Application of Particle Image Velocimetry in Hydraulic Engineering Research

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Particle Image Velocimetry (PIV) is a non-intrusive method used for ascertaining hydraulic information in a specific area of interest in either 2 or 3 dimensions. Using an illuminating light source, reflective particles, and a high speed camera, a time series of images in a specified area are captured and correlated thus producing a detailed representation of the flow field. Once the flow field is established, corresponding information such as velocity vectors, streamlines, and shear stresses, over a given duration can be calculated. This method of acquiring hydraulic information is proving vital for advancing the professions understanding of various hydraulic phenomenons, especially in and around hydraulic structures such as bridges, culverts, and guide-vanes used in stream restoration.

The Federal Highway Administration's Hydraulics Research Laboratory has been utilizing PIV as part of their experiments to assist in the design and analysis of various hydraulic structures. Situations which have been modeled include the development of the horseshoe vortex system at the base of piers, the wake vortex system on the downstream end of piers, the vena-contracta height of flow as it enters into box-culverts, the vortex system that forms downstream of guide-vanes used in stream restoration, and the turbulent shear profile at the outlet of culverts, among others.

The purpose of this paper is to explain the technology of PIV and give a broad overview of the benefits of its application in hydraulic engineering research, as well as a summary of selected results from various experiments which have been performed using the technology.

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INTRODUCTION

Obtaining the detailed characteristics of an expansive flow field in a fluid medium such as water or air is vital for theoretical advancements in the fields of fluid mechanics and hydraulic engineering. Information such as: the velocity field, streamlines, shear stress, and vorticity are all important characteristics which need to be ascertained in order to truly comprehend the mechanics of the flow in an area of interest. Knowing this information will ultimately lead to the development of reliable equations and coefficients which then can be used to aid the engineer in producing safe and reliable designs.

Previously, the only means of measuring the velocity profile in a fluid medium was by the insertion of a probe such as a Preston Tube or Total Head Tube. These probes either through mechanical or electronic means would record average point wise velocity measurements. These measurements then would be translated into a corresponding velocity curve. The problem with this type of measurement is that the probe acts as a flow retarding obstruction and therefore can skew the actual velocity distribution in the flow leading to errors in the results. Also, these probes are not capable of measuring the turbulent fluctuations necessary for the prediction of the Reynolds stresses. Furthermore, for the purposes of predicting shear stresses on the boundary, velocity measurements within the boundary layer are needed. In most cases the probes are incapable of such measurements.

As technology advanced, the Acoustic Doppler Velocimeter (ADV) was invented. The ADV is a device which sends out electrical impulses, usually to a range of about 5 cm beneath the probe. The impulses are reflected back into the probe and then calibrated to record turbulent fluctuations as well as point-wise average velocities (Lemmin 1997). This advancement allows for a more accurate measurement of velocities during uniform flow conditions due to the non-invasive aspect of the probe with respect to the point of interest. Additionally, the device allows for the measurement of velocities very close to the boundary layer. The limitations of ADV are realized when studying fluid phenomenon in front of objects where an oscillatory vortex may form (such as in front of a bridge pier due to the horseshoe vortex) or during cases of pressurized flow where it is not possible to insert the probe into the flow field due to the solid wall boundary of the pipe.

To date, Particle Image Velocimetry is the best method for acquiring detailed flow field information such as velocity fields, shear stresses and vorticity.

PARTICLE IMAGE VELOCIMETRY

Particle Image Velocimetry (PIV) is a non-intrusive method which uses light reflecting particles and high speed photographic imaging to ascertain the velocity profile under any condition during a certain time frame (Raffel 1998). The flow is laced with light reflecting particles, usually hollow glass spheres which have approximately the same density as water. The particles are circulated through the flume as part of the normal flow and are reflected using an illuminated laser beam. While passing through an area of interest, a high speed camera records images of the particles. Once a sufficient number of pictures are obtain, a cross-correlation analysis can be performed which tracks clumps of particles as they move from one frame to the next (Figures 1). Upon knowing the displacement of the particles and the time interval between pictures, the direction and velocity of the fluid is determined on a point by point basis. Integrating the velocity field allows for streamlines to be ascertained (Figure 2). Once the flow field is known, vorticity and shear stress can be calculated.

PIV reaches its limitations when trying to record images close to a fixed boundary. Research conducted at the Federal Highway Administrations Hydraulic Research Laboratory has shown that PIV can yield accurate results of the flow field to within .3mm of a fixed boundary. This method is therefore superior to the other methods of velocity profile acquisition mentioned previously, but like the other methods, does not produce an absolutely certain representation of the flow field approaching the boundary.

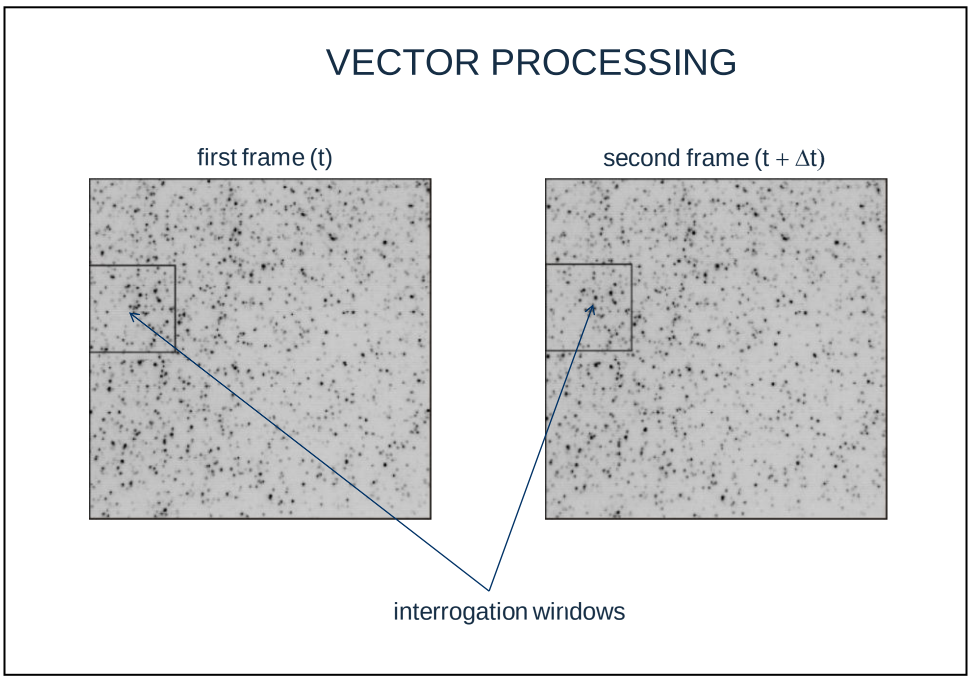

Figure 1 – Particle Image Velocimetry Successive Camera Images Used for Vector Processing.

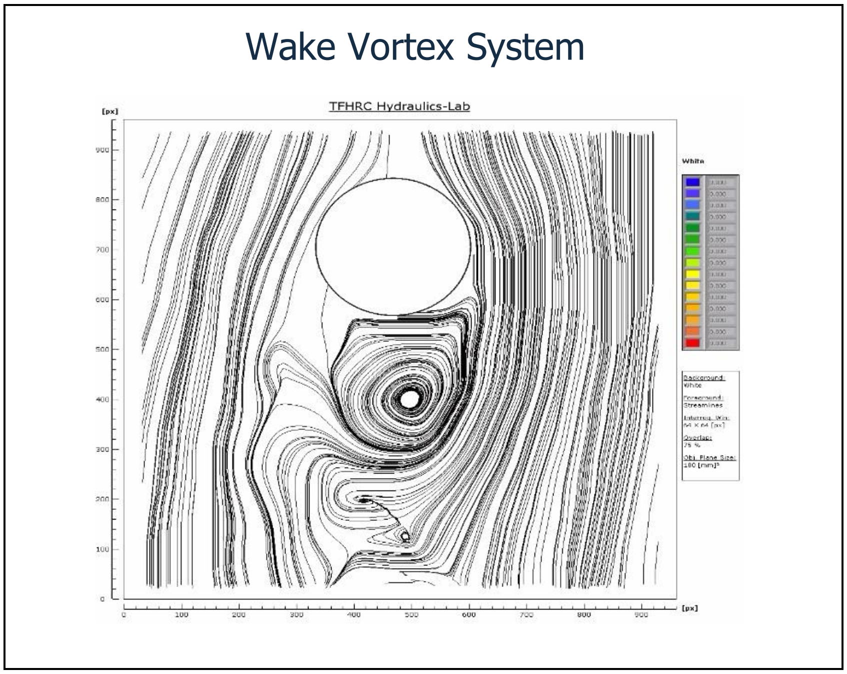

Figure 2 – Streamlines Showing the Wake Vortex System around a Circular Object

PRACTICAL APPLICATIONS OF PARTICLE IMAGE VELOCIMETRY

The Federal Highway Administrations Turner-Fairbanks Highway Research Center's (FHWA_TFHRC) Hydraulics Laboratory has been using PIV to aid in the analysis of flow phenomenon in and around hydraulics. Several types of flow conditions have been analyzed including: the effect of entrance conditions of box culverts on entrance loss coefficients, the effect of turbulent shear stresses on box culvert outlet scour location and depths, and the development of the horseshoe and wake vortex systems around bridge piers.

Box Culvert Entrance Loss Coefficients

The ability of a culvert to convey maximum flow under inlet conditions is governed primarily by its entrance configuration. As the flow enters the culvert it contracts and in some cases a flow separation occurs at the physical boundary of the culvert which leads to a loss in energy and a corresponding reduction in flow capacity (Figure 3). In order to maximize the efficiency of the culvert it should be designed to reduce the flow separation as much as possible and therefore also reduce the corresponding energy loss. Experiments were conducted using PIV for the purpose of determining an optimal geometry configuration which could be used in order to reduce the entrance loss coefficient as much as possible and thereby maximize the flow capacity of the culvert.

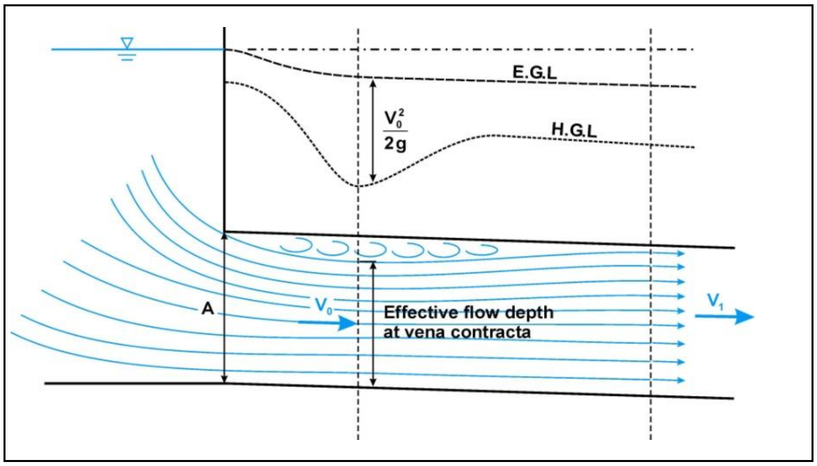

Figure 3 – Typical Entrance Condition at Box Culverts

A total of seven inlet geometry configurations were analyzed including a sharp 90^o entrance, 3 chamfered edge conditions, and 3 smooth radii conditions. The results of the analysis were plotted showing the effective flow depth at the vena contracta as a function of the tailwater depth. As suspected the longest smooth radii condition produced the best results. Figures 4 & 5 show the worst case and best case scenarios from the PIV analysis. The results of the study have helped manufacturers construct optimal inlet culvert geometries.

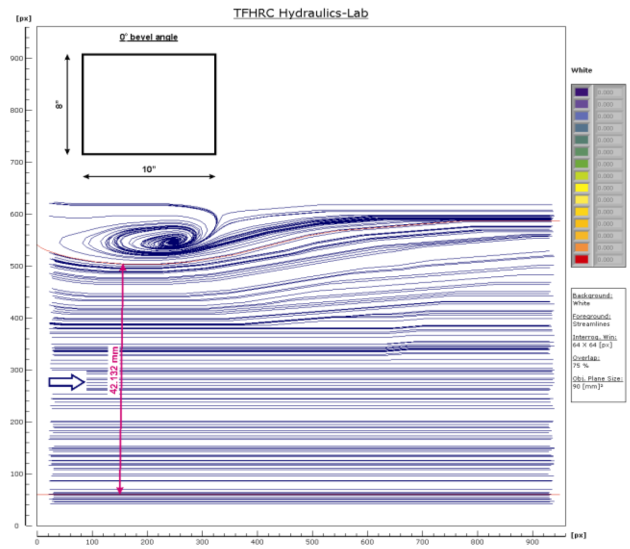

Figure 4 – Vena Contracta Height From Flow Passing through a 90^o Entrance Headwall

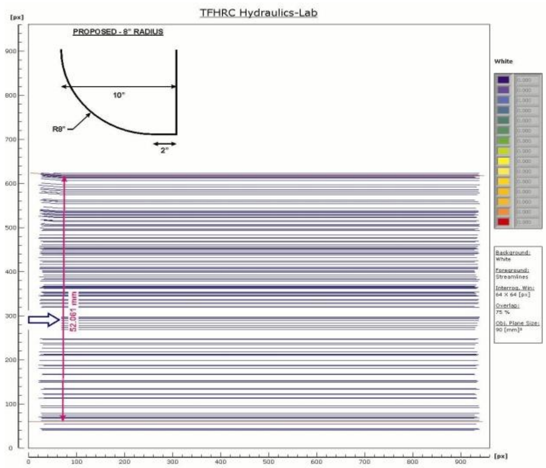

Figure 5 – Vena Contracta Height from Flow Passing through a Smooth Radii Entrance Headwall

Outlet Scour at Box Culverts

Scour at the outlet of culverts has received little attention in the literature as most studies focus on scour around the inlet based on the fact that most people agree that the worst scour depths occur at the inlet. However studies at the FHWA-TFHRC Hydraulics Laboratory have shown that scour depths at the outlet of culvert can in some situations actually be more severe than around the inlet walls. Additionally, it also was found that the deepest scour depths don't occur directly at the exit but instead some distance downstream An analysis of the situation using PIV was conducted in order to determine the cause of the increased scour depths downstream of the culvert exit. The flow field was determined and using this information the turbulent Reynolds stresses were calculated. Side-by-side images of the scour map and the Reynolds stress map show that the point of maximum scour occurs where the Reynolds stresses are also at a maximum (Figure 6). Additional research was conducted which showed that by streamlining the exit of the culvert the Reynolds stresses and corresponding downstream scour depths could be reduced (Figure 7).

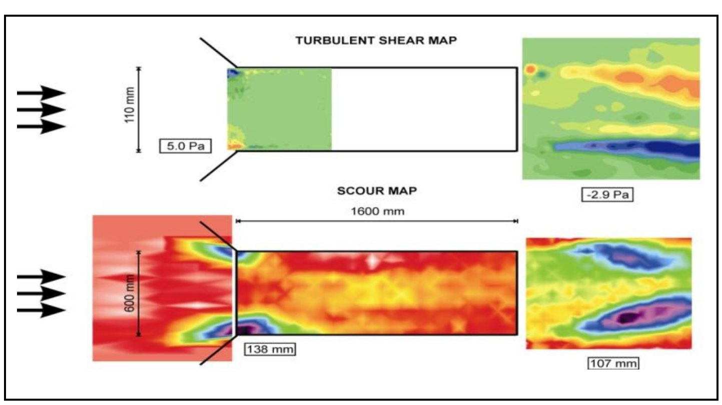

Figure 6 – Turbulent Shear Map with Corresponding Scour Map Dowstream of Culvert

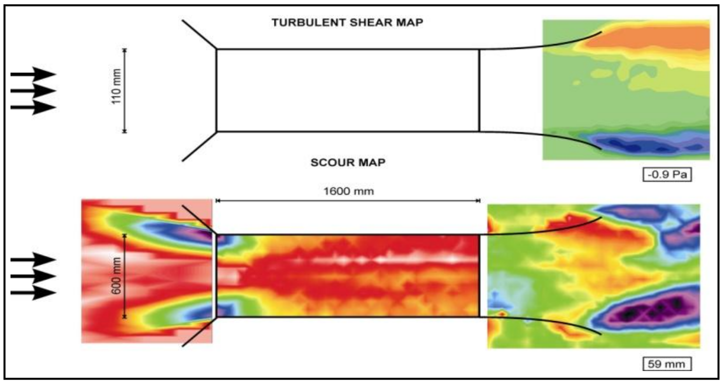

Figure 7 – Turbulent Shear and Corresponding Scour Map with Streamlined Exit

Horseshoe and Wake Vortex Systems

The horseshoe and wake vortex systems which form on the upstream and downstream sides of a bridge pier have long been known to be the driving forces for producing scour around bridge piers (Figures 8 & 2). Much research has been devoted to understanding these vortex systems in the hope that once understood an original design could be implemented which eliminates the vortex systems and corresponding scour. Using PIV an extensive analysis of each of these systems is now possible. Measurements involving the size and strength of the vortex, the turbulent shear stresses, and many other variables can now be analyzed. Additionally the effect of introducing flow retarding structures along a pier which potentially eliminate the generation of the vortex systems can also be studied.

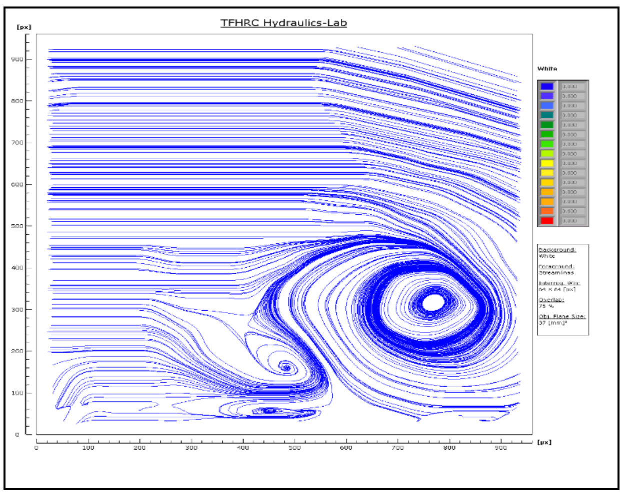

Figure 8 – Horseshoe Vortex System at the Upstream Face of a Bridge Pier

CONCLUSIONS

Fluid measurements using Particle Image Velocity are becoming increasingly valuable for advancing the fields of fluid mechanics and hydraulic engineering. Measurements such as turbulent shear stresses and vorticity within a flow field were once difficult to obtain with adequate precision but now are readily available. Additionally, because PIV captures the flow field over a given time frame, oscillatory phenomenon such as the horseshoe and wake vortex systems are able to be studied in greater detail. The ultimate goal of using PIV for hydraulic engineering applications is the understanding of the mechanics of the flow which then may lead to improved equations, coefficients, and designs.

REFERENCES

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