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Experiments Identifying Scour-Inducing Flow Patterns At a Gated Weir Stilling Basin

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ABSTRACT

Excessive scour downstream of stilling basins poses significant risk of structural failure. This problem was experimentally investigated at Michigan Technological University in a Froude-scaled, physical model of one such structure operated by the South Florida Water Management District. Detailed flow measurements were taken on a flow scenario that resulted in high scour, namely that of a high flow rate and upstream headwater depth and a low tailwater depth. Equilibrium bed scour and velocity measurements were taken using an Acoustic Doppler Velocimeter. Velocity data was used to construct a vector plot in order to identify which flow components contribute to the scour hole. It was found that downward-plunging flow upon leaving the stilling basin induces the primary scour hole.

INTRODUCTION

Despite the best efforts by engineers to design robust water control structures, bed scour can lead to unexpected structure failure if it is not monitored on a regular basis. Determining the extent of bed scour may require specialized equipment and training. In situations where bed scour is known to threaten a structure, steps should be taken to reduce the rate at which bed scour occurs. The costs of both monitoring and remediation of bed scour can be minimized by conducting experiments on a scale-model structure. A model of the structure in question may be constructed in order to study the effectiveness of the chosen method of bed scour reduction. These results, when used in conjunction with numerical modeling, should give the user a good idea of what to expect.

A significant amount of study has been devoted to address scour related issues in hydraulic structures including spillways, bridges, and culverts. Many researchers and scientists performed various kinds of experiments to understand the scour phenomena. Xu et al. (2004) performed an experiment in a glass flume and predicted scour depth ratio for non-aerated and aerated jets. Canepa and Hager (2003) performed experiments in which a free jet at an angle of 30° was injected to estimate the scour profile. Schmocker et al. (2008) conducted an experiment in a rectangular approach channel to study aeration distribution. Dey and Westrich (2003) conducted an experiment to study the scour hole profiles and flow characterization in a cohesive bed downstream of apron. Rahmeyer (1990) studied the effect of aeration on scour. Afify and Urroz (1993) studied the impact of jet height, nozzle impinging angle, and diameter on the air entrainment rate. The current paper presents the experimental results and analysis of flow characteristics and their impact on bed scour downstream of a stilling basin for one flow scenario. A real hydraulic structure, S65E, of the South Florida Water Management District (SFWMD) was modeled at a 1:30 scale in the hydrodynamic lab at the Michigan Tech to investigate the scenario.

SCOUR AT THE S65E

It was discovered that considerable scour had occurred downstream of the S65E control structure maintained and operated by the South Florida Water Management District. This structure consists of a gated weir stilling basin with six parallel lift-gates, and is the hinge-pin structure regulating flow from the Kissimmee River / C-38 canal into Lake Okeechobee (Gonzalez-Castro and Mohamed, 2009).

PROCEDURE

Preliminary experiments were conducted in the hydrodynamic lab at Michigan Tech to identify the flow scenario which yielded the most bed scour. Prior to starting the experiment, the scour region (see Figures 1-3) was filled with fine sand and leveled from the top of the end sill to the top of the partition separating the scour region from the sediment trap. The flume was then filled with water to the desired depth and a Nortek Vectrino Acoustic Doppler Velocimeter (ADV) was set up to measure scour in a location of expected deep scour until equilibrium condition were satisfied.

Description of Laboratory Set-up

A Scour Flume at Michigan Technological University, shown in Figure 1-3, was used to conduct the bed scour experiment. The flume is comprised of an inlet, flow-developing, spillway/stilling basin, scour, and sediment trap, and outlet sections (in order from upstream to down). The flume has an inside width of 0.92m (3ft) and a total inside length of 10.18m (33.39ft). The total flume height is 1.04m (3.41ft).

The bed contains 12.7mm (0.5in) gravel to roughen the boundary layer to ensure fully-developed flow prior to entering the spillway test section. Fully-developed flow was verified through the use of a Nortek Vectrino Fixed Probe Acoustic Doppler Velocimeter (ADV) in the flow developing section (ADV used for bed elevation previously). Data was collected at various elevations with the ADV, both at the beginning of the upward-slanted approach (x = -150) to the spillway and

30cm (11.81in) upstream (x = -180). The velocity of lateral and vertical flow was approximately zero at all elevations. The velocity profile of longitudinal flow was consistent with developed flow in that it was zero at the bed and increased as the distance from the bed was increased.

The spillway is 0.457m (1.5ft) wide and was modeled at a 1:30 vertical and longitudinal scale of a section of the SFWMD's gate structure S65E of 9.15 m (30ft) out of the prototype spillway length of 54.9m (180ft). The spillway is 0.1m (3.94in) high and 0.23m (9.05in) long (Figure 4) to comply with the 1:30 scale criterion. The spillway is followed by a stilling basin consisting of two rows of 40mm (1.57in) cubic blocks in which the blocks from each of the rows was offset from the other. At the end of the stilling basin was a 40mm (1.57in) tall triangular sill. There is a 90^{o} sudden expansion of the channel downstream of the stilling basin, even though in the S65E structure has a relatively smooth transition with sidewalls protected by rip-rap.

Downstream of the stilling basin was a 2.805m (9.20ft) long scour region filled to the top of the end sill with fine sand with a d_{50} = 0.56mm. This size was chosen to be as close as possible to the scaled size needed to model the sand size found in the prototype without being so small that it was cohesive. The scour region had an internal wall at the downstream end of 630mm (2.07ft) tall. The sand surface tilted downstream at a 1:30 slope to be consistent with the prototype.

Downstream of the scour section was a 1.70m (5.58ft) long sediment trap section where sediment settled out to keep it from re-circulating through the pump and return piping, thereby minimizing internal pump and pipe wear. This trap was seen to be effective in removing sediment as evidenced by the fact that virtually no sediment was observed going into the outlet section or anywhere else in the flume, especially going over the spillway and entering the stilling basin and scour region. The spillway height is high enough and vertical velocities low enough to ensure this.

Next the flow entered the 900mm (2.9 ft) long outlet section where it entered the 0.254m (10in) diameter outlet piping, after which it was re-circulated to the upstream end of the flume. Flow was re-circulated by a centrifugal pump and return piping.

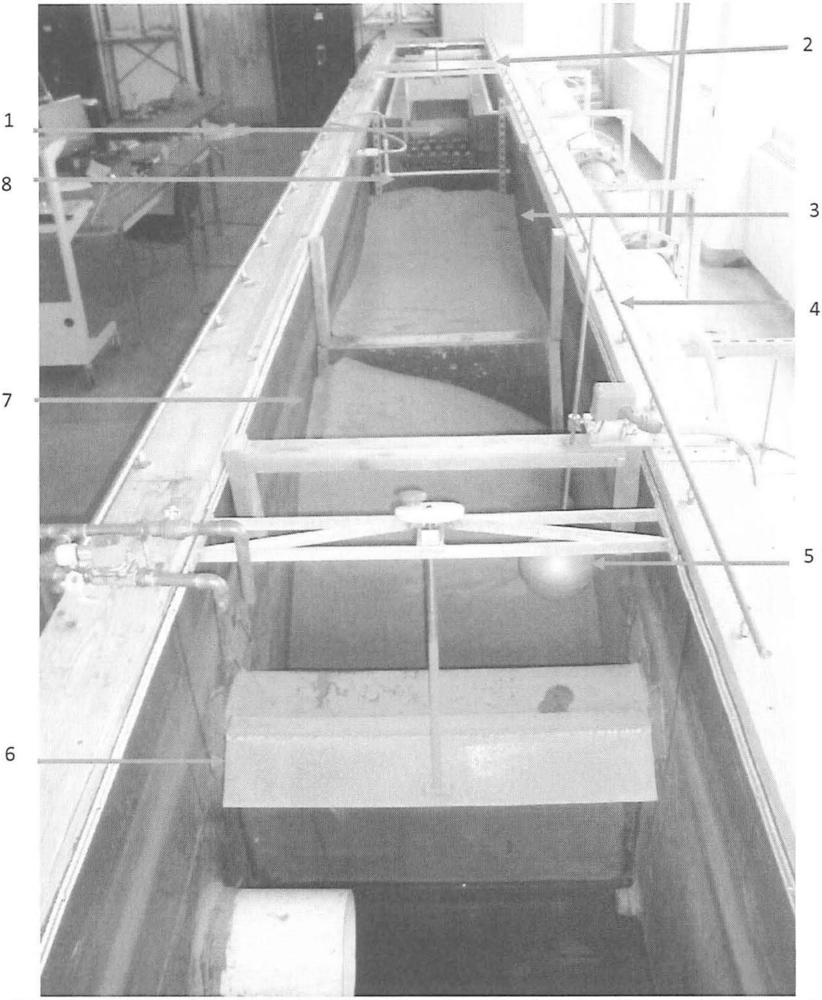

Figure 1. View of the flume looking upstream. (1. Gated spillway with blocks, 2. Instument carriage, 3. Sediment scour section, 4. Guide rails for instrument carriage, 5. Float valve to ensure constant water depth during experiments, 6. Adjustable tailgate to control downstream water level, 7. Sediment trap, 8. Pipe)

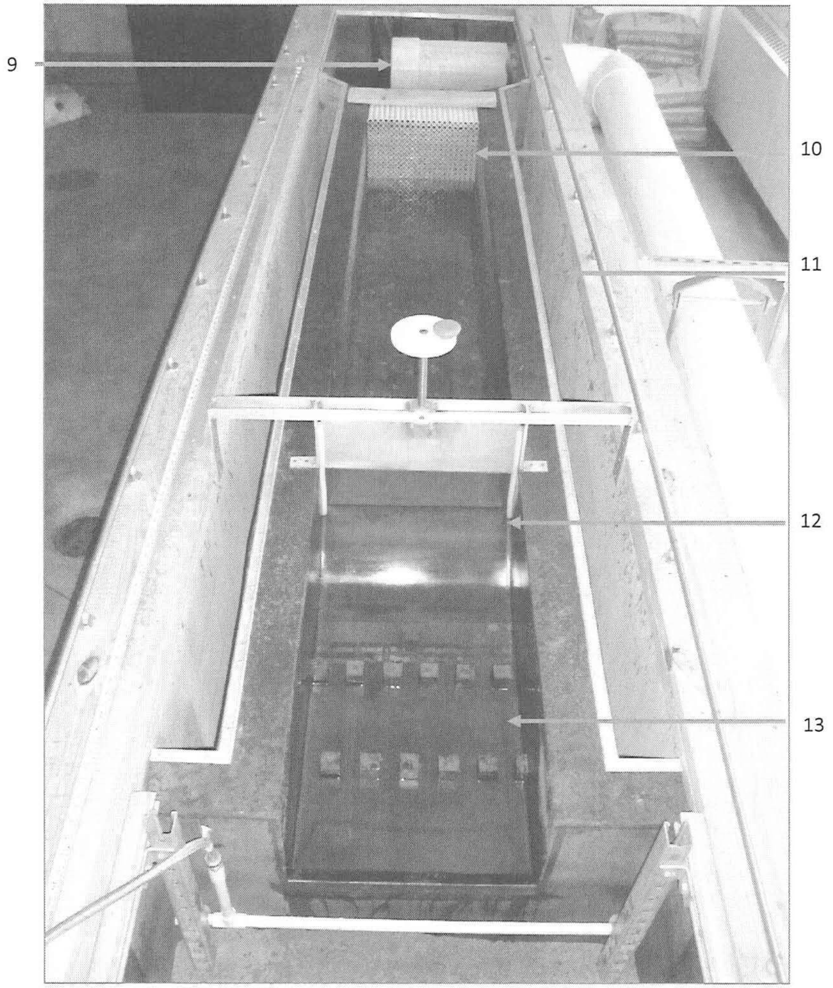

Figure 2. View of flume upstream section. (9. Inlet piping, 10. Flow straighteners, 11. Approach channel, 12. Gated spillway, 13. Stilling basin)

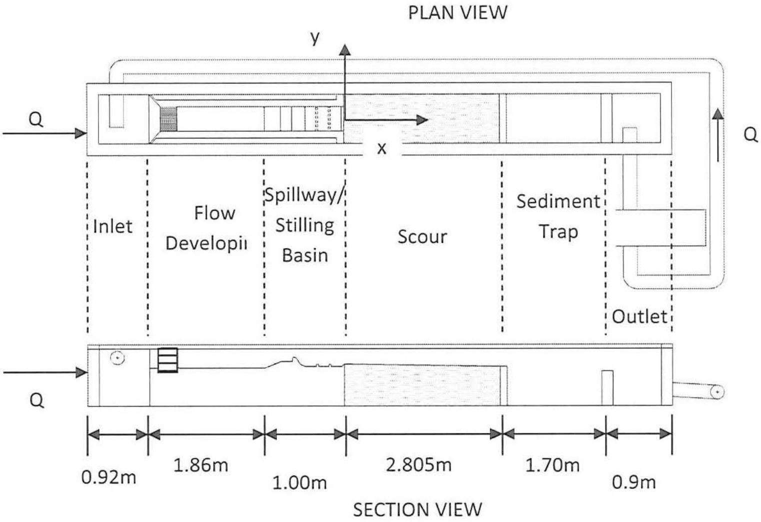

Figure 3. Scour flume with various sections and their dimensions

Since the water level can change during an experimental run due to evaporation or small leaks, the water level was kept constant by an adjustable float valve comprised of a buoyant bulb attached to an adjustable rod which triggers a valve connected to the inlet of the city water supply piping that fills the flume to shut off and on. This arrangement can maintain a constant water level of ±3mm. Surge protectors were installed to reduce the effects of water hammer from the sudden closing of the float valve.

The flow rate through the structure was controlled by a variable-speed electric controller/centrifugal pump and measured by a two-tube manometer/side contraction meter in the return piping. The rotation of the pump impellor is constant to within 0.005 Hz and the manometer has an accuracy of 0.79mm resulting in an accuracy of discharge of ±0.0060m^3/s (0.213 ft^3/s).

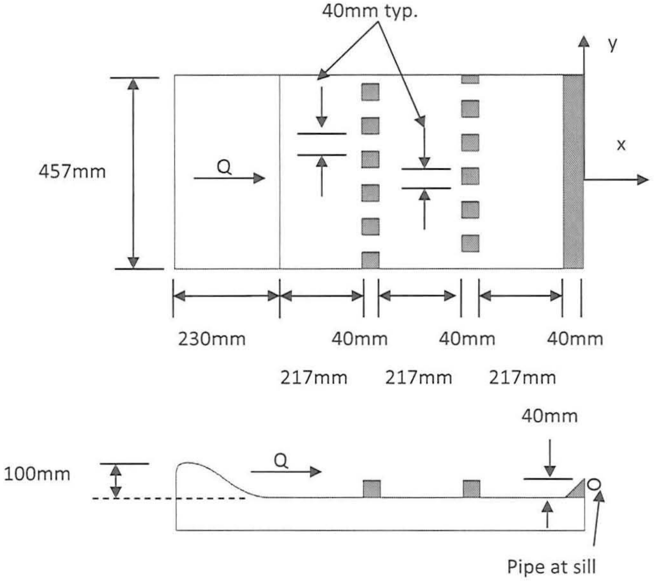

Figure 4. Spillway and stilling basin model

Water surface and bed profiles were measured by a point gage mounted on an instrument carriage that slides along rails installed on the top of the flume sidewalls.

Data Collection

The flow was then started and scour was measured periodically for the entire time to reach equilibrium using the depth function of the ADV at ten-hertz intervals. These data were then filtered by eliminating erroneous data identified visually and also by eliminating data which failed to satisfy minimum quality criteria. For ease of plotting and data analysis, the filtered data were then averaged in two-minute bins for presentation.

Flow was run for approximately 35 hours until sufficient time had elapsed for equilibrium scour conditions to occur, as determined by there being a change in scour depth over a 2-hr period of less than 0.5 percent. While measurements were taken at equilibrium-scour conditions, it is assumed that similar flow patterns were active throughout the experiment. After verifying equilibrium, the ADV was then used to begin collecting water velocity data. Velocity data was collected along the centerline of the flume using a grid resolution of 10 cm longitudinally and 2.5 cm vertically throughout the scour region of the channel. Data was collected at each point for 300 seconds at a frequency of 200-hertz utilizing a sample volume height of 7 mm.

The data was then processed through a series of filters to help identify erroneous velocity data. It was difficult to construct data filters that would remove erroneous data yet still capture intermittent vortex bursts in the flow. Trial and error revealed that a filter removing all data with acceleration greater than that of gravity proved most useful. After filtering, the average velocity was determined for each vector *u*, *v*, and *w*. This data was then aggregated to form a 2-D slice down the center of the channel. Plotting this data allowed the use of streamtraces to illustrate flow characteristics. Because the channel is symmetrical, transverse flow at the channel centerline is not expected and therefore *v* values are not included in this paper.

RESULTS

Uncontrolled free flow resulted in the greatest bed degradation with a scour hole of similar proportions to that observed at S65E control structure. In this flow scenario, flow through the structure is neither impeded by the sluice gate nor buffered by the tailwater before encountering the channel bed. Flow characteristics were determined by visual observation of both the flow and the ensuing scour patterns on the channel bed and velocity measurements collected. Behavior observed visually is the aerated nappe created by the flow exiting the stilling basin. Expectedly, flow in this area was organized with a high velocity. This flow split into two components as it approached the bed. A downward roller was formed with a near-bed component flowing upstream along with plunging region downstream of the separation point. The location of the separation point was several centimeters downstream from the bottom of the scour hole. Flow downstream from the scour hole formed a vertically contracting region due to the diminishing effects from the scour hole. This behavior is detailed with a vector plot in Figure 5, using streamtraces in Figure 6, and by dunes shown in Figure 7.

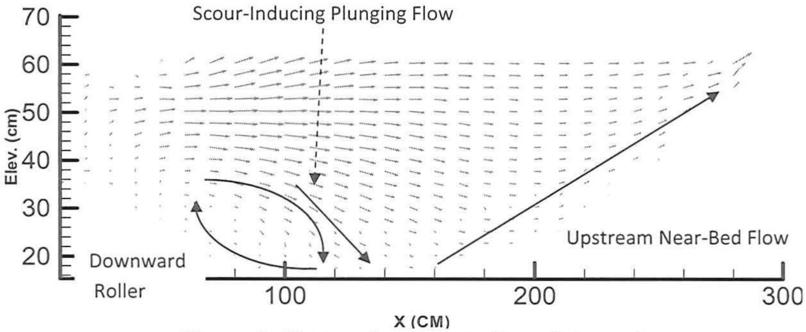

Figure 5. Vector plot at centerline of channel.

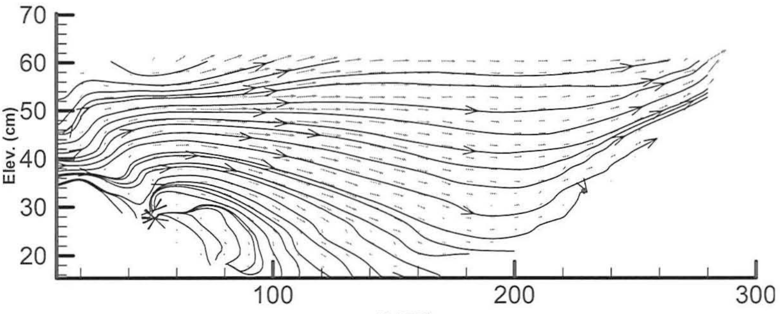

Figure 6. Streamtrace plot at centerline of channel.

Vertical vortices were found on both sides of the stilling basin due to the sudden expansion in channel width. This flow separation forms a downward roller upon contact with the channel side walls, which in turn travels down the channel sides where it splits upon contact with the bed. Flow then splits and forms two secondary vortices, one upstream and the other downstream, going along the corner formed by the channel wall and bed. This behavior was also confirmed while examining dune structure after ending the experiment (Figure 7).

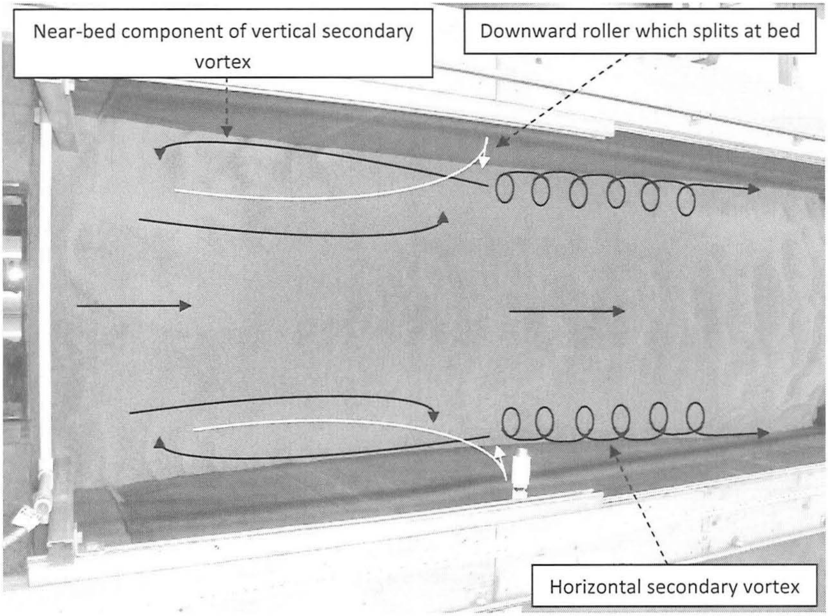

Figure 7. Dune structure (white is surface flow, black is near-bed flow).

CONCLUSION

The primary scour hole was formed due to concentrated flow exiting the stilling basin and impacting the channel bed. Scour geometry was affected by the primary downward roller in combination with the counter rotating vortices. To a lesser extent, numerous eddies caused by flow separation in the plan-view also contributed to the scour geometry. Future research will include the application of scour reduction mechanisms to the model structure in an effort to determine how their presence affect scour hole formation.

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