Report as of FY2007 for 2006OH39B: "The Scour and Deposition River and Estuarine Bridges"

Publications

- Conference Proceedings:
    - Hatton, K. A. and Foster, D. L., 2006, Vertical Pile Scour Induced by Random Free Surface Gravtiy Waves, in 30th Int. Conf. Coastal Engin. ASCE.
- Articles in Refereed Scientific Journals:
    - Hatton, K. A., Foster, D. L., Traykovski, P. A., and Smith, H. D., 2007, Scour and Burial of Submerged Mines in Wave Conditions, IEEE Journal of Ocean Engineering.
    - Hatton, K. A. and Foster, D. L., 2007, Scour and Ripple Migration Offshore of a Vertically Mounted Pile Subjected to Irregular Waves, Journal of Hydraulic Engineering, ASCE, in review.
- Dissertations:
    - Hatton, K. A. 2006, Vertically Mounted Pile Scour Subjected to Irregular Waves, M.S. Thesis, The Ohio State University. Dept. of Civil and Environmental Engineering and Geodetic Science, The Ohio State University. Columbus, OH.

Report Follows

WRRI Annual Report, June 22, 2007

"The Scour and Deposition around River and Estuarine Bridges"

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Problem and Research Objectives

This investigation is motivated by the amount of river, estuarine, and coastal infrastructure that is susceptible to extreme wave and flooding events. The high velocities and resulting shear stresses associated with high flow velocities are capable of scouring or depositing large quantities of sediment around hydraulic structures. Preventing the failure of these structures and sedimentation in inlets alone costs federal and state agencies billions of dollars annually. In addition to being costly, the manual monitoring of bridge scour - as mandated by the Federal Highway Administration - can be inefficient in states such as Ohio where the flood events that initiate the scour process occur sporadically. According to the National Scour Evaluation Database, there are 23326 bridges over waterways in the state of Ohio, of which 5273 are considered scour susceptible and 191 are considered 'scour critical'.

Previous methods for identifying bridge scour have relied on the manual (diver-based) sampling of local water depths that are generally limited to periods of low water flow. As the dynamic scour and deposition of sediments around structures is highest during periods of high flow, traditional sampling methods have limited our ability to predict quantitatively scour or deposition levels and to evaluate sediment transport models.

Related to problems generated by sediment scour are issues of sediment deposition in navigational channels. On the Maumee River, OH, alone, the Army Corp of Engineers spends millions of dollars annually to dredge an average of 850,000 cubic yards of sediment. With the elimination of open lake disposal of dredged sediments, an inter-agency collaboration of government and private citizens has been formed to identify possible methods for reducing the amount of deposition by reducing the soil erosion along river bank's. Clearly, an increase in our understanding of how sediment is scoured or deposited around structures will improve our ability to utilize available resources in

The overall objective of this research is to increase our ability to predict how variations in flow conditions will affect the scour and/or deposition of sediment around estuarine and river bridges. Specific goals for this project are:

1. Observe the flow field and morphologic variability induced by high water flows at bridge ODOT ID-BUT-128-0855 located on the Great Miami River in Hamilton, OH, using a suite of acoustic, video, and bathymetric survey instrumentation.

2. Simulate the three-dimensional flow and sediment transport surrounding both cylindrical and ellipsoidal bridge piers using a highly evolved CFD numerical model (Flow-3D, Flow Science, Inc.). The model simulations will be forced by and evaluated with laboratory observations obtained in a large wave flume in the summer of 2005, and with the field observations obtained in the first objective of this proposal.

3. Examine the effect variations in river stage will have on bridge scour. Particular attention will be paid to locations where the near field, but larger scale, river geomorphology results in complex three-dimensional velocities near the bridge piles.

Methodology

Modeling of the scour and depositional process is being performed with the computational fluid dynamics model FLOW-3D (Flow Science, Santa Fe, NM). FLOW-3D is a three-dimensional, non-hydrostatic computational fluid dynamics model that employs the FAVOR method to resolve the flow around obstacles without mesh regeneration. The primary strength of FLOW-3D is its ability to accurately resolve three-dimensional flows in great detail, while tracking complex flow behavior at fluid-structure and fluid-sediment interfaces. The flow-sediment-structure modules allow for coupled flow-sediment equations to be incorporated.

First, the model is being used to simulate the flow and sediment scour surrounding a single vertical pile with an initially flat bed. Laboratory observations obtained at a collaborative full-scale laboratory experiment, CROSSTEX, are used to evaluate the model. The fluid forcing for the model is provided by the observed free stream flow under random wave conditions. The modeled flow field is evaluated with *insitu* observations of the two-dimensional flow field upstream of the vertical pile (obtained with a Particle Image Velocimetry, PIV, system; **Figure 1**). The modeled sediment transport is evaluated with observations of suspended sediment and seabed elevations obtained by a two-axis variable frequency sonar.

In CROSSTEX, the flow and scour surrounding a vertical pile was measured under forcing by random free surface gravity wave fields. The observations were obtained in the shoaling region in approximately 1.5 *m* water depth of a 104 *m* long, 3.7 *m* wide flume at the O.H. Hinsdale Wave Research Laboratory. The 6 *cm* pile was placed in an erodible sand bed with a median grain size diameter of 0.1 *mm*. A Particle Image Velocimetry (PIV) system consisting of a camera focused on a laser sheet was used to observe the two-dimensional (x-z) time dependent flow fields at 3 *Hz*. A two-axis variable frequency acoustic backscatter sensor observed the sediment suspension at 1 cm range bins over the x-z plane and the bed geometry over a 1 *m* range in the x-y plane. Figure 1 shows a schematic of the underwater instrument deployment. The field of view for the PIV system was a 23 *cm* x 23 *cm* plane offshore of the pile.

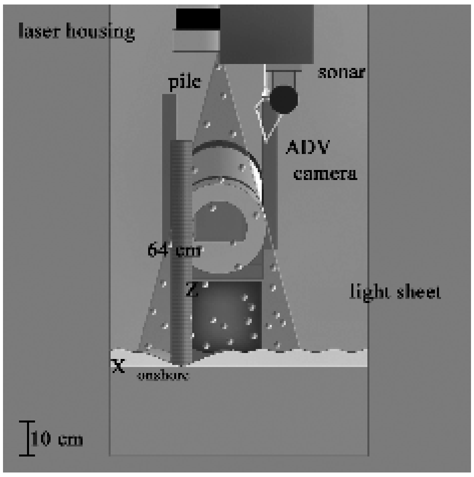

***Figure 1**. Snap shots of the x-z velocity field and bed geometry upstream of a vertically oriented cylinder (indicated by the gray shaded region in each panel) at (left) the initiation of sediment motion and (right) the equilibrium profile. Both images are taken during the wave crests. Red vectors represent the highest velocities, blue the lowest. The dashed line represents the still bed profile on the unrectified image.*

Secondly, the model is being used to simulate the morphologic evolution of the Great Miami River bed (in Hamilton, OH) in response to observed high flows. This situation is more complicated than the laboratory setting because of the large variability in the initial morphologic state and because of the large amount of flow disturbances generated by the detritus present on the riverbed. The initial scour simulations will follow the bed load transport calculations of Hatton *et al.* (2007). Regions of potential scour will be identified when the local bed stress exceeds the critical bed stress. Regions of potential deposition will be assumed when the Rouse number is of order 10.

Figure 2. The WaveRunner survey system is capable of measuring water depths from approximately 0.4 m to 15 m.

In this investigation, the model geometry is being initialized with observed river bathymetry obtained from an in-hand bathymetric survey system consisting of a Yamaha GP1200 WaveRunner equipped with differential GPS receiver, dual-transducer sonic altimeter, and custom navigation software (**Figure 2**). As part of previous research efforts, the system has been utilized extensively in coastal marine and fresh water environments where waves and currents are present (and sometimes energetic). The system has accuracies of about +/- 5-7 *cm* in both the horizontal and vertical coordinates of the measured bathymetry.

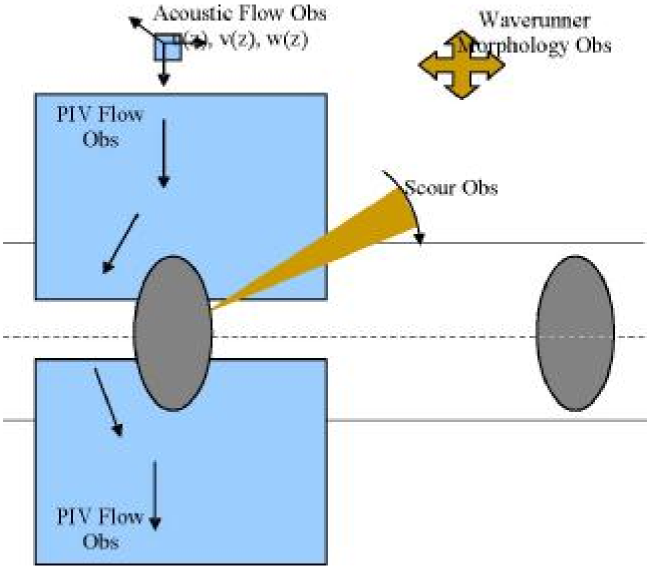

***Figure 3**. 2-D schematic of proposed deployment strategy at the Great Miami River bridge in Hamilton, OH. The hypothetical bridge piles are indicated by the gray-shaded ellipses. Blue highlighted areas represent regions where surface flows will be made with video-based PIV techniques. The yellow highlighted wedge represents a single slice of the IMAGENEX sonar used for local scour observations. Far-field bathymetric observations will be obtained with the WaveRunner survey system.*

Field observations of surface flow and local scour have be obtained during a field deployments. A schematic of the experimental design is shown in **Figure 3**. Vertical profiles of velocity can be measured at a single upstream location with a Pulse-Coherent Acoustic Doppler Profiler (PC-ADP). The sensor can remotely sample three-components of velocity at 5 *cm* range bins at a 2 *Hz* sampling rate. The observations can be used to specify the upstream boundary condition and be compared with observations of the surface flow. Measurements of the surface flow in and around the pier piling will be obtained from analysis of video data that utilizes PIV techniques. The recently developed PIV system uses visible particles on the water surface (such as from sediment patches, bubble clouds, or other passively floating detritus) to identify displacements between individual frames of the video imagery. Correlation and filtering techniques have been developed that allow mean and oscillatory flow to be measured with high accuracy, on the order of 10% of the measured velocity field.

For this project, cameras will be deployed on both the upstream and downstream sides of the bridge (**Figure 3**). The labor intensive nature of the PIV system will limit surface flow analyses to the initial model evaluation and to several high-flow events. The near-field scour and sediment suspension was measured with a rotating two-axis IMAGENEX profiling sonar attached to the bridge pier (**Figure 4**). The sonar will resolve the two-dimensional centimeter-scale bathymetric variations over a 5-20 *m* radius.

Figure 4*. Snapshot of an IMAGENEX deployment at the proposed Hamilton site (ODOT ID-BUT-128-0855). Figure courtesy of Dave Straub (USGS).*

The instrumentation will be deployed during one low flow event and several high flow events. Observations will be used to evaluate model performance as well as identify any flow patterns related to structure scour and deposition. Model simulations will also be qualitatively compared with observations from the National Bridge Scour Database (USGS). Ongoing model-data comparisons will improve model strengths and set limitations on present capabilities. Following successful model-data comparisons, the model can be used to predict the scour and deposition around bridge piers for extreme storm events with a variety of return periods that may include, for example, 20, 50, or 100 year events.

Principal Findings

Hatton and Foster (2007) observed the bed evolution offshore of a vertical pile subjected to five different forcing conditions. Bed evolution was resolved over a 23 cm by 23 cm window offshore of a 6 cm diameter vertical pile with our submersible PIV system. The duration of wave generation was long enough for each data set to reach equilibrium scour depths. In each of the five sets of observations, ripples migrated onshore towards the scour depression to a distance of one-half of a ripple wavelength from the scour depression, remaining roughly static until a series of larger waves causes the ripple to merge with the scour hole ($\theta_{2.5} > 0.45$) or plane off the bed ($\theta_{2.5} > 0.8$). **Figure 5** shows an example of ripple-scour mergers. Following the initial growth of the ripple field (t/T = 75), the offshore-most ripple (at x=15 cm) migrates onshore towards the growing scour pit at a rate of 0.6 cm/min until the ripple crest is within one-half of a wavelength from the edge of the scour pit (t/T = 120). At this point, the ripple stops migrating and the scour hole stops growing until a series of larger waves causes the ripple to merge with the scour ripple (t/T=200). These mergers occur at grain roughness Shields parameters ($\theta_{2.5}$) of more than 0.45 and cause fluctuations in the scour hole width. Bed planing events ($\theta_{2.5} > 0.8$) also lead to fluctuations in the scour width, but are accompanied by an increase in scour depth. These limited observations are the first full-scale observations of wave-induced ripple migration into a scour depression. The observations provide further support for the dependence of bedform evolution on the vortex dynamics and provide a valuable basis for the further study of bedform evolution in competitive environments.

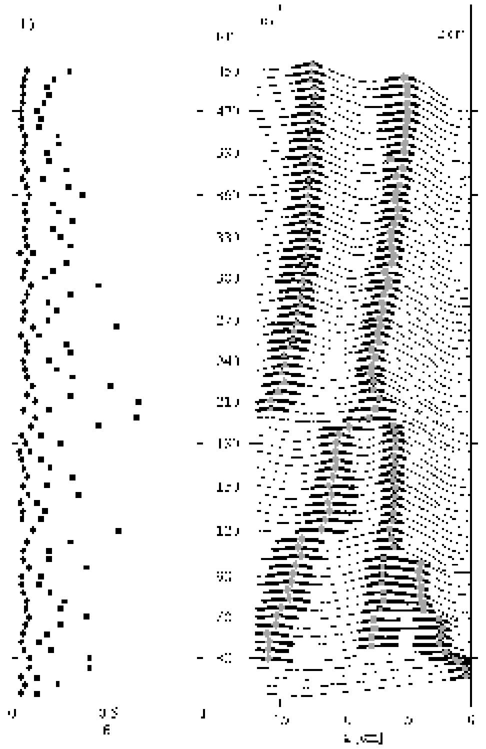

***Figure 5**. Bed profiles and forcing for irregular waves (H_{mo} =30 cm and T=4 s). The Shields parameter, θ, (* **u** *) and grain roughness Shields parameter, $\theta_{2.5}$, (**n**) for each consecutive, 24 s window. (c) Vertically offset timestacks of 24s averaged 2-D bed profiles (solid black lines). The scour ripple local maximum and first, second and third offshore local maxima are represented with ¢,**n**,**u**, and , respectively. The solid black dots show the locations where the elevation is within 10 pixels of an individual local maximum.*

We have simulated the response of the fine scale flow field and local morphology around submerged objects in both two- and three-dimensional environments. In the two-dimensional mode, the flow around fixed, scoured bed profiles is simulated and compared favorably with laboratory observations. These results show that the CFD model (FLOW-3D) well captures the complexities of flow very near the bed and around objects placed close to or on the seabed. **Figure 6** shows a simulation of wave-induced scour surrounding a horizontal pipeline. The simulations show that the vorticity structure evolves with the scouring bed (Smith and Foster, 2007). In the three-dimensional mode, the flow and scour of sediment beneath a cylindrical object lying on an initially flat bed is simulated and compared with laboratory observations that show excellent agreement in mean flow characteristics (Hatton et al, 2007). This work demonstrates the capabilities of the numerical model to accurately resolve fine scale flows near obstacles (vertically or horizontally oriented) impinging on bottom topography with arbitrary form and with unconsolidated sedimentary material.

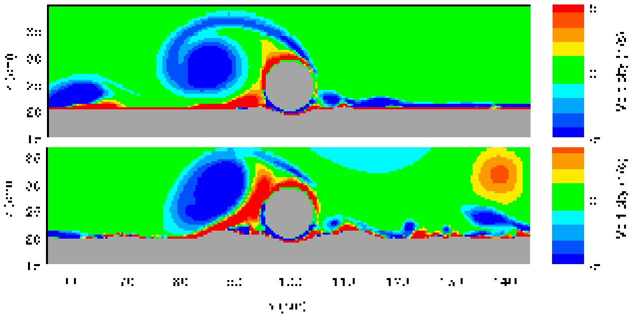

***Figure 6**. The vorticity surrounding a two-dimensional pipeline resting on a scouring seabed during the initial (top) and later (bottom) phase of scour hole development in wave environments. Both images are taken at the same flow phase as the flow is reversing from left to right.*

Numerical model results for combined wave-current flow about a vertical pile are in qualitative agreement with prototype laboratory observations, suggesting that the model is well reproducing the essential flow characteristics and sediment transport. In contrast, *in situ* acoustic observations of river topography at a bridge pier located on the Great Miami River (near Hamilton, OH), where wave motions are minimal and river flow is approximately unidirectional and steady, show a distinct region of deposition of sedimentary material just upstream of one of the pier pilings. This qualitative result suggests that deposition and scour around bridge piers in natural rivers can be significantly altered by the presence of large debris.

River and bank surveys of the Great Miami River at Hamilton, OH, were completed on August 9, 2006. The river survey was conducted with the Coastal Bathymetry Survey System (CBASS, described earlier), and the bank survey was conducted by walking with a backpack-mounted differential GPS receiver and antenna. The survey spans about 1.2 km along the river, and was done over 2.5 hours with about 60 cross-river transects spaced every 20 m. The river edge was surveyed by walking along and down the bank where accessible.

GPS-based bathymetry surveying is made difficult at the Hamilton site due to line of sight blockage of the GPS satellite constellation under and near the bridge. In past surveys this has resulted in sparse bathymetry data near the bridge because of positional uncertainties. Sonar data are collected for these areas, however, the lack of accurate positional data rendered the depths useless for producing accurate river topography.

To improve the survey in the areas near and under the bridge, a navigational method know as dead-reckoning was adapted from techniques developed over 500 hundred years ago by sailors to navigate open seas. Dead-reckoning is still used today. but now in combination with other navigational aids such as GPS and inertial systems. This method requires an initial known position and an assumed trajectory that does not vary in speed and direction. A simple form of dead-reckoning utilizes a measured velocity vector, then integrates the spatial positional components over a finite time scale to find the corresponding location associated with a particular time; in our case the time when the depth measurements were made.

In our methods, the initial and final positions of particular along river transects are known from the fixed GPS positions at times before the signal dropout under the bridge and the on the other (lea) side of the bridge when the signal is re-acquired. Velocity is maintained (and assumed) constant by the survey vehicle operator until a fixed position is established again. The vehicle is kept on a constant heading using visual landmarks by the operator to minimize spatial deviations from the assumed trajectory. An example of survey tracks used in our techniques is shown in **Figure 7**.

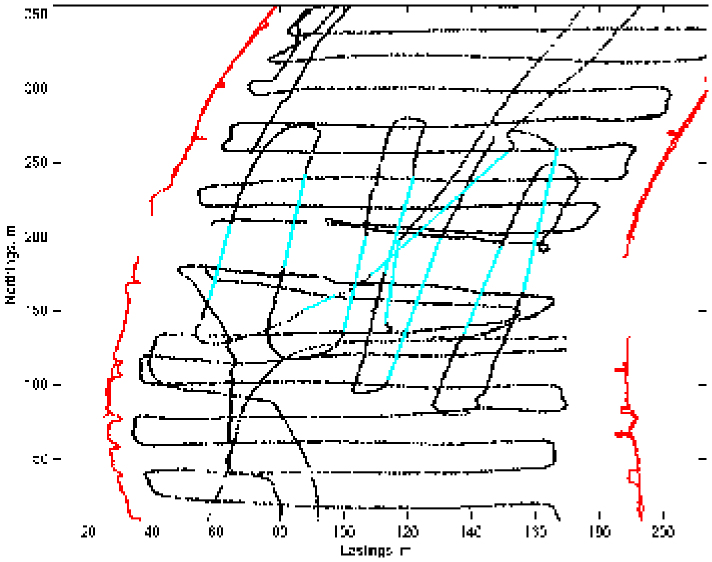

***Figure 7**. Close up plot of the survey tracks. Red tracks indicate walking survey, the black tracks indicate CBASS survey, and the cyan tracks indicate interpolated positions based on the dead-reckoning technique.*

The distance and heading between the last two known points, (x_0, y_0) and (x_1, y_1) respectively, can be easily calculated. The times of these two points are taken from the GPS record, and the times along this line are calculated based on the desired number of points and sampling frequency. The sonar record is then interpolated to these times and depths are extracted for the specified times. **Figure 8** shows a schematic of the simple dead-reckoning geometry used to interpolate intermediate points.

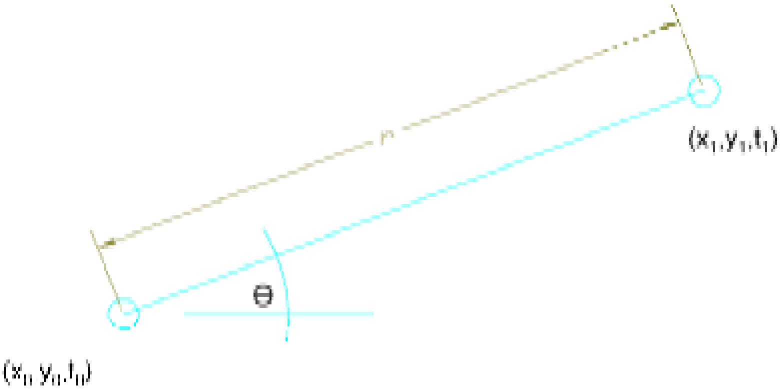

Figure 8. *Illustration showing two known points along with the heading and distance between them.*

This pseudo dead reckoning technique proved to work well. **Figure 9** shows the completed time series of water depths measured by the sonar from both the fixed GPS positional data (black dots) and the interpolated data (red dots) using the dead-reckoning approach. **Figure 10** then shows the completed bathymetric survey of the Great Miami River at Hamilton including the survey data obtained beneath the bridge with positions determined from the dead-reckoning approach. This technique, with our current equipment, is limited to areas that the water surface can be assumed flat because there is no way to determine fluctuations in water surface elevation (*i.e.*, waves). The incorporation of an inertial system may allow this technique to be effective in the presence of waves.

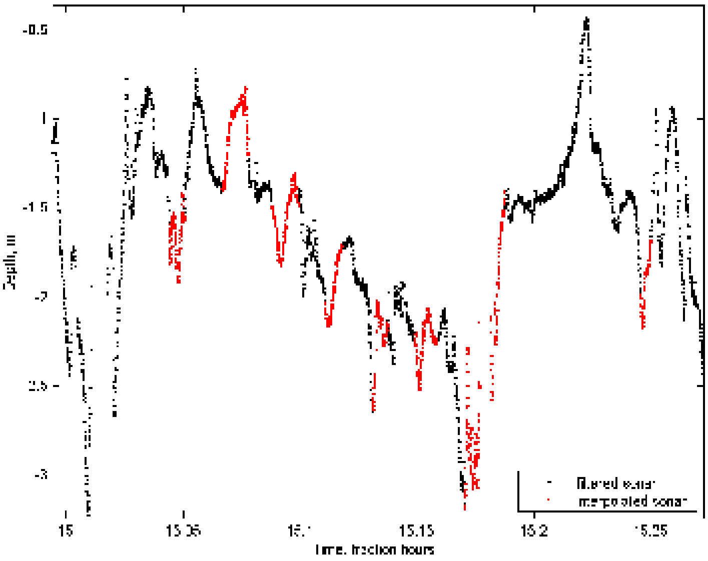

Figure 9. *Sonar data from CBASS. The black points are the data from the known x/y positions and the red points are the data extracted from the sonar record based on the interpolated spatial and temporal points.*

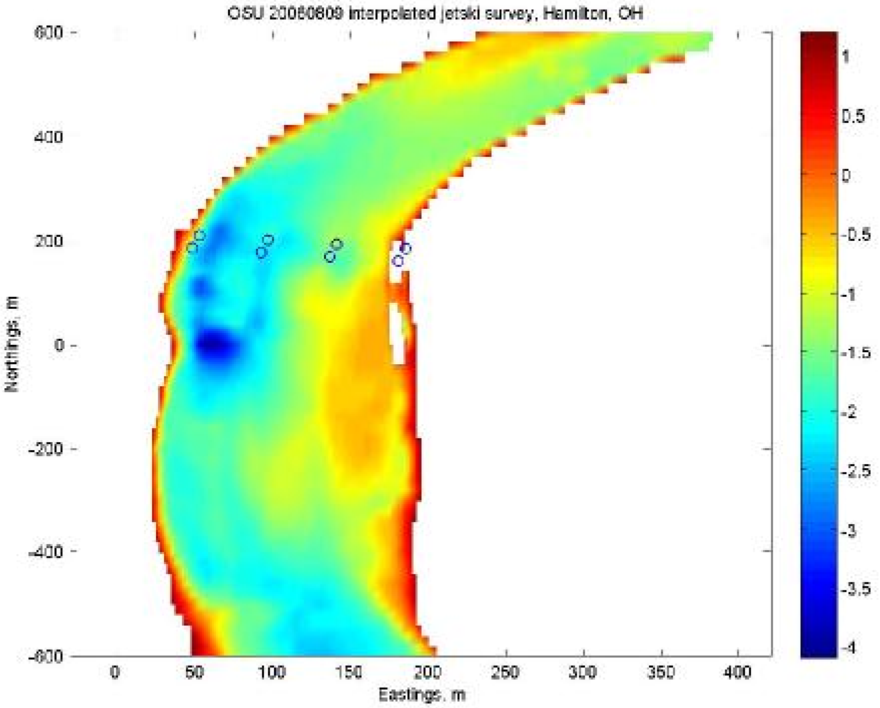

***Figure 10**. Interpolated river bathymetry including sonar data under the bridge from dead reckoning technique.*

Finally, mean surface velocity vectors of the river flow just upstream of the bridge at Hamilton have been initially estimated using Particle Image Velocimetry (PIV) techniques developed for oceanic applications. Continued development of the techniques for river applications is underway, and will be verified from manual tracking of obvious surface features in the flow (the manual methods being required owing to lack of *in situ* observations of the flows). These observations will be used to initialize the model and coupled with observations of the river bathymetry obtained with the CBASS survey system.

Significance

The coupling of detailed flow and bed elevation observations with a numerical fluid-sediment model will improve our understanding of the scour process. We also anticipate that engineers and river managers will use improved scour predictions to improve structural design, streamline mitigation procedures, and reduce response times to predicted high flow events by focusing resources to high scour regions. The results may also be used to select locations for future sampling sites, and to identify those sites where scour is expected to be problematic for future structural integrity. Our field and modeling methods represent new ways to monitor and evaluate bridge scour, and together these model-data results will highlight potential areas of concern.