DEPARTMENT OF ARCHITECTURE AND CIVIL ENGINEERING
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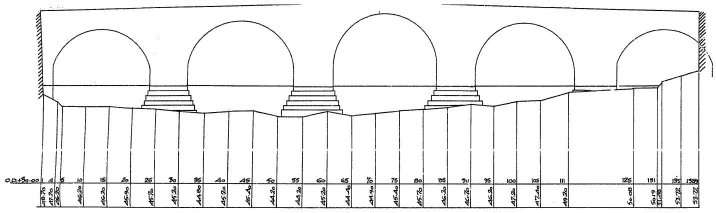

Experimental Study of Bridge Hydraulics in the City of Bath

AR30315 BEng Dissertation

By

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April 20, 2020

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2.1. Introduction to Flood Hydrology

Hydrology is the central factor which helps in determining the development of characteristics – ~~both biological and physical, of wetland~~ (Mitsch &Gosselink, 2000). ~~Tidal flooding is possibly the chief and evident hydrologic factor, which is known to affect zonation of plant species, growth of plants, soil properties (chemical and physical), as well as the biological processes within tidal marshes. Hydrology is predominantly ascertained by altitude, gradient, and tidal regime that interact for helping in ascertaining both the area of the intertidal zone and the depth as well as duration of flooding that ensues (Kirwan & Guntenspergen, 2010).~~ Hydrology is basically a natural science and flood hydrology is a science that offers various tools and forecast techniques used for calculating design floods in pursuit of flood prediction measures.

2.2. Historical Flooding

2.2.1. Past Flood Events in Bath

The Bristol channel and Avon river in the UK have had several instances of floods in the past right from 1700s when the river wrecked the whole of bridg s north side during the floods of the years 1799 and 1800. The reason for such wreckage was identified as the poor quality of the bridge’s construction. Regular flooding that was believed to have curtailed the life of numerous constructions in the lowest part of Bristol city, was normal till the time some crucial flood control works were carried out and completed successfully during the 1970s (Classico Rural LLP, 2010). The city center of Bath is actually built upon the floodplain of river Avon. Apart from the above, there is believed to have another incident of flooding in

Bristol city when tidal surge along with the intensely high levels of water that resulted from the floods in neighboring areas of the city (BBC News, 2014).

The evening of 10th July 1968 was a day of joy and happiness for the members of the West Country who had gathered in the city of Bristol for commemorating the 150th anniversary of the Institution of Civil Engineers that was founded way back in the year 1818. The venue for this event was the Art Gallery of Bristol City and the proceedings of the event were interspersed by colorful flickers of lightning and thunder rifts through the glazed roof of the building. The territory had been enduring a long period of drought due to the summer storm, and the same was terminated because of heavy rainfall. Indeed, a few handfuls of the speakers at the event were enticed about boasting about numerous ways in which engineering had effectively curbed several natural forces within Britain. This was actually an astonishing and unexpected declaration about *hubris*, as the recent hurricane created unimaginable and massive mayhem and destruction across the West Country (Buchanan, 2007).

Specific examples of such destruction caused by the storm included "*underground aquifers erupted on the Mendips; rivers rose alarmingly; roads and embankments were washed away; and many bridges, including the County Bridge across the Avon at Keynsham and the bridge at Pensford across the Chew, were destroyed (Buchanan, 2007).*" Particularly in relation to Bath, tributaries originating from almost all of the surrounding valleys ended up flooding rapidly due to the storm, which resulted the Avon rising portentously to alarming levels. The level of the Avon continued to rise and by midday of the next day, the Southgate street was flooded because of the river water, which was not the first time for the people there as similar incidents of flooding have happened several times in the past.

2.2.2. Historical Catchment of Bath

Bath's catchment is covered under the Bristol Avon catchment plan. It essentially comprises of Bristol Avon, North Somerset streams, and Lower Sevem Vale. It is estimated that this catchment drains roughly over 2,800 sq. km., covering West of England, Wiltshire, Somerset, and Gloucestershire. The Avon is also believed to possess a rich farming heritage in its upper catchment while other activities of angling, recreation, navigation and wildlife are also key in the catchment area. The catchment area also comprises of various other nearby townships like Trowbridge, Radstock, and Frome, among others located in its lower reaches, through the ancient cities of both Bristol as well as Bath, eventually resulting in spectacular landscapes – both urban as well as rural (Bristol Avon Catchments Partnership, 2012). The Avon catchment is also home to about 1.25 million inhabitants. It is important to maintain water quality and a healthy river environment as it is an important asset to economic and social well-being. There are several partnerships that have been developed in this catchment area which involve the local communities by encouraging them to take part in decision-making and share evidence. The catchment is in excellent physical condition and has a brilliant ecological status. It is highly invaluable asset to Bristol's society and its local econom

2.2.3. Past Flood Prediction Techniques

The primary aim of flood forecasting has always been cautioning in advance about the level of water or the discharge of the same, in situations when such a discharge or level tends to threaten the safety of the structures in addition to also the activities related to flood plains. There were predominantly five different categories that are prevalent in relation to flood forecasting. ~~They were as under:~~

- Techniques that used correlation/coaxial diagrams amidst two or more variables;
- Mathematical equations that used regression techniques or multiple linear regression techniques that are normally unite independent variable with one or more variables;
- Hydrological models – there were two subcategories under this namely
    - "*Rainfall run-off model*

        - ◊ *Lumped*
        - ◊ *Quasi-distributed*
        - ◊ *Distributed*
    - *Routing techniques*
        - ◊ *Lumped, & Distributed*
- *Hydraulic models*
    - *Dynamic Wave routing*
- *Data driven hydrological models*
    - *Artificial Neural Networks*
    - *Fuzzy expert system design for FF*
    - *ANFIS (Adaptive Neuro-Fuzzy Inference System) models (Sankhua & Srivastava, 2010).”*

2.3. Hydraulics of Arch Bridges

2.3.1. Hydraulics Principles

~~The term hydraulics, known to have derived from Greek word for water (*hydor*) and another Greek word for a reed instrument (*aulos*), had been study focused on understanding water’s physical behavior, both in motion as well as at rest. However, with the passage of time and the increased focus on research and development that has happened in the last few decades, this particular branch of study had been broadened in order to encompass a wide range of liquids and their physical behaviors, and these oils include the ones that are utilized in various hydraulic systems that are used in today’s modern times. (Aronne Armanini, 2018).~~

Pascal’s law is believed to be the foundation of contemporary hydraulics. This particular law was discovered by the French philosopher Blaise Pascal, who was also a mathematician, way back in the end of 1600s. This law is fundamentally the principle of transmission of fluid pressure. According to this principle, pressure change in a confined and incompressible fluid is uniformly transmitted throughout the fluid and all changes occur uniformly in the fluid (Aronne Armanini, 2018).

Another common theory of hydraulics is the Bernouilli's principle. Named after Bernouilli, a Swiss mathematician and theorist who discovered it, this theory was first circulated in the book '*Hydrodynamica*', way back in 1738 (Spaid, 2017). This principle or law states that there is an upsurge in a fluid's speed resulting concurrently either with the decline in static pressure or reduction in the fluid's potential energy. The theory is applicable to all types of fluid flows that are in compressible in nature. The simplest form of this theory's equation is reasonably applicable to all forms of fluid flows (incompressible). The advanced form of this theory is also applicable to compressible fluid flows, albeit at greater numerical values. The basis of this theory is the law of "*conservation of energy (Spaid, 2017),*" which effectively means that "*in a steady flow of a fluid, the sum of all forms of energy along a streamline must be the same at all points within the streamline. This further means the sum of kinetic, potential (Spaid, 2017),*" as well as the internal energy must remain constant along the streamline. Therefore, increasing the speed of the fluid (increasing kinetic energy) results in reduction of potential energy and internal energy.

2.3.2. Open Channel Flow

Scientists and hydraulic engineers employed with river restoration are the ones who generally acknowledge and appreciate the necessity for a thoughtful consideration of natural streams being a highly intricate and dynamic classification that not only entails mere abiotic fundamentals like flow or deposits for example, but also is inclusive of organic elements as well. It is from this perspective, the role that riverine vegetation plays within river dynamics and flow conditions turns out becoming crucial (Velasco, Bateman, Redondo, & DeMEdina, 2003).

There have been studies that have been conducted in pursuit of understanding the hydro-mechanic interaction occurring amidst the water flow and the flexible plants that cover a riverbed wherein experimental test as well as dimensions of commotion on the flow within an open channel were carried out. In these experiments, plastic plants that were seeded within a gravel bed were used to find out the dimensions of the flow's commotion (Velasco, Bateman, Redondo, & DeMedina, 2003).

The classification of friction factors that were part of flow resistance resulting because of the vegetation flexible coarseness for various plant densities were reached; besides, determining comprehensive turbulent velocity profiles of the submerged and flexed stems – both within and above, which further allowed in differentiating various regimes of turbulence within the flow (Velasco, Bateman, Redondo, & DeMEdina, 2003). The experiments yielded in a few fascinating links that were identified among the velocity field and the swerved height of the plants, like a direct (linear) fit amidst the non-dimensional flexural parameter and the plants' comparative deflection (Velasco, Bateman, Redondo, & DeMedina, 2003).

Another study was also identified in support of the current review wherein the engineers/scientists had conducted laboratory experiments for investigating the open channel flow reaeration. In this particular study, the laboratory tests were based on the conventional dimensional assessment method. The tests were conducted with use of three 15 m long channels having different cross-sections – "*1) 0.5 m wide semi-circular cross-section; 2) 0.4 m wide rectangular cross-section; 3) 0.2 m wide rectangular cross-section (Maradei, Veltri, Morosini, & Verbeni, 2014).*"

There was also independent variation that was identified between the longitudinal bottom slope, the coarseness as well as the discharge flow in these channels. The method of disturbed equilibrium was implemented within novel experimental process, which involved linking the dissolved oxygen measures that were obtained during the tests without the presence or inclusion of de-oxygenation (the so-called white tests) with those tests that were conducted in turns including the de-oxygenation agent or the reaeration tests. Further to the experiments and the subsequent results, the scientists proposed a new link among the reaeration coefficient as well as the hydrodynamic qualities of the open channel. The suggested link is deemed applicable to an exhaustive range of hydraulic characteristics and values that have formerly not been explored in the past studies and is also characteristic of small rivers. (Maradei, Veltri, Morosini, & Verbeni, 2014).

2.3.3. Multiple Semi-Circular Arches

Arch bridges have been a popular trend in civil engineering an there are several of them around the world which have been constructed several decades ago. Maintenance of such arch-bridges is a serious challenge faced by civil engineers. As the age of the bridges grows, some or the other deficiency arises in an arch bridge and this mandates and engineer to make a decision if the bridge is safe in view of the deficiencies identified, or if there is a need for any repair towards strengthening the structure of these arch bridges. In case the engineer decides that there is a need for repair in order to strengthen the structure, the next question that he posed with is to what type of strengthening is required. Besides, there is another key component that needs to be thought of which is if higher axle loads can be permitted on the bridge. With the changing times, the construction of arch bridges is no longer being done, which has resulted in engineer completely forgetting the golden rules or the thumb rules of designing such bridges (Indian Railways, 2009).

The design of masonry arch bridges has long been based upon practical rules – most being highly conservative in nature, and the same has led to the structures of these bridges to possess an innate ability of withstanding not only applied loads, but also extreme conditions of weathering. Arch-bridges are possibly the oldest structures, particularly in the Indian railways, with several of them still being in service in spite of their age as well as the dramatic load conditions that have emerged since the time of their original construction. The figure here presents the fundamental components of masonry arch bridge.

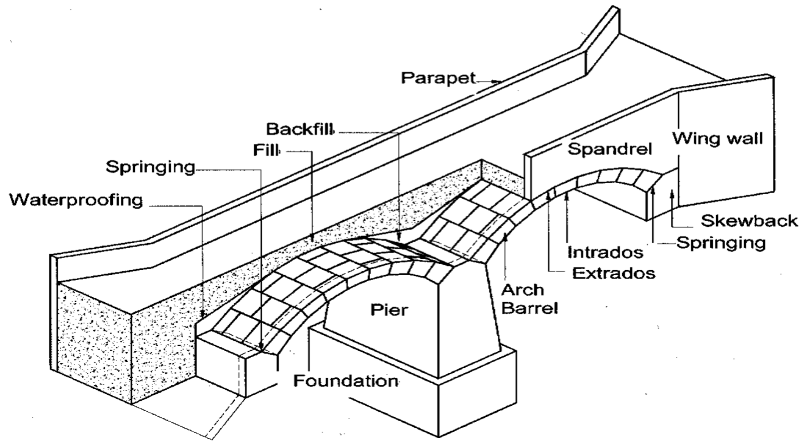

Figure 1: Elements of a Masonry Arch (Indian Railways, 2009).

The primary element of an arch-bridge is the arch barrel which is normally built using either dressed stones or bricks. Bridges constructed using bricks has multiple layers of rings that are normally glued together, which makes them innately less robust in comparison to those built using stone voussoirs. It is because of this reason that the structures built using brick are thicker when compared to those built using stone, despite having the same rise as well as span (Harding, Parke, Ryall, & Civil, 1996).

In a study by Johnson et al. (Johnson, Sheeder, & Newlin, 2009) shows that the bridge piers create local obstructions that create a three-dimensional flow. It is a proven fact that a vertical obstruction in a unidirectional flow creates a highly three-dimensional flow (Biglari & Stum, 1998) as illustrated below:

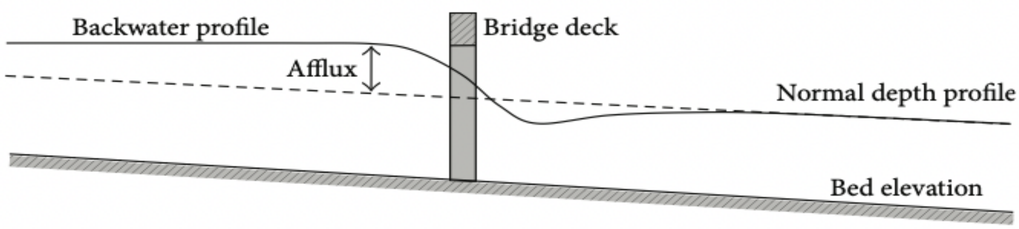

Figure 2: Sketch Diagram of Flow through Constricted Bridge (Graf & Istiarto,2002) (Haltigin, Biron, & Lapointe, 2007)

Usually it is one-dimensional numerical models that have been used for prediction of water surface. However, there are two-dimensional models that are available like the Matz and Benn afflux estimator model.

For Newtonian, incompressible fluid flow, the mass and momentum equations, which constitute the RANS equations, are given as:

$$\frac{\partial}{\partial x_i}(u_i A_i) = 0,$$
$$\frac{\partial u_i}{\partial t} + \frac{1}{V_f}\left(u_j A_j \frac{\partial u_i}{\partial x_j}\right) = -\frac{1}{\rho}\frac{\partial p}{\partial x_i} + G_i + f_i, \tag{1}$$

where x represents the coordinate, u_i is mean velocity, A_i is fractional area open to flow in subscript direction, t represents time, V_f is fractinal volume open to flow, p is pressure, ρ is fluid density, G_i represents the body accelerations, and f_i represents the viscous accelerations given as follows:

$$f_i = \frac{1}{V_f}\left[\frac{\tau_{b,i}}{\rho} - \frac{\partial}{\partial x_j}\left(A_j S_{ij}\right)\right],$$
$$S_{ij} = -(v + v_T)\left[\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right], \tag{2}$$

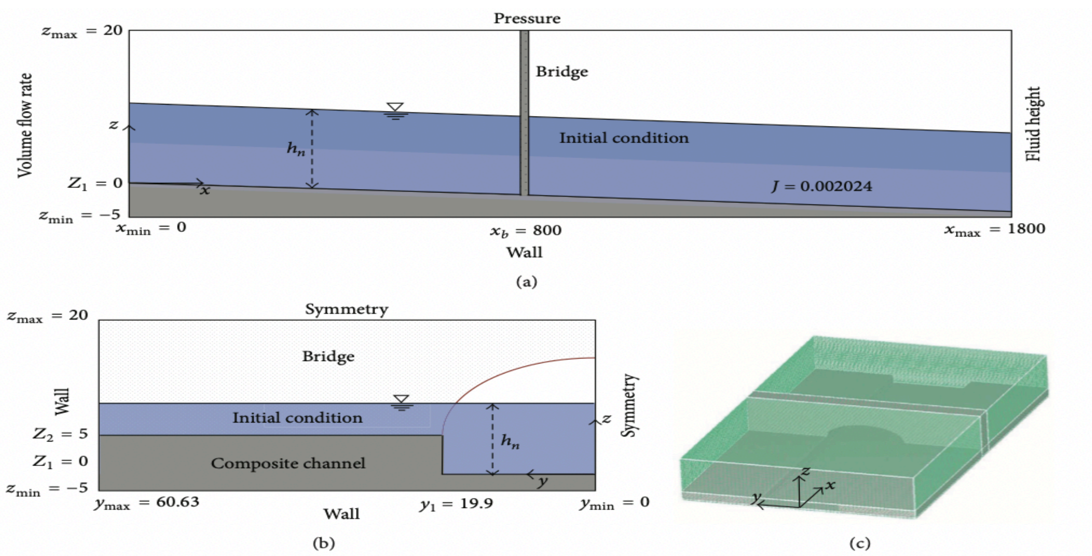

Figure 3: Computational domain and boundary conditions: (a) longitudinal profile of the channel with boundary conditions, (b) cross-section of the channel with boundary condition, and (c) overall 3D view of the channel, dimensions in (cm) (Kocaman, 2014).

2.4. Conclusion to Literature Review

The impacts that the design and construction of bridges have upon the safety of the public and the natural ecosystem is highly significant. A bridge that is not only safe but also is economically viable is one that is appropriately sized, devised, constructed, and preserved. Generally, even though longer bridges are slightly more expensive in terms of their design and construction when compared to the shorter ones, they are beneficial in the sense that they result in less backwater, witness reduced scour, and can even minimize the impacts to the ecosystem. Increased scour from a bridge that is too short in size can call for deeper footings and subsequently demand countermeasures that help resist such effects. In this review, the historical flooding of Bath including the catchment descriptions of the same, various principles of hydraulics, open-channel flow, and arch-bridges have been discussed in relation to past literature and studies.

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