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Research paper

Investigation of bridge afflux on channels by experiments and HEC-RAS package

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Abstract

The bridges are an important part of the transportation network which is constructed over rivers and canals in the urban. The water surface increases upstream of the bridge and constitutes a backwater profile. The maximum afflux and location were investigated via using model test experiments and three different methods by using HEC-RAS package. Laboratory experiments were carried out at ten different flow rates and smooth flow conditions. Measurements and numerical calculations are performed for four different opening ratio M=b/B= 0.3, 0.5, 0.7 and 0.9 where b is the bridge opening and B is the cross-section width. The HEC-RAS package was determined to be closer to the measured values for maximum afflux and wsp (water surface profiles) for large openings. When the opening ratio increases, the distances where maximum affluxes observed also shifted to upstream of the channel.

Keywords: *Bridge Afflux; Channel; Opening Ratio; Flow Rate; HEC-RAS.*

1. Introduction

Bridges are an important part of the transportation network which constructed over rivers and canals in the city. Depends on short assessment during the bridge planning can be encountered major problems. Especially afflux at the upstream of the bridge that occurs during floods can cause increasing of the life and property damages. Also, today traffic volumes have become so great on primary roads that bridge failures or bridge out of service for any length of time can cause severe economic loss and inconvenience. The bridge which is located on urban transport must be surveyed for all loading and hydraulic conditions. Although the bridge structurally very stable, it can be collapse or damage by floods. Bridge structures are subject to damage during their service lives due to many factors such as extreme scour around the abutments or piers, dynamic impulses on the bridge substructure elements, hydraulic jumps, pressured flow and weir type flow, and human-induced problems [1]. Confining flood waters extremely by bridges can cause excessive backwater resulting in flooding of upstream property, backwater damage suits, overtopping of roadways, excessive scour under the bridge, costly maintenance, or even loss of a bridge. On the other hand, over-design or making bridges longer than necessary for the sake of safety can add materially to the initial cost, especially when dual or multiple lane bridges are involved. Both extremes in design have been experienced. Somewhere between the two extremes is the bridge which will prove not only safe but the most economical to the public over a long period of time [2].

The water surface upstream of the bridge increases and forms a backwater profile. Afflux is defined as the maximum increase in water surface elevation above that of an undisturbed stream. To computation of accurate wsp through bridge waterways is a very important aspect for engineers. These studies are necessary for flood risk management activities, flood damage reduction studies, flood risk mapping, scour evaluation and maintenance of rivers and channels.

It is necessary to know the hydrological characteristics of rivers for flood forecasting and flood protection work. Bridges have various types and characteristics on natural rivers must be handled carefully for flood planning studies. The opening formed by the bridge infrastructure elements must be enough for hydraulic conditions. For this purpose, foundation depths of bridge piers, geometric characteristics of the element, and also the highest point on the low chord of the bridge opening attentively must be determined. Hydraulic loads acting on bridge infrastructure elements are rather small compared to the structural load. However, hydraulic problems that may occur around the bridge due to the geometrical characteristics of the bridge infrastructure element, will affect building safety negatively. The bridge has a high safety factor may cause more afflux on the upstream which will increase the cost of river regulation structures.

Liu et al. [3] carried out model studies at Colorado State University using a vertical-faced abutment as an obstruction to flow. From the results of their laboratory studies, they proposed an empirical backwater equation depends on Froude number and opening ratio. Biery and Delleur [4] achieved model studies using semicircular arch bridge constrictions. They proposed a simple backwater formula using the single semicircular arch bridge data obtained from the results of their studies and data collected from the works of Liu et al. Brown [2] carried out a series of experiments to investigate the hydraulic behavior of arch bridges. Single and multiple opening semicircular and single opening elliptic bridge models were used in the testing program. Nevertheless, all the experiments were carried out in single rectangular flumes without floodplain areas and with fairly smooth surfaces. Kaatz and James [5] pointed out that two-dimensional models may not yield accurate results for the backwater, and the one-dimensional models may give a more realistic magnitude for the net backwater with proper magnitudes of the loss coefficients. Seckin et al. [6], investigated the performance and reliability of four different methods used by HEC-RAS and ISIS software package programs for one-dimensional flow analysis around a bridge with rectangular piers. They informed that HEC-RAS was able to accurately simulate the measured backwater profiles.

Seckin et al. [7] proposed an empirical equation based on laboratory experiments to give afflux at the arch and straight deck bridge sites in compound channels. The equation can predict afflux value with known values of downstream Froude number, normal depth, and downstream blockage ratio. They informed that the proposed model is limited to type A and B low flow only in a compound flume with the vertical abutment. Seckin et al. [8], investigated water surface profiles at 15 different cross-sections around a prototype bridge structure were measured for 10 different flow rates. Four different methods; Energy, Momentum, Yarnell, and WSPRO in HEC-RAS package were used for modeling and relative average errors between measured and calculated values were found as %0.55, %0.3, %0.89 and %1.33 respectively. Ardiclioglu et al. [9], achieved model experiments to determine the effect of bridge structures on water profiles. Experiments have been performed for two different roughness conditions, on rectangular, circular and elliptical bridge type and suggested polynomial equations for maximum afflux. The equation obtained for rectangular cross-sections is more reliably (R^2=0.90) and also could be used for circular and elliptical cross-sections. Kocaman et al. [10], investigate the performance of a commercially available three-dimensional numerical software, which solves the Reynolds averaged Navier–Stokes equations, to predict the free surface profiles from up to downstream of four different bridge types with and without feet in a compound channel. The model results were compared with the available experimental data. Comparisons indicate that the model provides a reasonably good description of free surface profiles under both gradually and rapidly varied flow conditions in the bridge vicinity. Atabay et al. [11], Parametric studies on a single-opening semicircular arch, single-opening semielliptical arch and single-opening straight deck bridge were conducted using the commercial software HEC-RAS to investigate the influences of different factors on backwater level. The results obtained using the proposed formula corresponded well with the experimental data and the results obtained using the energy method, which is accurate and the most commonly used method to calculate backwater level. Naik et al. [12],a 3D Computational Fluid Dynamics(CFD) model is used to establish the basic database under various working conditions. Numerical simulation in two phases is performed using the ANSYS-Fluent software. k-ω turbulence model is carried out to solve the basic governing equations. The results have been compared with high quality flume measurements gained from different converging composite channels in order to discover the numerical accuracy. Then ANN (Artificial Neural Network) are trained based on the Back Propagation Neural Network (BPNN) technique for depth-averaged velocity prediction in different converging sections and these test results are compared with each other and with actual data. The study has focused on the ability of the software to correctly forecast the complex flow phenomena that happen in channel flows.

2. Bridge hydraulics

The hydraulic performance of a bridge is a function of the channel geometry, the structure geometry, and the flow conditions. Many types of flow can occur through bridge openings. These depend primarily upon the water levels upstream and downstream of the structure, the flow discharge, the extent of constriction and its shape. The water levels and the discharge at the structure are controlled either by the channel or by the structure (constriction) itself. The effects of a bridge constriction on the water surface profile are seen in Fig. 1 for a subcritical flow condition. In this figure; B = channel width, L_c and L_e =contraction and expansion lengths, C_R and E_R =contraction and expansion rates, b = bridge opening ,W_b = bridge deck width ,L_{obs}: is the length of approach embankment.

In this study, bridge experiments were conducted in a rectangular smooth channel for ten different flow conditions and four opening ratio M (=b/B). The amount of afflux was investigated by experiment and HEC-RAS software package by using three different methods [13]. These are the energy method, the momentum method, and the water surface profile (WSPRO) method. Location of maximum afflux was also investigated and HEC-RAS results are compared with experiments.

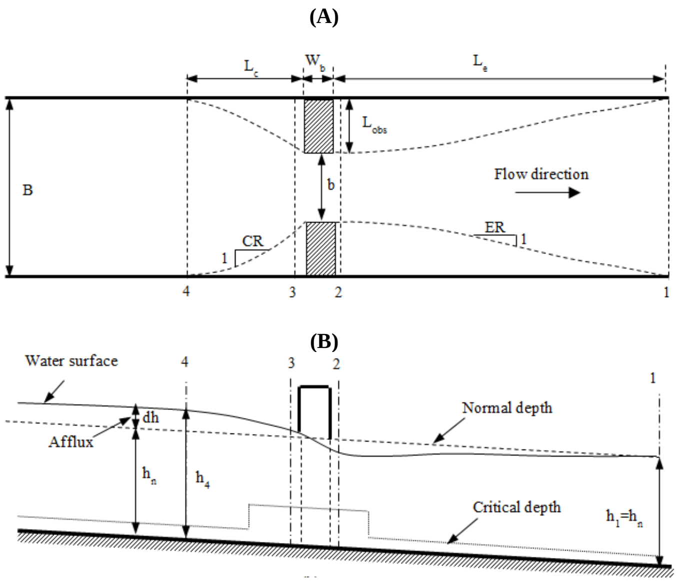


Fig. 1: Definition Sketch of Flow (A) Plan, (B) Profile Through A Bridge Waterway.

2.1. Energy method

Wsp is computed along the river by solving the Energy equation with an iterative procedure called the standard step method. The energy equation is written as follows:

$$z_2 + h_2 + \frac{\alpha_2 V_2^2}{2g} = z_1 + h_1 + \frac{\alpha_1 V_1^2}{2g} + h_e \quad (1)$$

Where; z=elevation of the main channel, h=depth of water at cross section, V=average velocity, α=kinetic energy correction factor, g=gravitational acceleration, and h_e=energy head loss. The energy head loss between two cross-sections is comprised of friction losses and contraction or expansion losses and given as follows:

$$h_e = LS_f + C\left|\frac{\alpha_2 V_2^2}{2g} - \frac{\alpha_1 V_1^2}{2g}\right| \quad (2)$$

Where: L=Reach length, S_f=friction slope between two section, C= contraction or expansion loss coefficient. Contraction or expansion of flow due to changes in the cross-section is a common cause of energy losses within a reach. Typical values for contraction or expansion coefficient for subcritical flow are 0.1 and 0.3 respectively. When the change in effective cross-section area is abrupt such as at bridges, contraction or expansion coefficients of 0.3 and 0.5 are often used.

2.2. Momentum method

The momentum method is based on performing a momentum balance from cross section 2 to cross section 3. The equation for this momentum balance is as follows:

$$A_3Y_3 + \frac{\beta_2 Q_3^2}{2g} = A_2Y_2 + \frac{\beta_2 Q_2^2}{2g} - A_{p2}Y_{p2} + F_f - W_x \quad (3)$$

Where: A= active flow area, the A_p=obstructed area of the pier, Y=vertical distance from water surface to the center of gravity of flow area, β=momentum correction coefficient, Q=discharge, g=gravitational acceleration, the F_f=external force due to friction, the W_x= force due to the weight of water.

2.3. WSPRO method

WSPRO computes water-surface profiles for subcritical, critical, or supercritical flow as long as the flow can be reasonably classified as one-dimensional, gradually-varied, steady flow through bridges and culverts. WSPRO is designated by the Federal Highway Administration (FHWA). Single-opening bridge backwater free-surface flow uses an energy-balancing technique that uses a coefficient of discharge (which is a function of flow characteristics and bridge geometry) and estimates an effective flow length (which takes into account the conveyance characteristics of both the bridge opening and the valley upstream from the bridge). The energy equation is written between 1 and 4 cross-sections as follows:

$$h_4 + \frac{\alpha_2 V_4^2}{2g} = h_1 + \frac{\alpha_1 V_1^2}{2g} + h_{L(1-4)} \quad (4)$$

Where; h=depth of water at a cross section, V=average velocity, α= kinetic energy correction factor, g=gravitational acceleration, and h_L= energy head loss between 1 and 4.

3. Experimental study

Bridge experiments were performed in a glass-walled rectangular laboratory flume at the Hydraulics Laboratory of Erciyes University, Kayseri, Turkey, which has 9.5m long, 0.6m wide, and 0.6m depth. Four different opening ratio M=b/B (0.3, 0.5, 0.7 and 0.9) were used for rectangular straight deck bridge. The flow rate of the water passing through the flume was measured with the help of a UFM-600 type of an ultra-sound current meter mounted on the pipe transferring the water from a constant-head tank to the flume entrance. Wsp were measured using a point gage mounted on a tripod, which can move freely in three dimensions. Wsp were measured for ten different steady flow conditions as given in Table 1. Where Q = discharge, h_n = uniform flow depth, V (=Q/A) = average velocity, S=slope of the channel, Re $(= 4VR/\upsilon)$ Reynolds number and Fr $(= V/\sqrt{gh_n})$ Froude number.

Table 1: Flow Properties

Test	Q (lt/s)	h_n (cm)	V (m/s)	S -	Re -	Fr -
1	10.23	2.73	0.625	0.0035	54835	1.21
2	15.42	3.48	0.739	0.0050	80802	1.26
3	16.92	7.91	0.357	0.0005	78302	0.40
4	18.98	6.09	0.519	0.0015	92264	0.67
5	19.25	6.85	0.468	0.0006	91647	0.57
6	21.29	13.55	0.262	0.0005	85766	0.23
7	21.83	4.68	0.777	0.0035	110433	1.15
8	34.04	8.53	0.665	0.0020	154994	0.73
9	34.19	5.80	0.982	0.0050	167549	1.30
10	37.62	7.83	0.801	0.0050	174465	0.91

4. Results and discussion

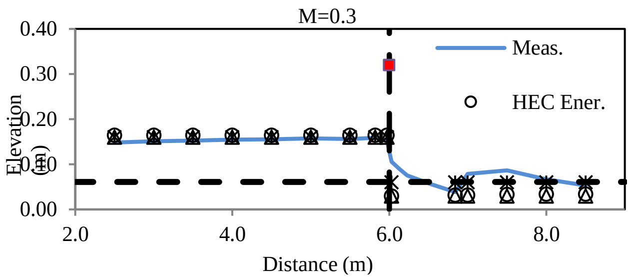
For each flow condition uniform flow was obtained by using a weir located at the end of the channel. Bridge models were placed and fixed by an apparatus at 6.0th meters of the channel In order to determine the wsp along the mid-section of the channel. Wsp measured for ten flow conditions and four different opening ratios. In Figure 2 (a)-(d) measured wsp were given for Test 4, Q=18.98 lt/s and four different opening ratio M. In the figures normal depth (h_n) also shown as dash lined. Maximum afflux (dh=h_4-h_n) and its location (L_c) were determined using measurements.

Bridge channel flows modeled for ten different flow rates and four different openings ratio with HEC-RAS package program. HEC-RAS package is able to account with four different methods. These methods are energy (standard step method), momentum, Yarnell, and WSPRO. The Yarnell method considers piers for the bridge opening. In this study single opening rectangular bridges are used for bridge afflux. Therefore Yarnell method is not considered for HEC-RAS calculation. The Program can calculate water surface profiles for three different flow conditions that are subcritical, supercritical and mixed flow. Depends on bridge structures and flow conditions usually subcritical flows and supercritical flows occur at the upstream and downstream of the bridge respectively. In this case upstream and downstream boundary condition must be defined for each flow. For this purposes measured profiles were used at x=2.5m, and, 8.5m from the channel beginning.

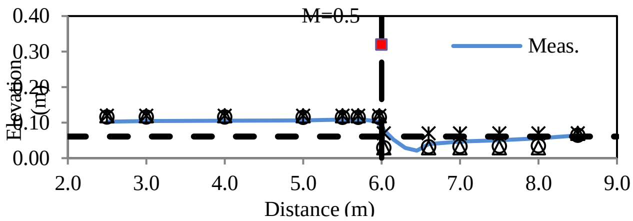
In Figure 2 (a)-(d) calculated water surface profiles at same flow conditions also have shown for Energy, Momentum and WSPRO methods. As can be seen, in the figures for small opening ratios (M=0.3 and 0.5) three methods give little bit higher values. For large opening ratios (M=0.7 and 0.9) flow reach uniform flow conditions closed the bridge structure at downstream of the channel. Similar situations are observed for other flow conditions.

Measured dimensionless h_{max}/h_nvalues were compared with HEC-RAS Energy results and shown in Figure3 for ten flow conditions and four opening ratios. h_{max} shows maximum water depth (h_4= h_{max}=h_n+dh) at the upstream of the channel. For the opening ratio M=0.3 dimensionless maximum afflux higher than measured values for a lot of flow condition. For other opening ratios these dimensionless values closer to the measurement ones. Similar conditions were observed for Momentum and WSPRO methods.

(A)



(B)



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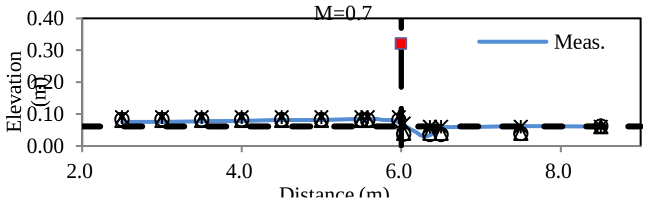

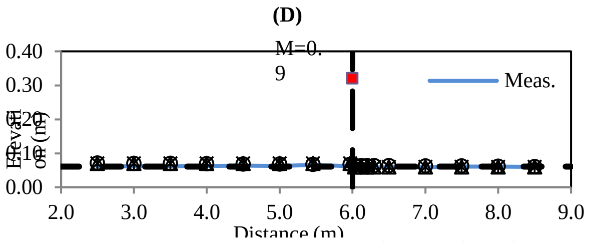

Fig. 2: Measured and Calculated Water Surface Profiles for Test 4 (Q=18.98 Lt/S).

Locations of maximum afflux (Lc) from the bridge axis were determined using measured values for different opening ratios (M). Upstream constriction ratios (CR) were calculated using the bridge embankment width (B-b)/2 and measured constriction length (Lc). Average values of CR were calculated for different opening ratios M=0.3, 0.5, 0.7, 0.9 and found as 2.2, 4.2, 4.8 and 18.1 respectively. As it can be seen from these values, the maximum afflux distance increases when the opening ratio increases.

Relative average differences between the measured and calculated water surface profiles with three different methods were calculated by $\varepsilon(\%) = \left|\frac{h_{meas}-h_{HEC}}{h_{meas}}\right| * 100$. For all flow conditions, average differences for Energy, Momentum, and WSPRO methods were found as 19.1, 19.9, and 24.1 respectively. As seen these values Energy method calculates water surface profiles better than the other two methods. The relation between average errors for h and Froude number (Fr) given in Figure 4. As seen this figure for three methods errors were increased with the Froude number for subcritical flow conditions. For supercritical flows, these errors have been almost constant.

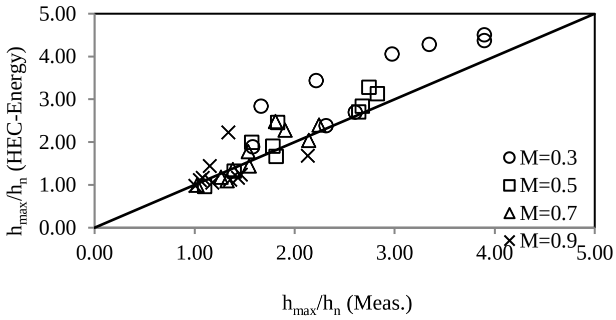

Fig. 3: Measured and Calculated (HEC-Energy) H_{max}/H_nvalues.

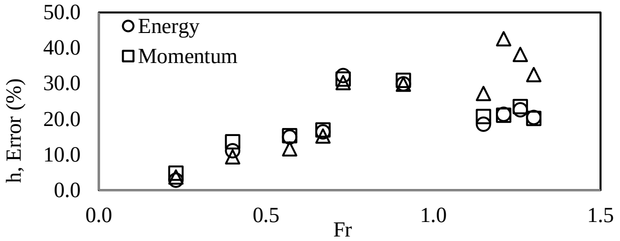

Fig. 4: Relation between Average Depth (H) Error and Froude Number.

5. Conclusion

Bridge afflux was investigated for urban transport based on laboratory experiments and HEC-RAS package. Three methods were used for water surface profiles calculation and compared with measured data. HEC-RAS package for three methods gives little bit higher values from measured profiles for the small opening ratio (M=0.3 and 0.5). For M=0.7 and 0.9 calculated profiles close to the measured profiles and flow reach uniform flow conditions closed the bridge structure at downstream of the channel. For small opening ratio, dimensionless maximum afflux (h_{max}/h_n) that calculated with three methods higher than measured values. Locations of maximum afflux (L_c) distance from the bridge increases when the opening ratio increases. An energy method calculates wsp better than the other two methods.

6. Acknowledgements

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