right) \quad \text{Equation 4}$$

Equation 4 was used to estimate the friction force between Sections 1 and 2. The force on the bridge deck for the 1-ft wide flume is then given by

$$F_d = F - F_f = \gamma \left[\left(\frac{by_1^2}{2} + \frac{(V_1 by_1)^2}{gby_1} \right) - \left(\frac{by_2^2}{2} + \frac{(V_2 by_2)^2}{gby_2} \right) \right] - \gamma L \left(\frac{n\bar{V}}{1.49} \right)^2 \left(\frac{(b + 2\bar{y})^{4/3}}{(\bar{y})^{1/3}} \right) \quad \text{Equation 5}$$

Where $\bar{y} = 0.5(y_1 + y_2)$ and $\bar{V} = 0.5(V_1 + V_2)$.

Since $b = 1$ foot for the laboratory flume width the force, F_d , in pounds calculated from Equation 6 is also equal to the unit force, f_d , in lb/ft.

2.3 Model-Prototype Similitude Considerations

Froude number similarity is used for free surface flow model. This means that if the model and prototype are geometrically similar, to insure dynamic similarity the Froude number in the model and prototype must be equal. This is stated by the following equation

$$\frac{V_m}{\sqrt{gL_m}} = \frac{V_p}{\sqrt{gL_p}} \quad \text{Equation 6}$$

This, in turn, gives the relationships

$$V_r = \frac{V_m}{V_p} = \frac{\sqrt{L_m}}{\sqrt{L_p}} = \sqrt{L_r} \quad \text{Equation 7}$$

$$Q_r = V_r A_r = V_r L_r^2 = L_r^{1/2} L_r^2 = L_r^{5/2} = \left(\frac{L_m}{L_p} \right)^{5/2} \quad \text{Equation 8}$$

Dynamic similitude gives the force ratio as

$$\frac{F_m}{F_p} = \gamma_r L_r^3 = \frac{\gamma_m L_m^3}{\gamma_p L_p^3} \quad \text{Equation 9}$$

Where F_m = force in the model; F_p = force in the prototype; $L_r = L_m/L_p$; L_m = characteristic length in the model and L_p = characteristic length in the prototype.

The unit force modeling ratio is, therefore,

$$\frac{f_m}{f_p} = \gamma_r L_r^2 = \frac{\gamma_m L_m^2}{\gamma_p L_p^2} \quad \text{Equation 10}$$

The dimensionless unit force on the bridge deck used in this study can be expressed as

$$f_d^* = \frac{f_{d,m}}{\gamma_m L_m^2} = \frac{f_{d,p}}{\gamma_p L_p^2} \quad \text{Equation 11}$$

The characteristic length used herein will be the bridge deck thickness, d , as shown in Figure 2.1. Also, the specific weight for both model and prototype conditions will be equal to 62.4 lb/ft³. An empirical relationship will be developed expressing f_d^* as a function of flow and geometric parameters.

CHAPTER 3 - EXPERIMENTAL RESULTS

3.1 Experimental Data

A total of 382 experiments were performed. The approach Froude number, $V_1/(gy_1)^{1/2}$, ranged from 0.071 to 0.503. The experimental data is shown in table form in the EXCEL file Experimental Data.xls on the Appendix CD. A portion of the table is shown below.

Table 3.1: Experimental data calculated in the Excel software found on the Appendix CD.

Run No.	y_1 (cm)	Δy (in)	h/d	L/d	y_1 (in)	y_2 (in)	Q (cfs)	V_1 (ft/s)	V_2 (ft/s)	M_1 (ft ³)	M_2 (ft ³)	Fr_1	F (lb)	y_{ave} (ft)	F_f (lb)	f_d (lb/ft)	f_d^*
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	77.4	0.056	2	4	9.69	9.63	0.60	0.74	0.75	0.340	0.336	0.146	0.230	0.805	0.024	0.205	0.211
2	79.6	0.040	2	4	10.55	10.51	0.70	0.80	0.80	0.404	0.401	0.150	0.176	0.878	0.029	0.147	0.151
3	73.9	0.057	2	4	8.31	8.25	0.50	0.72	0.73	0.251	0.248	0.153	0.200	0.690	0.021	0.179	0.184
4	78.9	0.087	2	4	10.28	10.19	0.90	1.05	1.06	0.396	0.390	0.200	0.371	0.853	0.050	0.322	0.330
5	72.6	0.096	2	4	7.78	7.68	0.60	0.93	0.94	0.227	0.222	0.203	0.307	0.644	0.034	0.273	0.280
6	73.8	0.089	2	4	8.27	8.18	0.70	1.02	1.03	0.259	0.255	0.216	0.302	0.685	0.042	0.260	0.267
7	75.2	0.141	2	4	8.82	8.68	0.80	1.09	1.11	0.297	0.289	0.224	0.507	0.729	0.050	0.457	0.469
8	68.4	0.157	2	4	6.15	6.00	0.50	0.98	1.00	0.147	0.140	0.240	0.388	0.506	0.035	0.353	0.363

Column 15 is the average depth, $y_{ave} = (y_1 + y_2)/2$ and is used in the friction calculation. The other parameters in the table are described above. The tailwater depth y_2 was above the bridge deck for all runs.

The dimensionless unit force is a function of the variables shown below.

$$f_d^* = f\left(\frac{L}{d}, \frac{h}{d}, Fr_1 = \frac{V_1}{\sqrt{gy_1}}\right) \quad \text{Equation 12}$$

Figure 3.1 shows f_d^* versus Fr_1 for the different values of h/d . The log plots show that the data for each h/d -value follows a power-curve plot fairly well. Thus the relationship $f_d^* = \alpha Fr_1^\beta$ can be applied where α and β are coefficients. In this case the coefficients are functions of h/D and perhaps other variables.

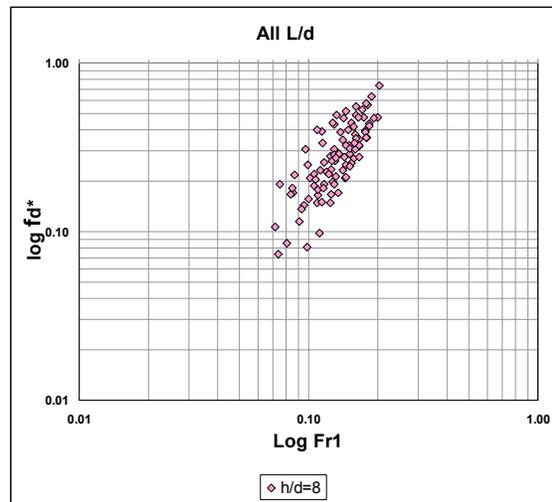
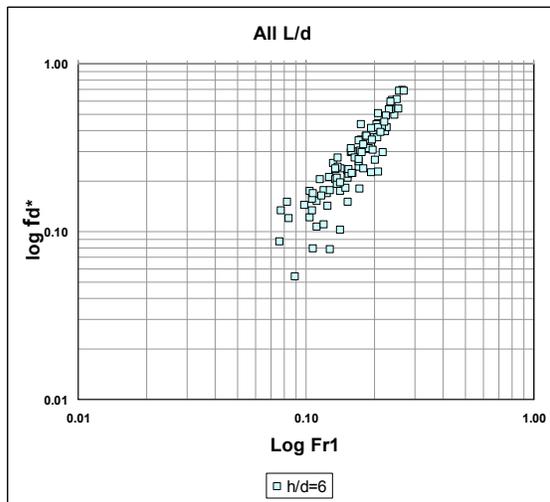
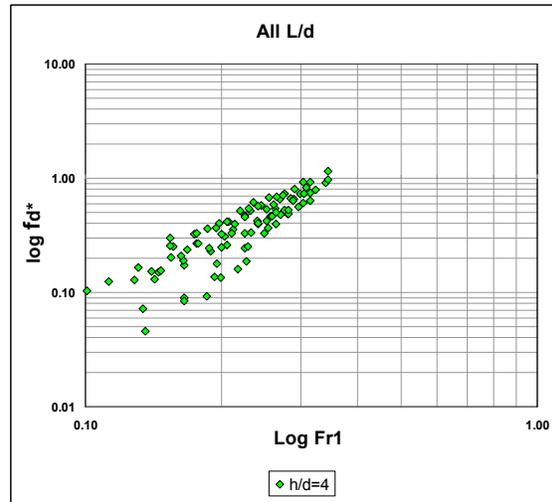
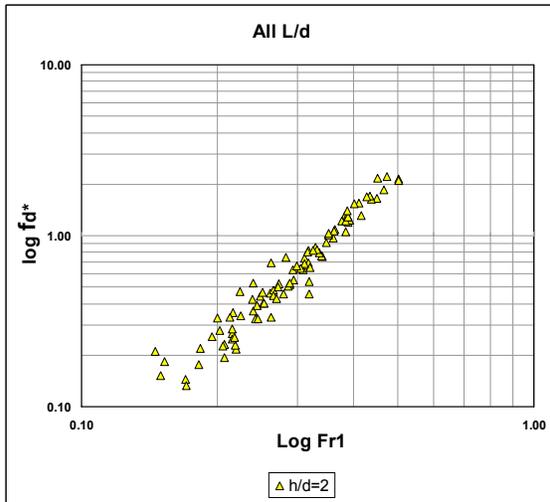
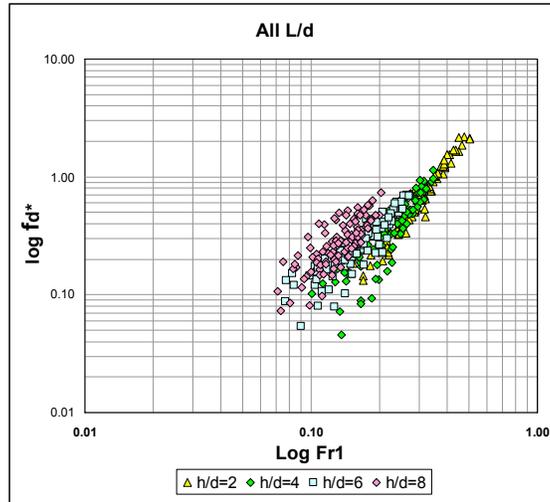


Figure 3.1: Log-Log Plots of f_d^* versus Fr_1 .

3.2 Empirical Equations

Statistical analysis involving minimization of the sum of the residuals squared yielded the following equation with a standard error of 0.0961.

$$f_d^* = 20.4(h/d)^{-0.789} Fr_1^{3.34(h/d)^{-0.396}} (L/d)^{0.0663} \quad \text{Equation 13}$$

(The analysis procedure is presented in Section 3.3.) Note that the coefficient for L/d in Equation 13 is quite small which indicates that the variable is not too important.

The following equation without L/d was derived using statistical analysis. It has a standard error of 0.0969.

$$f_d^* = 22.6(h/d)^{-0.767} Fr_1^{3.32(h/d)^{-0.389}} \quad \text{Equation 14}$$

Figure 3.2 shows a plot of Equation 14 and the measured data.

A third equation was derived that has a standard error of 0.0879. It is shown below. Note that it includes y_1/d but not L/d.

$$f_d^* = 8.85(y_1/d)^{0.809} (h/d)^{-1.06} Fr_1^{3.42(h/d)^{-0.359}} \quad \text{Equation 15}$$

Plots like those shown in Figure 3.2 for Equation 14 cannot be made for Equation 15 since it has an additional independent dimensionless.

Figure 3.3 shows the predicted f_d^* -values versus measured f_d^* -values for Equations 13, 14 and 15. Since the standard error is lowest and the R^2 -value is highest for Equation 15, it will be adopted for subsequent analysis.

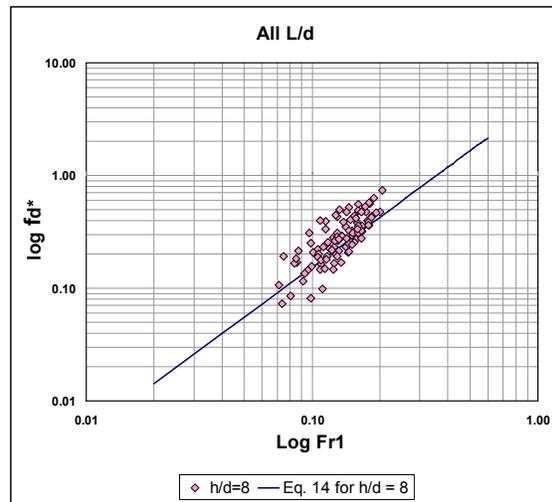
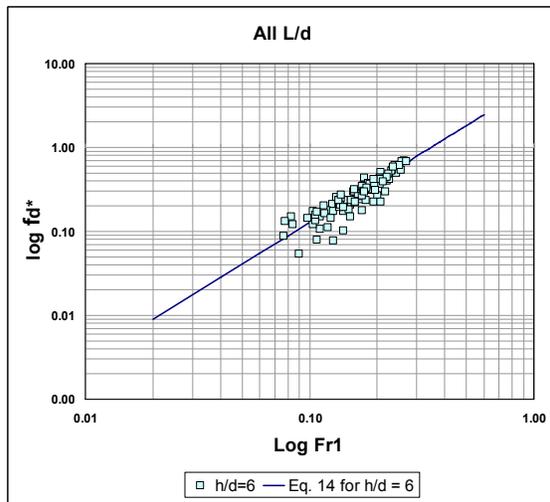
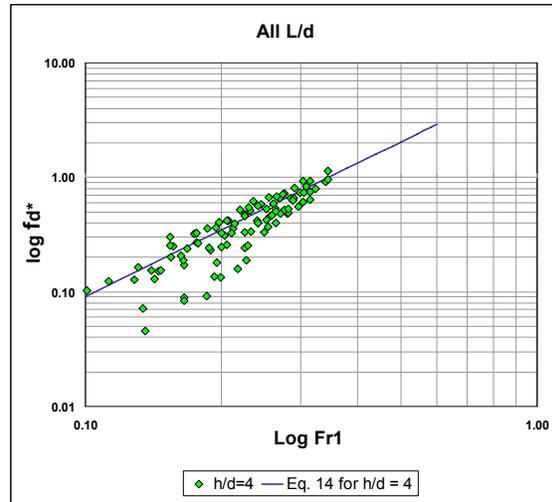
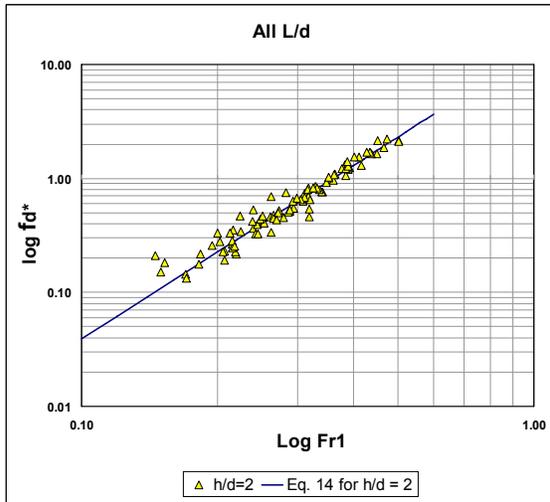
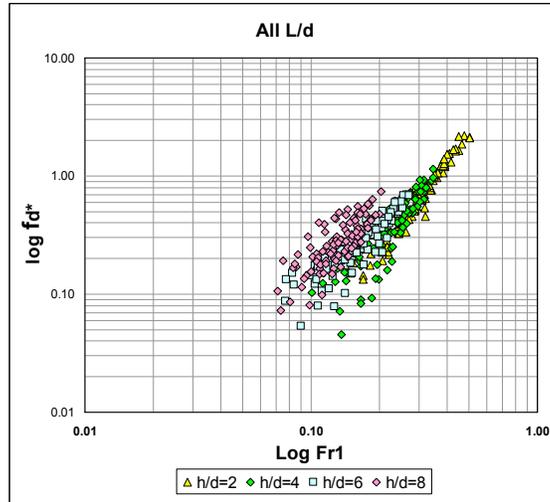


Figure 3.2: Measured Data and Equation 14 for h/d-values of 2, 4, 6 and 8.

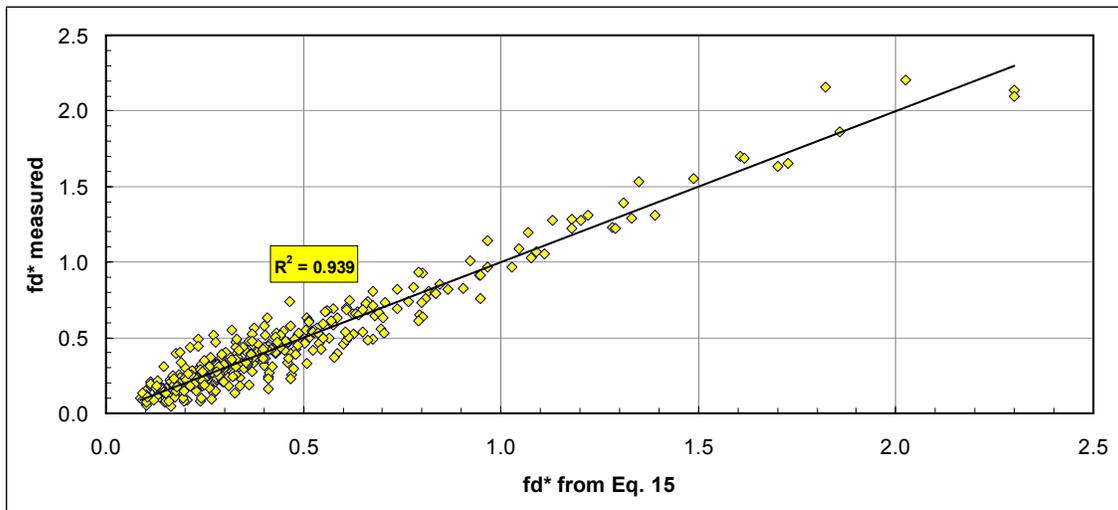
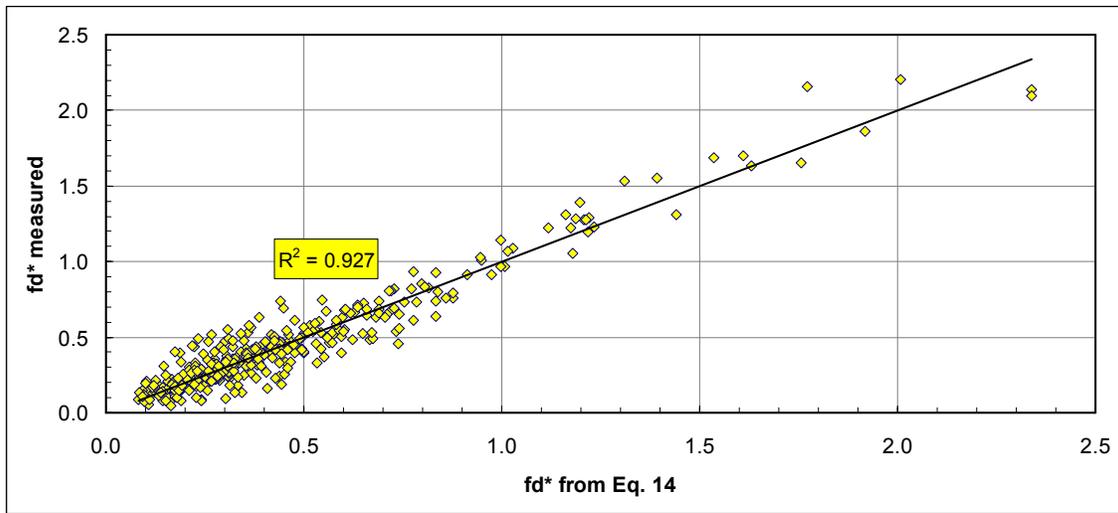
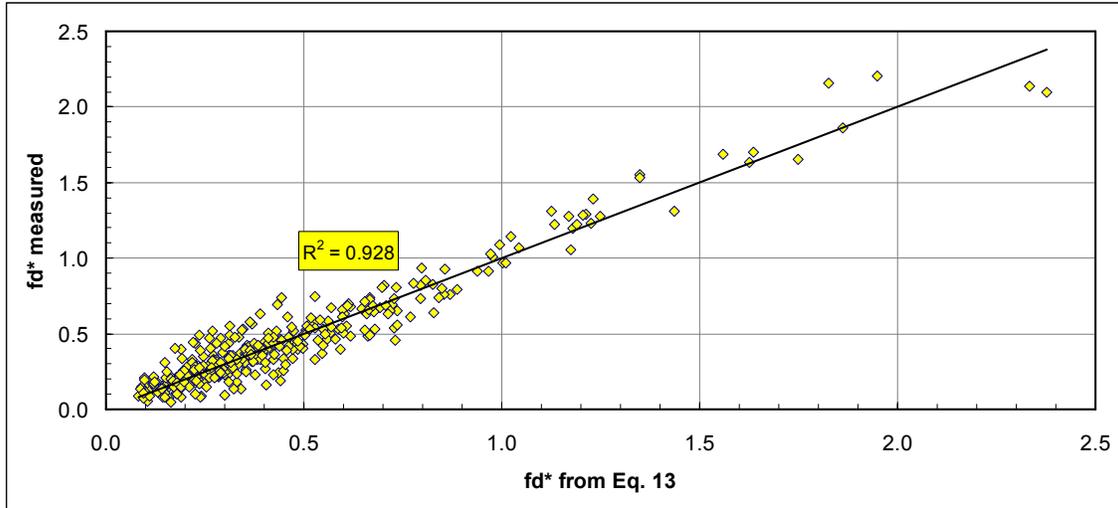


Figure 3.3: Plots of Predicted versus Measured values of f_d^* for Equations 13, 14 and 15.

3.3 Curve Fitting Procedure

The curve fitting process used to derive Equations 13, 14 and 15 in the previous section used the Solver tool in EXCEL. Equation 15 above was based on an equation of the form shown below. The process will be illustrated below using Equation 16 to determine the five coefficients in Equation 15.

$$f_d^* = a(y_1 / d)^e (h / d)^b Fr_1^{c(h/d)^d} \quad \text{Equation 16}$$

Initial values for the coefficients a-e are assigned then the f_d^* -value is predicted for each of the runs using the y_1/d , h/d and Fr_1 values. The square of the residuals were then calculated and summed for all runs in accordance with the equation.

$$SRS = \sum (f_{d,\text{measured}}^* - f_{d,\text{equation}}^*)^2 \quad \text{Equation 17}$$

Open the Solver tool (*Tools, Solver*). Set the **Target Cell** to the cell containing SRS and set the *By Changing Cells* to the cells containing the coefficients a, b, c, d and e. Set the *Equal To:* to *Min* the select *Solve*. This procedure is shown in Figure 3.4. After executing the solver it will ask if you want to keep the solution (*Keep Solver Solution*). Select *Yes* and the best-fit values of the coefficients will be saved in appropriate cells. The values in the table below were used to produce Equation 15. The statistical analyses for Equations 13, 14 and 15 are included in the Appendix CD as the file **Statistical Analysis.xls**.

<i>a</i>	8.846
<i>b</i>	-1.055
<i>c</i>	3.418
<i>d</i>	-0.359
<i>e</i>	0.809

$$f_d^* = 8.85(y_1 / d)^{0.809} (h / d)^{-1.06} Fr_1^{3.42(h/d)^{-0.359}}$$

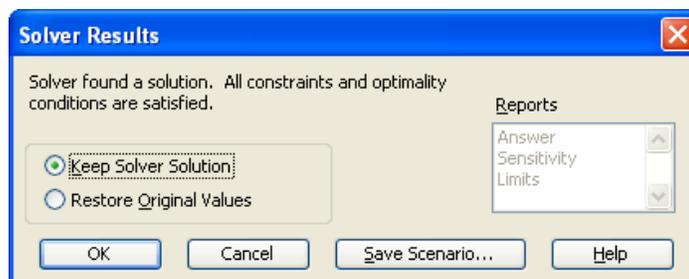
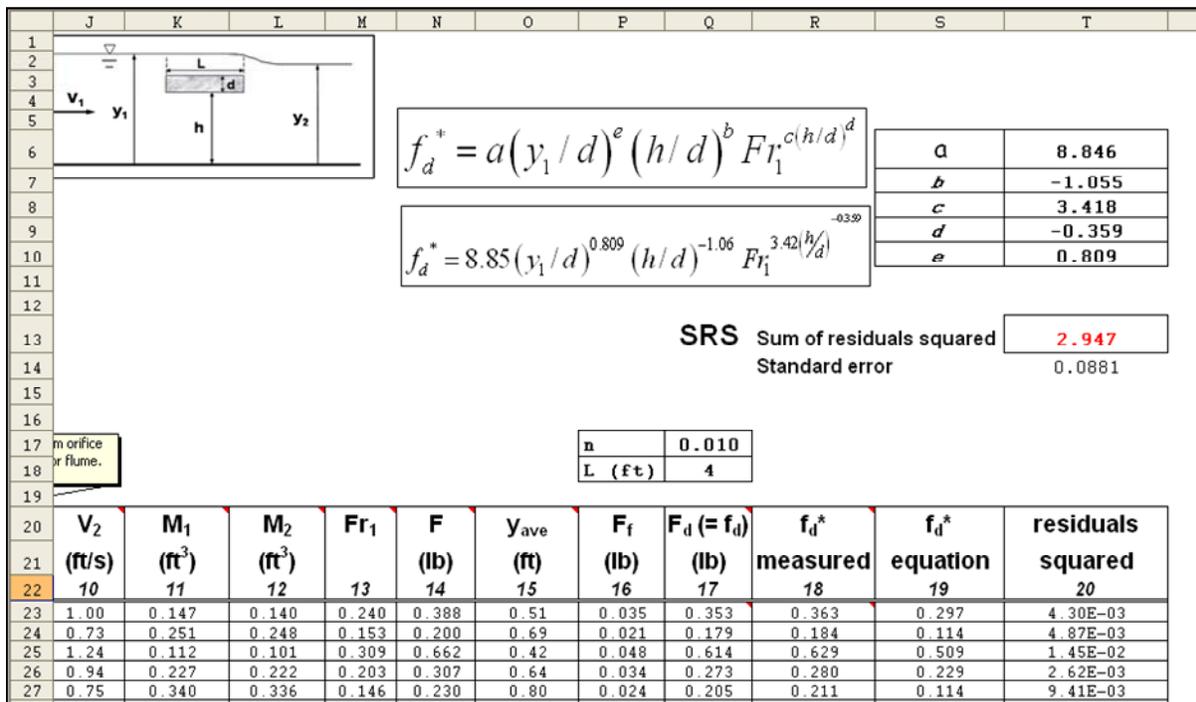
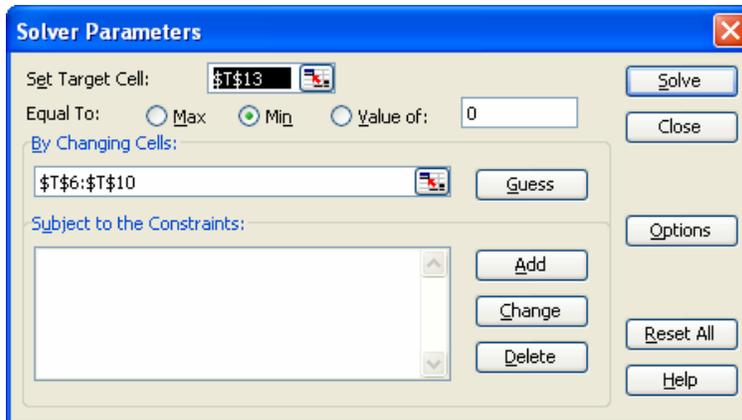


Figure 3.4: Using EXCEL Solver Tool to Obtain a “Best-fit” Equation.

CHAPTER 4 - APPLICATION OF EMPIRICAL EQUATIONS

4.1 Basic Equations

Equation 11 can be rearranged to yield the following expression for the prototype force per unit width of bridge deck in English units.

$$f_{d,p} = \gamma_p L_p^2 f_d^* = 62.4 d^2 f_d^* \quad \text{Equation 18}$$

Where d is the thickness of the bridge deck in feet. If f_d^* were constant, then $f_{d,p}$ would also be constant and you could simply multiply $f_{d,p}$ times the width of the bridge deck subjected to the flow to get the total force on the bridge. This will seldom be the case since both the flow depth and velocity vary across most bridge openings. This variation, in turn, causes a variation in f_d^* and, thus, $f_{d,p}$ across the bridge. The variation of f_d^* is given by Equation 15 shown again below.

$$f_d^* = 8.85(y_1 / d)^{0.809} (h / d)^{-1.06} Fr_1^{3.42(h/d)^{-0.359}} \quad \text{Equation 15}$$

4.2 EXCEL Spreadsheets and HEC-RAS Models

Two EXCEL files were prepared for determining the forces on horizontal and variable depth bridge decks. They are called ***Forces on Horizontal Bridge Decks.xls*** and ***Forces on Variable Depth Bridge Decks.xls***, respectively. The horizontal bridge deck is defined herein has a constant depth, horizontal bridge deck that is horizontal. The depth of the water under the horizontal bridge deck can vary, however. The variable depth bridge deck can vary in deck depth as well as the high and low steel elevations.

Two HEC-RAS models, ***Horizontal.prj*** and ***Variable.prj***, were developed to analyze bridges with horizontal and variable depth bridge decks, respectively. These

models are the HEC-RAS example problem **Single Bridge-Example 2, BEAVCREK.prj** with the bridge deck modified for each case.

The HEC-RAS model **Horizontal.prj** will be used to demonstrate the application of **Forces on Horizontal Bridge Decks.xls**. The computer model HEC-RAS 3.1.3 has a flow distribution option that is useful in applying Equation 15. The option computes the flow, velocity, hydraulic depth and other parameters for up to 45 subsections at a cross section. Figure 4.1 shows a bridge cross section and the upstream-face cross section for a bridge under overtopping conditions. The HEC-RAS Flow Distribution table from the HEC-RAS model **Horizontal.prj** is shown in Figure 4.2. The Flow Distribution Output table can be copied into an EXCEL spreadsheet by selecting *File, Copy to Clipboard*. Table 4.1 shows the entire Flow Distribution Output Table as copied into EXCEL.

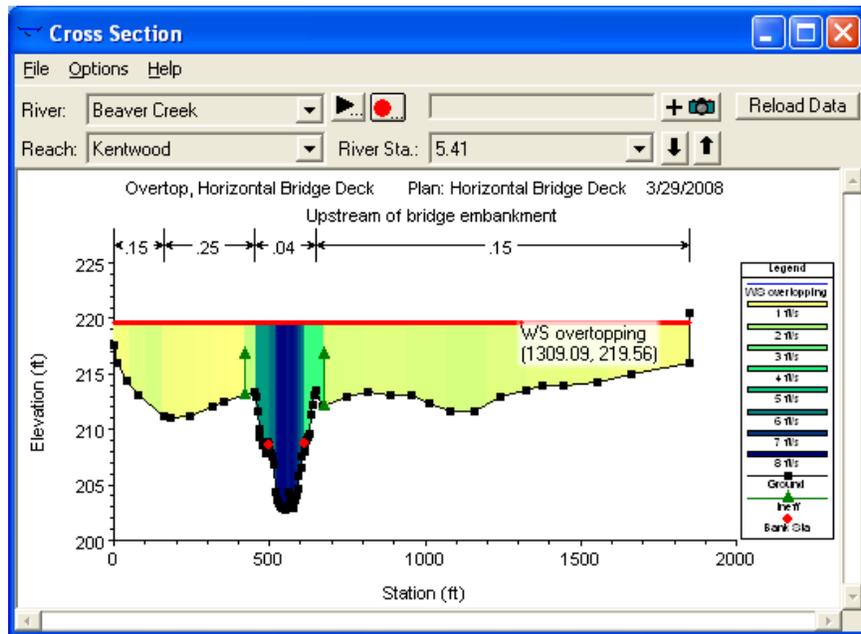
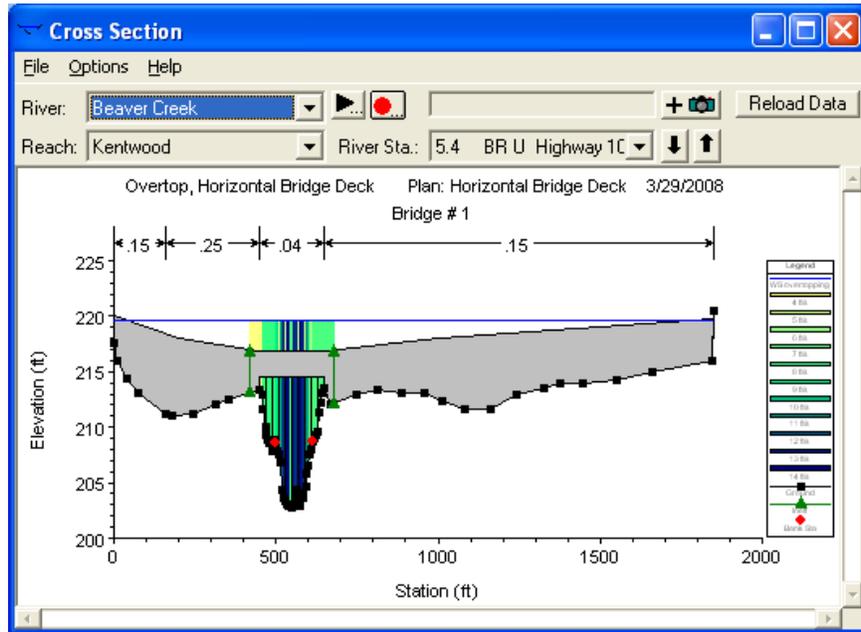


Figure 4.1: HEC-RAS Plot of US Internal Bridge Cross Section and US Bridge Face Bounding Cross Section.

Flow Distribution Output

File Type Options Help

River: Beaver Creek Profile: overtopping

Reach: Kentwood RS: 5.41 Plan: Hor Br Deck

Plan: Hor Br Deck Beaver Creek Kentwood RS: 5.41 Profile: overtopping

	Pos	Left Sta (ft)	Right Sta (ft)	Flow (cfs)	Area (sq ft)	W.P. (ft)	Percent Conv	Hydr Depth(ft)	Velocity (ft/s)
1	LOB	0.00	52.50	170.23	224.08	54.66	0.68	4.27	0.76
2	LOB	52.50	105.00	346.12	337.59	52.52	1.38	6.43	1.03
3	LOB	105.00	157.50	466.35	403.71	52.51	1.87	7.69	1.16
4	LOB	157.50	210.00	344.91	444.56	52.50	1.38	8.47	0.78
5	LOB	210.00	262.50	324.62	441.29	52.50	1.30	8.41	0.74
6	LOB	262.50	315.00	291.69	413.87	52.50	1.17	7.88	0.70
7	LOB	315.00	367.50	252.74	379.77	52.50	1.01	7.23	0.67
8	LOB	367.50	420.00	221.85	351.18	52.50	0.89	6.69	0.63
9	LOB	420.00	459.60	362.90	253.03	39.86	1.45	6.39	1.43
10	LOB	459.60	499.20	2175.27	412.99	40.07	8.70	10.43	5.27
11	Chan	499.20	503.80	288.13	51.64	4.63	1.15	11.23	5.58
12	Chan	503.80	508.39	311.01	53.99	4.62	1.24	11.75	5.76
13	Chan	508.39	512.99	327.87	55.75	4.62	1.31	12.13	5.88
14	Chan	512.99	517.58	338.36	59.35	5.15	1.35	12.91	5.70

Figure 4.2: HEC-RAS Flow Distribution Output Table US Bridge Face Bounding Cross Section.

Table 4.1: HEC-RAS Flow Distribution Output Table (Copied to EXCEL).

Plan: Hor Br Deck Beaver Creek Kentwood RS: 5.41 Profile: overtopping

	Pos	Left Sta	Right Sta	Flow	Area	W.P.	Percent	Hydr	Velocity
		(ft)	(ft)	(cfs)	(sq ft)	(ft)	Conv	Depth(ft)	(ft/s)
1	LOB	0	52.5	170.23	224.08	54.66	0.68	4.27	0.76
2	LOB	52.5	105	346.12	337.59	52.52	1.38	6.43	1.03
3	LOB	105	157.5	466.35	403.71	52.51	1.87	7.69	1.16
4	LOB	157.5	210	344.91	444.56	52.5	1.38	8.47	0.78
5	LOB	210	262.5	324.62	441.29	52.5	1.3	8.41	0.74
6	LOB	262.5	315	291.69	413.87	52.5	1.17	7.88	0.7
7	LOB	315	367.5	252.74	379.77	52.5	1.01	7.23	0.67
8	LOB	367.5	420	221.85	351.18	52.5	0.89	6.69	0.63
9	LOB	420	459.6	362.9	253.03	39.86	1.45	6.39	1.43
10	LOB	459.6	499.2	2175.27	412.99	40.07	8.7	10.43	5.27
11	Chan	499.2	503.8	288.13	51.64	4.63	1.15	11.23	5.58
12	Chan	503.8	508.39	311.01	53.99	4.62	1.24	11.75	5.76
13	Chan	508.39	512.99	327.87	55.75	4.62	1.31	12.13	5.88
14	Chan	512.99	517.58	338.36	59.35	5.15	1.35	12.91	5.7
15	Chan	517.58	522.18	456.18	70.01	4.97	1.82	15.23	6.52
16	Chan	522.18	526.78	511.71	72.8	4.62	2.05	15.84	7.03
17	Chan	526.78	531.37	530.51	74.3	4.6	2.12	16.17	7.14
18	Chan	531.37	535.97	542.5	75.3	4.6	2.17	16.38	7.2
19	Chan	535.97	540.56	554.79	76.31	4.6	2.22	16.6	7.27
20	Chan	540.56	545.16	554.38	76.25	4.6	2.22	16.59	7.27
21	Chan	545.16	549.76	561.51	76.94	4.61	2.25	16.74	7.3
22	Chan	549.76	554.35	556.22	76.45	4.6	2.22	16.63	7.28
23	Chan	554.35	558.95	522.92	74.11	4.67	2.09	16.13	7.06
24	Chan	558.95	563.54	482.95	70.71	4.68	1.93	15.38	6.83
25	Chan	563.54	568.14	511.52	72.94	4.64	2.05	15.87	7.01
26	Chan	568.14	572.74	543.15	75.47	4.62	2.17	16.42	7.2
27	Chan	572.74	577.33	551.58	76.12	4.61	2.21	16.56	7.25
28	Chan	577.33	581.93	526.61	74.11	4.62	2.11	16.12	7.11
29	Chan	581.93	586.52	497.99	71.68	4.63	1.99	15.6	6.95
30	Chan	586.52	591.12	471.99	69.39	4.62	1.89	15.1	6.8
31	Chan	591.12	595.72	413.07	64.92	4.78	1.65	14.13	6.36
32	Chan	595.72	600.31	385.3	61.43	4.62	1.54	13.37	6.27
33	Chan	600.31	604.91	340.34	57.65	4.75	1.36	12.54	5.9
34	Chan	604.91	609.5	314.88	54.36	4.61	1.26	11.83	5.79
35	Chan	609.5	614.1	289.91	52.02	4.67	1.16	11.32	5.57
36	ROB	614.1	677	1622.36	504.48	63.61	6.49	8.02	3.22
37	ROB	677	807.33	923.2	876.16	130.34	3.69	6.72	1.05
38	ROB	807.33	937.67	841.59	828.81	130.33	3.37	6.36	1.02
39	ROB	937.67	1068	1008.86	924.07	130.34	4.04	7.09	1.09
40	ROB	1068	1198.33	1198	1024.41	130.34	4.79	7.86	1.17
41	ROB	1198.33	1328.67	885.29	854.39	130.34	3.54	6.56	1.04
42	ROB	1328.67	1459	696.19	739.66	130.34	2.78	5.68	0.94
43	ROB	1459	1589.33	629.92	696.58	130.33	2.52	5.34	0.9
44	ROB	1589.33	1719.67	491.89	600.51	130.34	1.97	4.61	0.82
45	ROB	1719.67	1850	360.63	500.41	131.61	1.44	3.86	0.72

The Hydr Depth term is the area of a subsection divided by the width of the subsection. For example for Subsection 14 (highlighted), Hydr Depth should be defined by the equation.

$$\text{HydrDepth} = \frac{59.35}{(517.58 - 512.99)} = 12.93$$

This compares with the value 12.91 in the table. The parameter Hydr Depth will be assumed to be the depth, y_1 , in our analysis. The parameters V_1 and y_1 in Equation 15 are determined directly from the Flow Distribution Output table. The parameter h in Equation 15 is the distance from the channel bed to the bottom of the bridge deck. It can be computed by the equation

$$h = \text{HydrDepth} - (\text{W.S. Elev} - \text{low steel elevation})$$

The water surface elevation, W.S. Elev, at the upstream face bounding cross section is determined from the HEC-RAS Summary Profile Output Table, Standard Table 1 (*View, Profile Summary Table, Std. Tables, Standard Table 1*). You can also just click on the water surface in the cross section plot (*View, Cross-Sections*) after running the model. The low steel elevation is determined from the Deck/Roadway window in the Brdg/Culv editor of the HEC-RAS Geometry editor . The low steel elevation may vary across the bridge opening.

4.2.1 Horizontal Bridge Deck

The bridge deck for the HEC-RAS project *Horizontal.prj* is shown below. To use this program the bridge deck must be constant and the bridge must be horizontal.

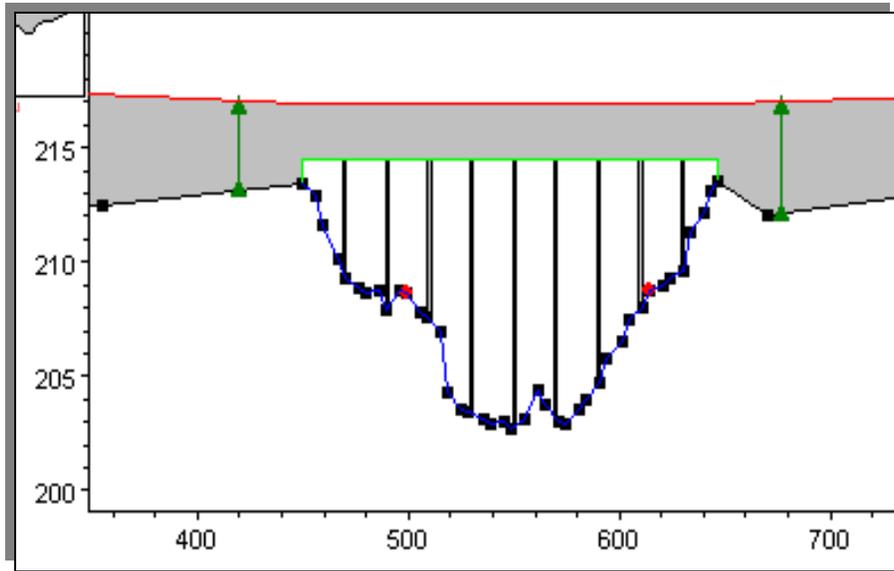


Figure 4.3: Horizontal Bridge Deck

The following steps are used to determine the force distribution on the bridge.

- (a) Open the flow distributions table and set the Global SubSections to 10, 25 and 10 in the LOB, MC and ROB. (*Run, Steady Flow Analysis, Options, Flow Distribution Locations*)

Set Locations for Flow Distribution

Set Global Subsection Distribution

Set Global SubSections LOB 10 Channel 25 ROB 10

Set Specific Location Subsection Distribution

River: Beaver Creek

Reach: Kentwood Number of SubSections (Max 45 total)

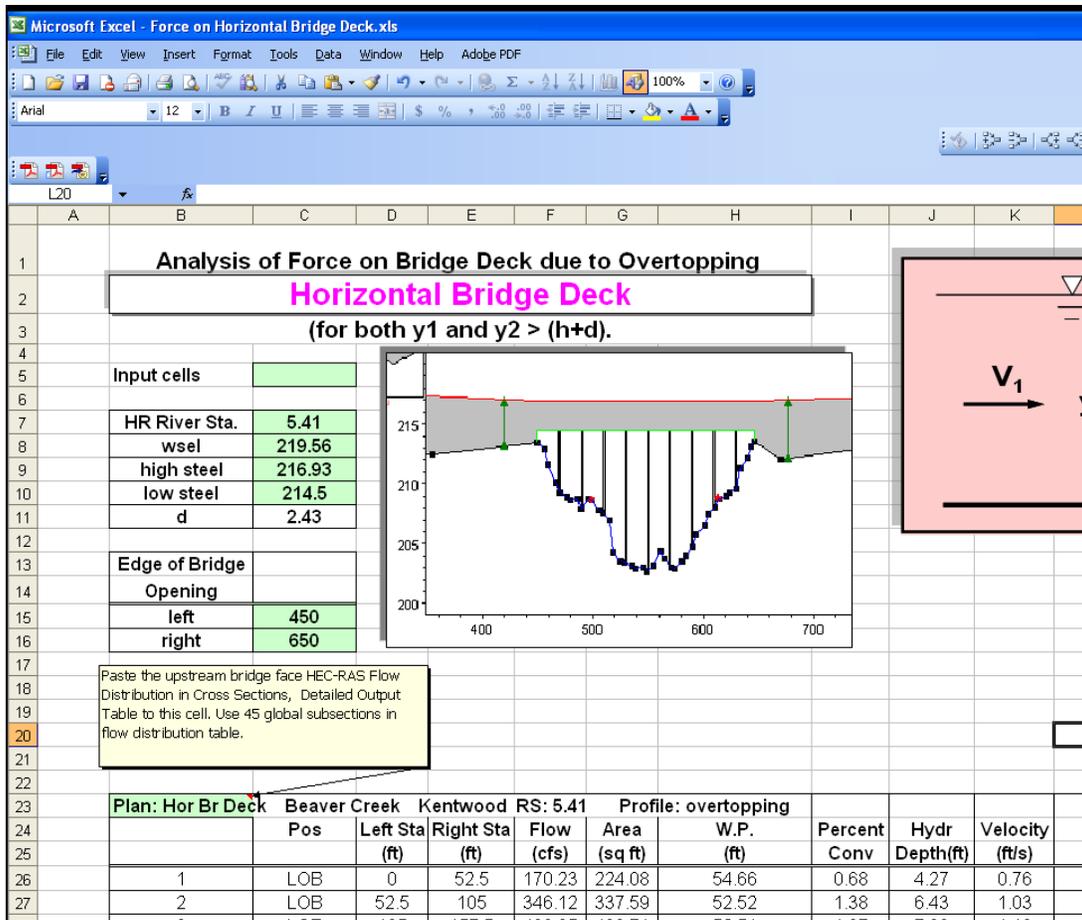
Upstream RS: 5.41 LOB 1 Channel 1 ROB 1

Downstream RS: 5.41 Set Selected Range

OK Cancel Help Clear All

Enter to accept changes

- (b) Run the HEC-RAS program.
- (c) View the Profile Summary Table (*View, Profile Summary Table*) to determine the W. S. Elev for Section 5.41, the upstream bounding bridge cross section. Write it down. (219.56 ft)
- (d) Open the flow distribution table. (*View Detailed Output Tables, Type, Flow Distribution in Cross Sections, RS 5.41*)
- (e) Copy the table to the clipboard. (*File, Copy to Clipboard*)
- (f) Open the EXCEL spreadsheet named **Forces on Horizontal Bridge Deck.xls**.
- (g) Paste the Flow Distribution Table from Step (e) into cell b23.
- (h) Input the appropriate values in cells c7-10 and c15-16. These are green cells.



- (i) The unit force distribution is given for the bridge deck in Columns 7 and 8 of the yellow portion of the worksheet. A plot of the distribution for this example is shown below. The limits on this plot will need to be changed for other bridges.

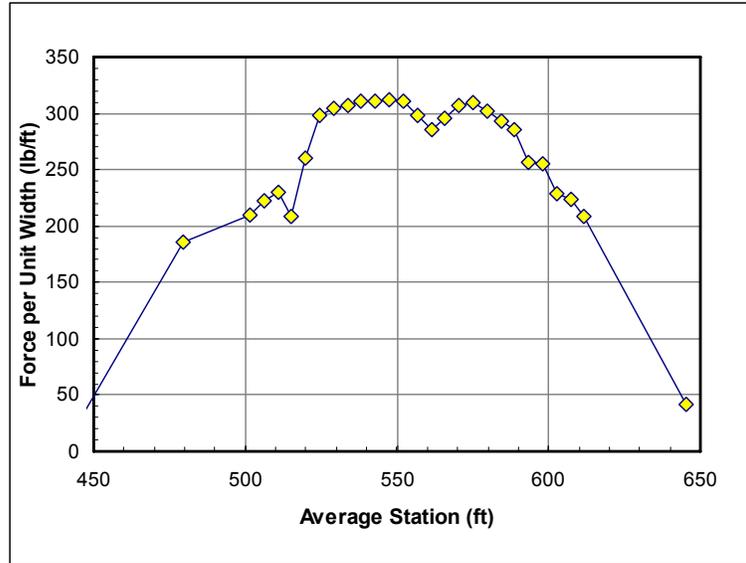


Figure 4.4: Unit Force Distribution for Horizontal Bridge Deck

(j) The cumulative force distribution on the bridge deck is given in Columns 9 and 10 of the yellow portion of the worksheet. A plot is shown below.

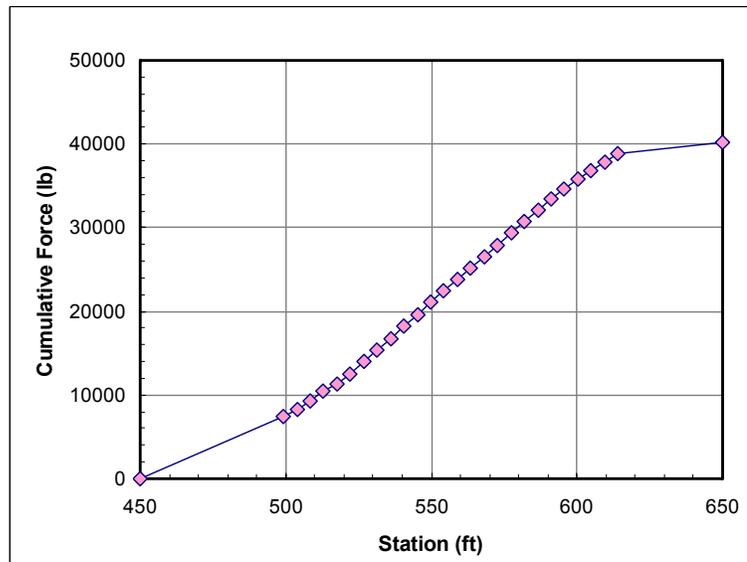


Figure 4.5: Cumulative Force Distribution for Horizontal Bridge Deck

Table 4.2 shows the table values referenced in Steps i and j above. Note the total force of 40,263 lbs at Station 646 (red arrow).

Table 4.2: Computed Forces for Horizontal Bridge Deck Example

Streamtube Centerline Station (ft)	Force on Bridge Deck for Streamtube Fd (lb)	Bridge Station (ft)	Cumulative Force on Bridge Deck $\sum F_d$ (lb)
7	8	9	10
26	0		0
79	0		0
131	0		0
184	0		0
236	0		0
289	0		0
341	0		0
394	0		0
440	7	450	7
479	7367	499	7374
502	963	504	8338
506	1019	508	9357
511	1058	513	10415
515	960	518	11375
520	1199	522	12574
524	1370	527	13944
529	1395	531	15339
534	1412	536	16751
538	1426	541	18177
543	1430	545	19607
547	1434	550	21041
552	1429	554	22470
557	1369	559	23839
561	1309	564	25148
566	1361	568	26508
570	1410	573	27919
575	1420	577	29339
580	1389	582	30728
584	1346	587	32074
589	1312	591	33386
593	1178	596	34563
598	1169	600	35732
603	1052	605	36784
607	1029	610	37813
612	956	614	38770
646	1493	650	40263
742	0		0
873	0		0
1003	0		0
1133	0		0
1264	0		0
1394	0		0
1524	0		0
1655	0		0
1785	0		0



4.2.2 Variable Depth Bridge Deck

The bridge deck for the HEC-RAS project *Variable.prj*, is shown below.

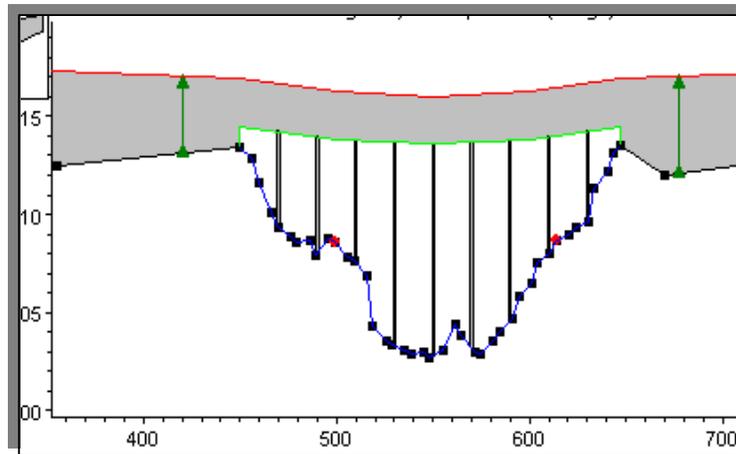


Figure 4.6: Variable Depth Bridge Deck

The EXCEL file *Forces on Variable Depth Bridge Decks.xls* uses a macro developed by a former KU student, Rick Greenfield. Install the macro called *Interp.bas* in EXCEL as follows before using this spreadsheet. You may need to change the macro security to use this macro (*Tools, Macro, Security, Medium*).

Instructions for Installation of the Interpolate Function (Macro)*

These procedures copy the interpolate macro to your spreadsheet. The installation of this macro is required for operation of the variable depth bridge deck spreadsheet. It is a one-time installation.

Using Interpolate with Excel versions 97 and higher.

1. Open your spreadsheet file.
2. Select the menu items *Tools>Macro>Visual Basic Editor* (or press Alt & F11 at the same time).
3. Select the menu items *File>import File...* (or press Ctrl & M at the same time).
4. Pick the file *interp.bas* in the file dialog and press the *Open* button.
5. Select the menu items *File>Close and Return to MS Excel* (or press Alt & Q at the same time).

The functions are now part of your spreadsheet in the form of a module. See the Excel File *Interpolate Example.xls* for illustration of function.

To test the function, put different numbers in the unprotected Input X cells (yellow cells). The macro will interpolate Y-values from the given X- and Y-values.

The formula for invoking the Interpolate macro is shown below.

```
=InterpolateTable($N$26:$N$70,$O$26:$O$70,X26)
```

An EXCEL file named ***Interpolate Macro Example.xls*** is included on the CD. It demonstrates the use of the Interpolate macro.

The following steps are used to determine the force distribution on the bridge.

- (a)** Open the flow distributions window in HEC-RAS and set the Global SubSections to 10, 25 and 10 in the LOB, MC and ROB. (*Run, Steady Flow Analysis, Options, Flow Distribution Locations*)

Set Locations for Flow Distribution

Set Global Subsection Distribution

Set Global SubSections LOB 10 Channel 25 ROB 10

Set Specific Location Subsection Distribution

River: Beaver Creek

Reach: Kentwood Number of SubSections (Max 45 total)

Upstream RS: 5.41 LOB 1 Channel 1 ROB 1

Downstream RS: 5.41 Set Selected Range

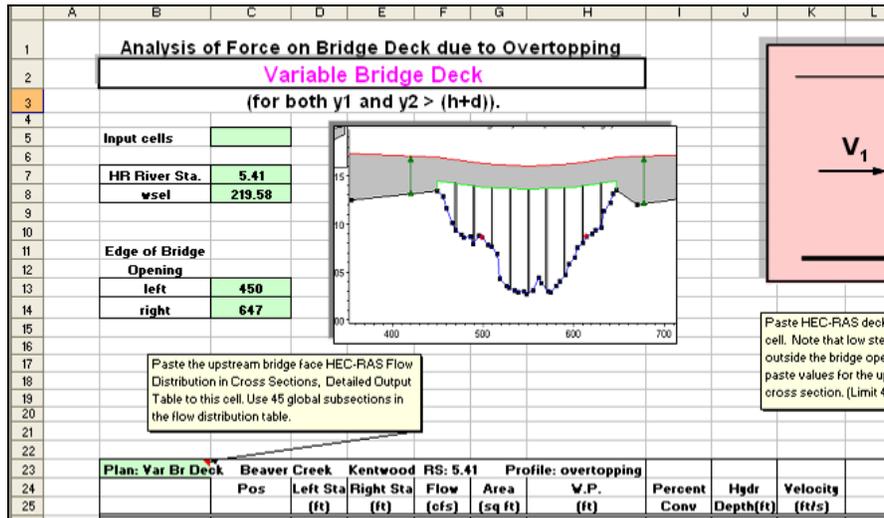
OK Cancel Help Clear All

Enter to accept changes

- (b)** Run the program.
- (c)** View the Profile Summary Table (*View, Profile Summary Table*) to determine the W. S. Elev for Section 5.41, the upstream bounding bridge cross section. Write it down. (219.58 ft)
- (d)** Open the flow distribution table. (*View Detailed Output Tables, Type, Flow Distribution in Cross Sections, RS 5.41*)
- (e)** Copy the table to the clipboard. (*File, Copy to Clipboard*)

(f) Open the EXCEL spreadsheet named ***Forces on Variable Depth Bridge Deck.xls***.

(g) Paste the Flow Distribution Table from Step (e) into cell b23.



(h) Input the appropriate values in cells c7-8 and c13-14. These are green cells.

The can be found on a HEC-RAS Standard Table 1, Profile Summary Table and in the Deck/Roadway window in the Brdg/Culv portion of the Geometric Data Editor of HEC-RAS.

(i) Open the Deck/Roadway portion of the Bridge Editor in the Geometric Data Editor. (*Edit, Geometric Data, Brdg/Culv, Deck/Roadway*) Hold the mouse down and drag it across the headings for the first 3 columns in the table for the upstream bridge. Hit Ctrl C to copy the data to the clipboard.

Deck/Roadway Data Editor						
Del Row	Distance		Width		Weir Coef	
Ins Row	30		40		2.6	
Upstream			Downstream			
Station	high chord	low chord	Station	high chord	low chord	
1 0.	220.		0.	220.		
2 200.	218.		200.	218.		
3 450.	216.93		450.	216.93		
4 450.	216.93	214.5	450.	216.93	214.5	
5 500.	216.25	213.82	500.	216.25	213.82	
6 550.	216.	213.57	550.	216.	213.57	
7 600.	216.25	213.82	600.	216.25	213.82	
8 647	216.93	214.5	647	216.93	214.5	

U.S Embankment SS: 2 D.S Embankment SS: 2

Weir Data
 Max Submergence: 0.95 Min Weir Flow Et:

Weir Crest Shape
 Broad Crested
 Ogee

OK Cancel Clear Copy US to DS

Enter station, high chord and low chord for deck/roadway.

(j) Paste the Deck/Roadway data into cell N26. This data is used to interpolate the local high steel and low steel for each subsection as shown in Columns 11 and 12 of the yellow portion of the worksheet.

(k) The unit force distribution is given for the subsection upstream from the bridge opening in Columns 7 and 8 of the y portion of the worksheet. A plot of the distribution for this example is shown below. The limits on this plot will need to be changed for other bridges.

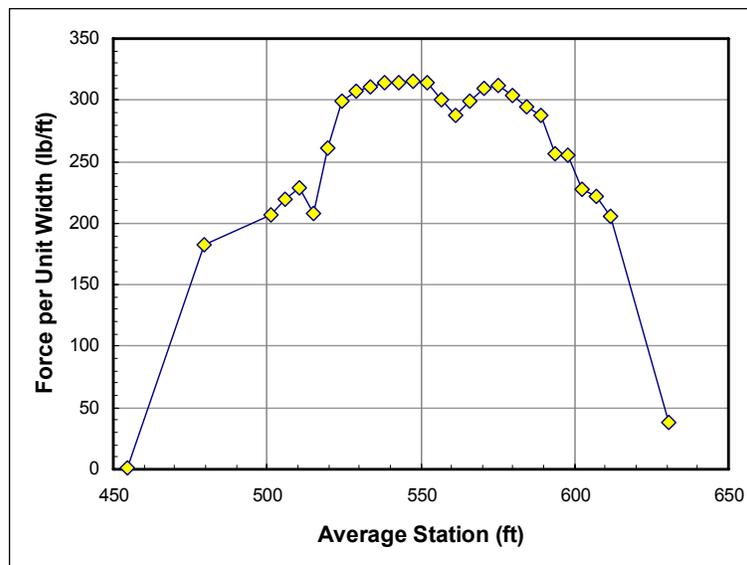


Figure 4.7: Unit Force Distribution for a Variable Depth Bridge Deck

(l) The cumulative force distribution is given in Columns 9 and 10 of the yellow portion of the spreadsheet. A plot of the values is shown below.

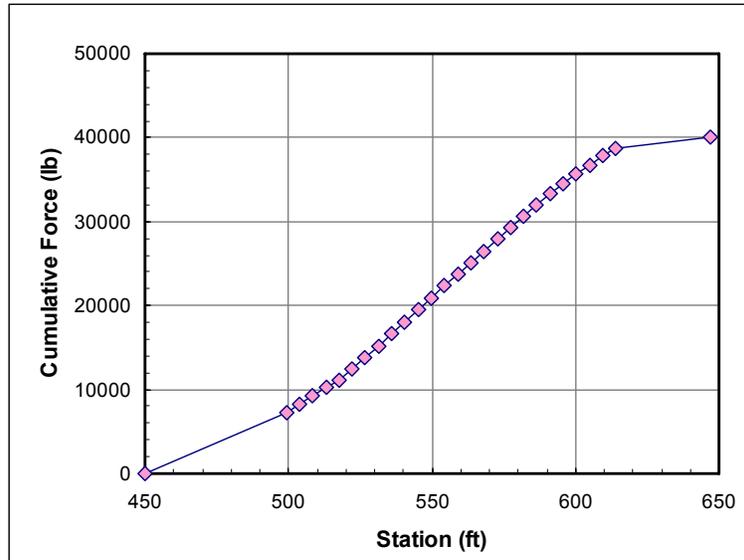


Figure 4.8: Cumulative Force Distribution for a Variable Depth Bridge Deck

(m) Table 4.3 shows the table values referenced in Steps k and l above. The total force is 40,017 lb as indicated by the red arrow in Table 4.3.

Table 4.3: Computed Forces for Variable Bridge Deck Example

Streamtube Centerline Station (ft)	Force on Bridge Deck for Streamtube Fd (lb)	Bridge Station (ft)	Cumulative Force on Bridge Deck Δ Fd (lb)
7	8	9	10
26	0		0
79	0		0
131	0		0
184	0		0
236	0		0
289	0		0
341	0		0
394	0		0
455	6	450	6
479	7224	499	7230
502	949	504	8179
506	1010	508	9189
511	1051	513	10240
515	952	518	11192
520	1200	522	12392
524	1379	527	13771
529	1410	531	15181
534	1428	536	16609
538	1440	541	18049
543	1444	545	19492
547	1450	550	20942
552	1444	554	22385
557	1381	559	23766
561	1321	564	25087
566	1375	568	26462
570	1422	573	27883
575	1431	577	29315
580	1398	582	30713
584	1354	587	32066
589	1321	591	33387
593	1180	596	34567
598	1170	600	35737
603	1046	605	36783
607	1020	610	37803
612	948	614	38751
631	1266	647	40017
742	0		0
873	0		0
1003	0		0
1133	0		0
1264	0		0
1394	0		0
1524	0		0
1655	0		0
1785	0		0



CHAPTER 5 - SUMMARY, CONCLUSIONS AND REFERENCES

5.1 Summary

This study involved the investigation of forces on bridge decks for overtopping flows. Laboratory experiments were carried out in a glass-walled flume. Forces were determined using the momentum equation for a wide range of flow and geometry conditions. The experimental work was summarized in 3 different dimensionless equations of different forms. The equations were determined using statistical analysis. The equation that gave the “best-fit” was Equation 15 shown below.

$$f_d^* = 8.85(y_1/d)^{0.809} (h/d)^{-1.06} Fr_1^{3.42(h/d)^{-0.359}} \quad \text{Equation 15}$$

Where

$$f_d^* = \frac{f_{d,m}}{Y_m L_m^2} = \frac{f_{d,p}}{Y_p L_p^2} \quad \text{Equation 11}$$

Two EXCEL spreadsheets were developed to use Equations 9 and 15 together with output from HEC-RAS 3.1.3 to compute the distributions of unit force and cumulative force on horizontal, constant depth bridge decks and for variable depth bridge decks. Detailed procedures are provided for use of the spreadsheets. Two example HEC-RAS models that were used to illustrate the procedures are included on the CD.

5.2 Conclusions

The empirical equations were good predictors of the measured results for the bridge deck models. Also, the equations provided an excellent tool for use with Flow Distribution Output Tables from HEC-RAS to compute forces on prototype bridge decks.

The bridge deck models used for the experimental data presented in this report did not include explicit geometric modeling of either railings or girders. The effect of these features should be studied. The Hurricane Katrina bridges experience large lift forces due to water entrapped between the girders. This effect should also be considered.

REFERENCES

- [1] Brunner, G. W., *HEC-RAS, River Analysis System User's Manual*, US Army Corps of Engineers Hydrologic Engineering Center (HEC), Davis CA, USA, 2002.
- [2] Henderson, F.M., *Open Channel Flow*, The Macmillan Company, NY, pp 66-75, 1966.

APPENDIX

The APPENDIX is on a CD attached to this report. It includes the application software, experimental data, demonstration HEC-RAS models, EXCEL macro (Interp.bas) required to run the software for the variable depth bridge deck analysis and the statistical analysis spreadsheets. The folders and files on the CD are shown below.

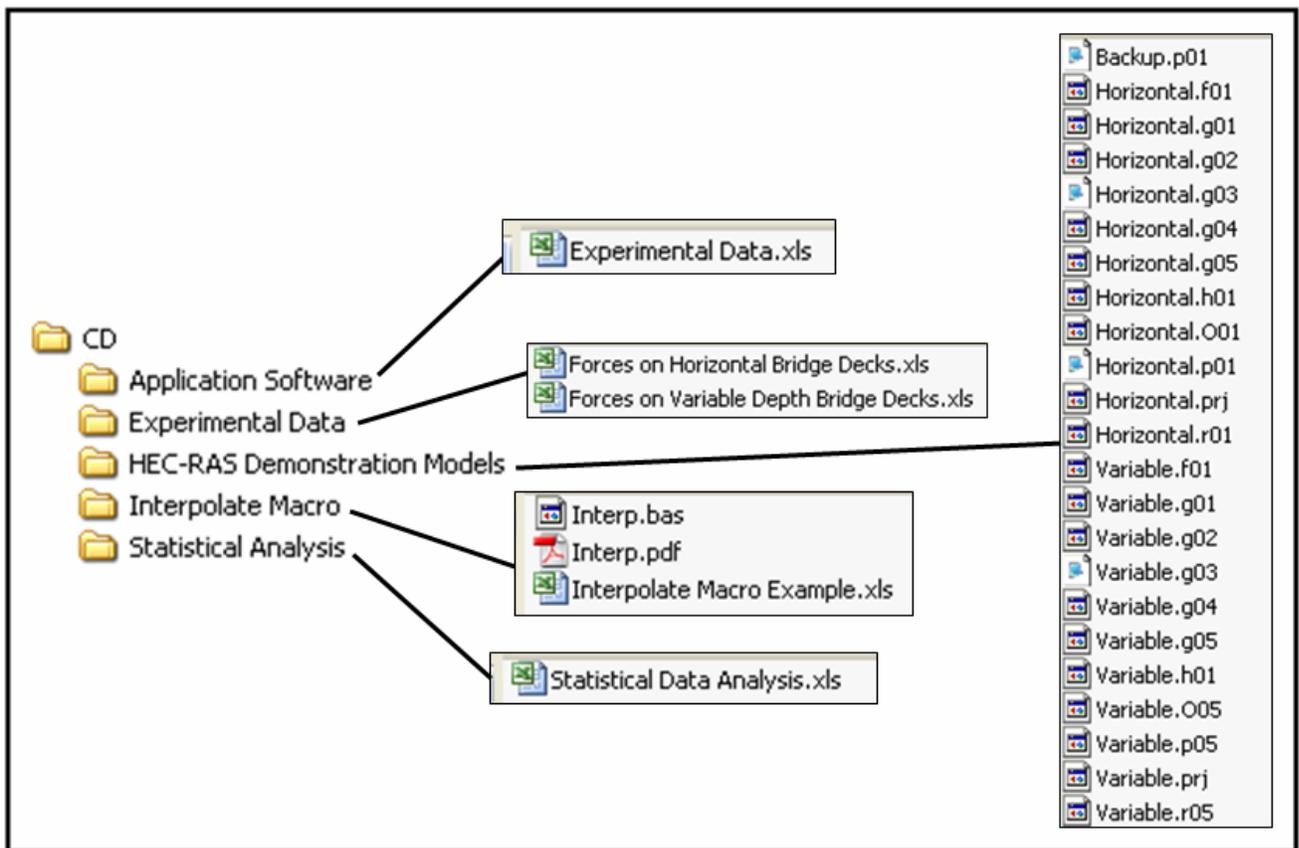


Figure A.1: Folders and Files on APPENDIX CD

