

## **Report for 2004OH13B: The Scour and Deposition around River and Estuarine Bridges**

### Publications

- There are no reported publications resulting from this project.

### Report Follows

# **The Scour and Deposition around River and Estuarine Bridges**

## **Final Report**

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### **Abstract**

This report gives the results of a two-year effort directed at increasing our understanding of sediment scour and deposition surrounding bridge piers exposed to wave and mean flows. A combined numerical and observation effort resulted in new techniques for more accurately resolving the flow and bed evolution surrounding submerged objects. Results from this study may 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.

### **Introduction**

This investigation was 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 23,326 bridges over waterways in the state of Ohio, of which 5,273 are considered “scour susceptible” and 191 are considered “scour critical”.

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 most efficient manner.

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

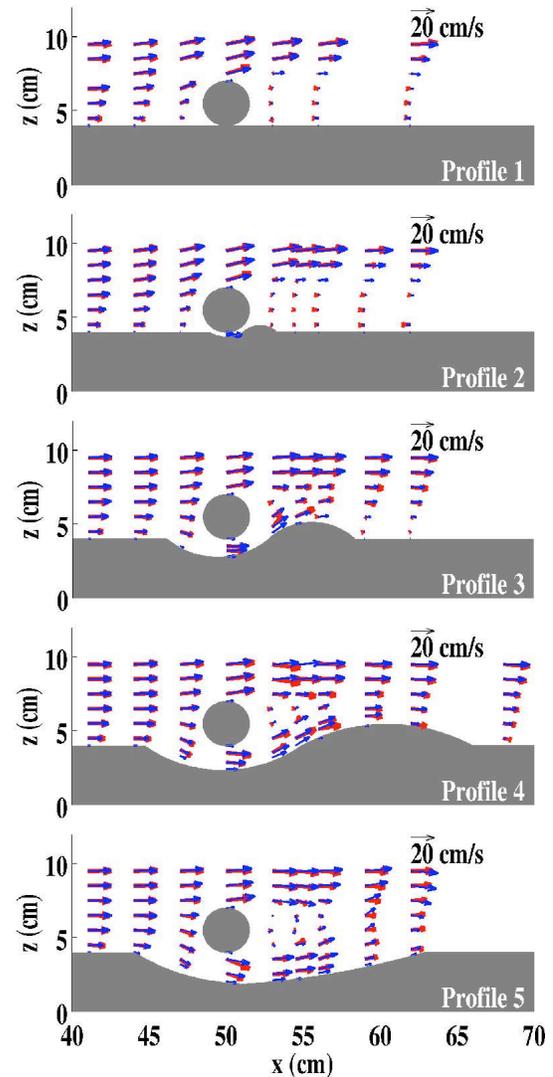
scour or deposition levels and to evaluate sediment transport models.

The objectives of this research were to increase our ability to predict how variations in flow conditions affect the scour and/or deposition of sediment around bridge piers. We have approached this objective through a combination of pilot field observations, detailed laboratory observations, and three-dimensional numerical simulations. This synergistic effort will ultimately allow results derived from small-scale numerical model and laboratory studies to field applications.

## Methodology

### Model

In this work, we simulate the flow and sediment transport field surrounding submerged objects in both wave and current dominated flows with FLOW-3D (Flow Science, Inc., Santa Fe, NM), a robust three-dimensional, non-hydrostatic computational fluid dynamics (CFD) numerical model that solves the nonlinear Navier Stokes equations (*e.g.*, Chopakatla, *et al.*, 2006). FLOW-3D incorporates one of several closure schemes, including large eddy simulations (LES) and  $k-\epsilon$  models, to resolve fine scale turbulence and dissipation throughout the domain. FLOW-3D uses a fixed rectangular grid (Eulerian approach), and overcomes the problem of incorporating geometry in a structured grid by using the trademark Fractional Area Volume Obstacle Representation method (FAVOR; FLOW-3D manual, 2002). The primary strength of FLOW-3D is its ability to accurately resolve three-dimensional flows in great detail, while tracking complex fluid behavior at flow-structure and flow-sediment interfaces, allowing coupled fluid-sediment equations to be incorporated. The sediment transport module of FLOW-3D is based on the bulk conservation of mass with an advection/diffusion scheme coupled with the interface tracking capabilities of the Volume-of-Fluid (VOF; Hirt and Nichols, 1981) scheme for bed level tracking. This method differs significantly from traditional sediment transport models as the grid is not fitted or regenerated to match morphology changes.



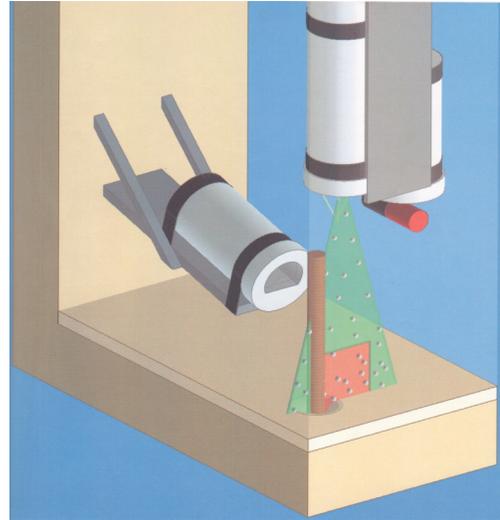
**Figure 1. Observed (blue) and simulated (red) velocity profiles around a two-dimensional pipeline over 5 bed static-bed profiles. The model resolves the recirculating region present on planar and near-planar beds (profiles 1 and 2) and vortex shedding present on present on scoured beds (profiles 4 and 5).**

### Laboratory

Laboratory observations of the wave-induced flow field, suspended sediment, and morphologic response surrounding a vertical pile were obtained at the collaborative 2005 CROSSTEX prototype laboratory experiment held at the O. H. Hinsdale Research Lab in Corvallis, OR. The laboratory facility is 104 m long, 3.7 m wide, and 5 m deep, and capable of generating prototype scale random wave fields with greater than 1 m wave heights impinging on a sloping beach with a single, subtle sand bar approximately 40 m from the shoreline. In our experiments, the evolution of the flow field and seabed offshore of a vertical pile was observed under both random and monochromatic waves in the shoaling region (seaward of the breakpoint) in approximately 1.5 m water depth. A 6 cm diameter pile was hydraulically jetted vertically into the bed composed of a mixture of quartz sand with median grain size diameter of 0.19 mm. An underwater Particle Image Velocimetry (PIV) system consisting of a 1 mega-pixel digital camera focused on a two-dimensional laser sheet oriented along the tank in the direction of the shoreward propagating wave field 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, as well as the bed geometry over a 1 m range in the  $x$ - $y$  plane. Figure 2 shows a sketch of the instrument deployment. Scour simulations were performed for offshore wave heights ranging from 20 to 40 cm with wave periods ranging from 4 to 6 sec for both regular and irregular waves.

### Field

The riverbed topography upstream, downstream, and right at one of the support piers of a bridge located on the Great Miami River (ODOT ID-BUT-128-0855) in Hamilton, OH, was observed under high flow using state-of-the-art acoustic survey instrumentation. The river bottom topography was measured with a bathymetric survey system consisting of a Yamaha GP1200 waverunner equipped with differential GPS receiver, dual-transducer sonic altimeter, and custom navigation



**Figure 2. A sketch of the CROSSTEX laboratory deployment. The red highlight box shows the location of PIV observations of velocity and scour. The location of the two-axis sonar is identified with the red and black cylinder in the mid-water column.**



**Figure 3. The waverunner survey system is capable of measuring water depths from approximately 0.4 m to 15 m.**

software (Figure 3). 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  $\pm 5-7$  cm in both the horizontal and vertical coordinates of the measured bathymetry.

The local deposition upstream of one of four bridge piers was measured with a rotating two-axis IMAGENEX profiling sonar attached to the upstream side of a bridge pier. The sonar resolved the two-dimensional centimeter-scale bathymetric variations over a 5-20 m radius. Figure 4 shows the IMAGENEX sonar system attached to the upstream side of the ellipsoidal pier for deployment on 30 November 2005.



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

## Results

### *Model*

The CFD model (FLOW-3D) was evaluated for two-geometries, (1) a short, horizontally oriented cylinder placed on and near the bed and exposed to both steady and oscillatory flow similar to environments with both surface waves and mean flows, and (2) a vertical pile embedded into the bottom and exposed to steady flow similar to that found in unidirectional river flow.

In the first numerical study, the short-cylinder simulations were run in a small domain approximately 1 m horizontally and 15 cm vertically with dense,  $O(cm)$ , grid cells. The simulations were repeated over differing seabed geometries that were fixed in time and space and thus not allowed to evolve (*i.e.*, no sediment transport was allowed). The mean flows averaged over about 1 min time period are compared with laboratory observations obtained by Testik, *et al.* (2005) over similarly sized cylinders and bed topographies that approximately matched the idealized geometries used in the simulations. Results show for the first time that the LES model is able to accurately reproduce the vortex shedding surrounding near bed structures (Smith and Foster, 2006). Results from this work were used in a recent follow-up study, in which the model was evaluated with field observations of submarine scour around a horizontally oriented cylinder placed in 15 m water depth on the continental shelf offshore of Martha's Vineyard in 2005. Results (non shown) indicate that FLOW-3D accurately predicts the scour and depositional regimes from an undisturbed flat bed (Hatton, *et al.*, 2006).

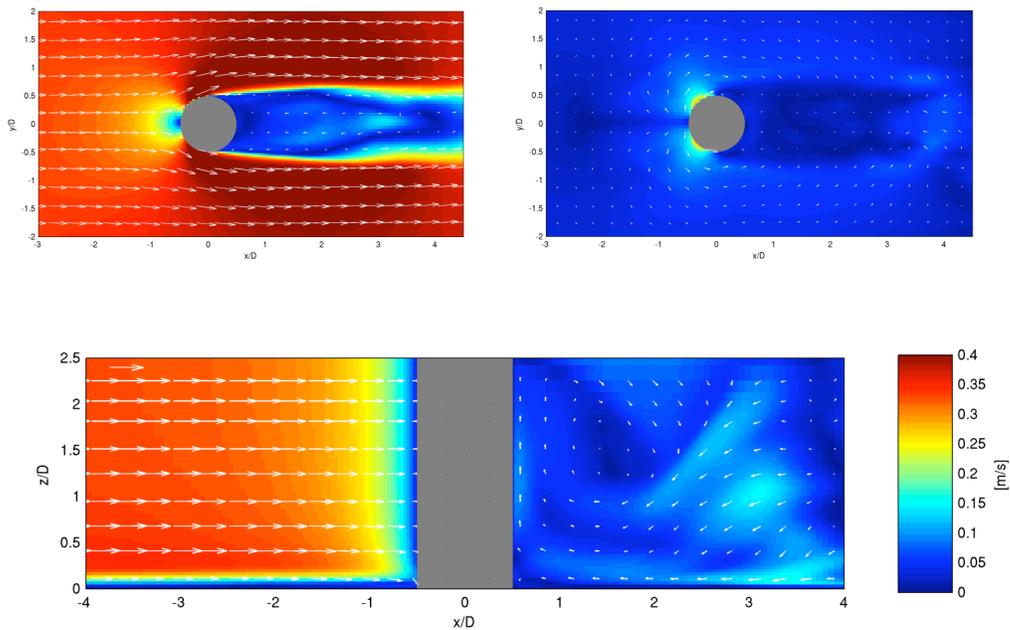
In the second numerical study, steady unidirectional flow surrounding a vertical pile of 56.3 cm diameter was simulated and compared qualitatively to laboratory observations. In this work, the three-dimensional flow field was computed over a domain with 11.5 m length (downstream direction), 5.9 m width (cross-stream direction), and 1.7 m height. The grid

dimensions varied with coarser cell volumes (cubes with 9.0 *cm* sides) at the edges (far field relative to the pile) and finer cell volumes (cubes with 1.8 *cm* sides) near the pile to better resolve the flow near the pile while speeding up the simulation run time without loss in resolution of flow structure. The flow was initiated at the upstream (inflow) boundary with steady mean currents of 32.6 *cm/s*. A continuous outflow boundary condition at the downstream end of the domain was specified that minimized wave reflections. The bottom boundary condition allows no flow through the bottom, and contains small roughness elements needed for numerical stability. The surface boundary condition was specified as rigid lid (no temporal variations in the sea surface elevation). Figure 5 shows both downward and sideward looking predictions of the velocity field. In this case, the water depth was twice that of the pile diameter. Upstream of the pile, the simulations show a region of high stress induced by the presence of a horseshoe vortex, visual in the figure by the velocity magnitudes larger than the undisturbed flow. The presence of the horseshoe vortex suggests a region where sediment will be removed and the potential for a scour hole to develop on the upstream side of the pile. On the other hand, downstream of the pile the mean flow field shows lower velocities than the undisturbed flow suggesting a region where sediment would be deposited. Interestingly, the simulations predict the presence of vortex shedding downstream of the pile, which should decrease the depositional regimes.

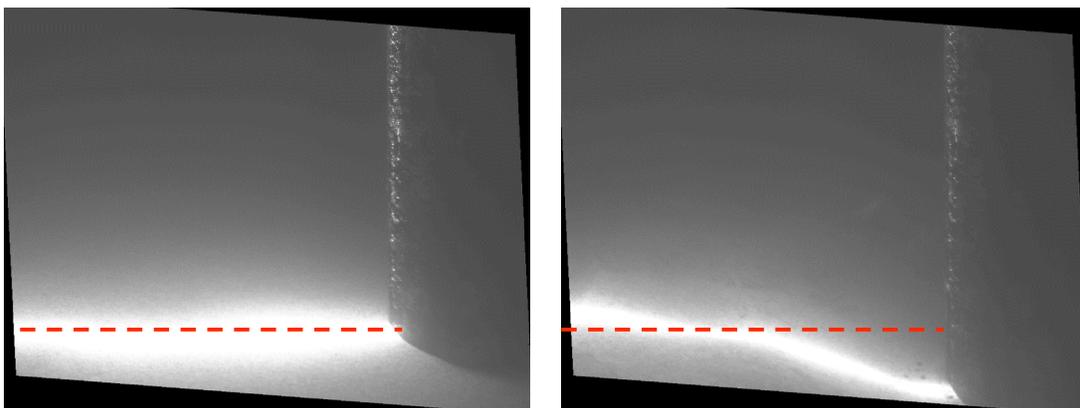
### *Laboratory*

The nature of the complex flow field modeled with FLOW-3D, characterized by an erosional regime on the upstream side of the pile and with potentially competing accretional and depositional regimes downstream of the pile, is qualitatively evaluated with laboratory observations obtained as part of the CROSSTEX experiment. The fluid forcing for the model was determined by the observed free stream flow during CROSSTEX, and thus shows the predicted bed changes that would arise from flow patterns initially over a featureless, flat bed with no scour hole or depositional wedge by the pile. Figure 6 shows two snapshots of the velocity field in the *x-z* plane over a 22 *cm* x 22 *cm* region just offshore (upstream) of the pile. The snapshots occur at the start and end of the 20 *min* experiment. At the beginning of the run, a stagnation point eddy was qualitatively observed at the sediment-pile interface (not shown in the figure). At the equilibrium bed state (which occurred at 26 *min* into the run), the bed has developed ripples and a 3 *cm* scour hole has developed around the upstream side of the pile. This bed change is qualitatively consistent with the predicted bed changes from the model simulations.

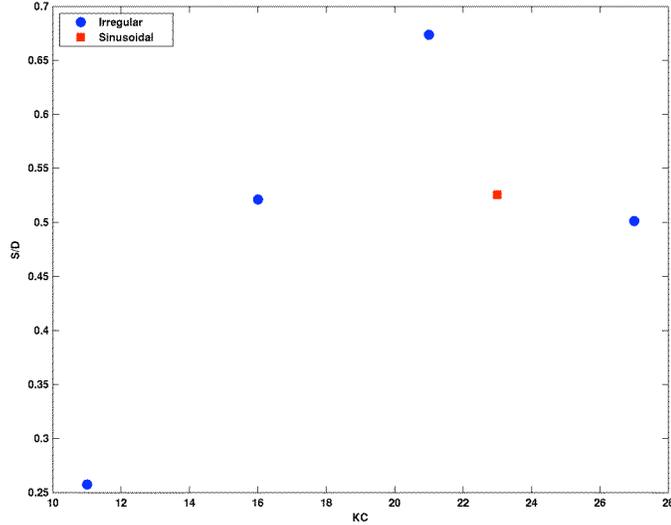
In ongoing research conducted by our graduate students, the modeled flow field will be quantitatively evaluated with the CROSSTEX observations in a similar manner as with the horizontal cylindrical experiments (Smith and Foster, 2005). Preliminary results (Figure 7) show that the scour depth, *S*, relative to the vertical pile diameter, *D*, is increases for increasing wave period (*T*) but is relatively insensitive to wave period or the narrowbandedness of the wave spectrum. The modeled sediment transport will also be evaluated with observations of suspended sediment and seabed elevations obtained by the two-axis variable frequency sonar co-located with the PIV system.



**Figure 5. (top panels) Mean of the modeled flow around a vertical pile, viewed from above, and taken at a depth of (right panel) one pile diameter and (left panel) at the bed. (bottom panel) Mean of the modeled flow around a vertical cylinder, viewed from the side at the centerline of the pile. The pile diameter,  $D$ , is 53.6 cm. The along-tank (horizontal axis) and cross-tank (vertical axis) dimensions are scaled by the pipe diameter,  $D$ . Flow is traveling from left to right in the figure, with a mean velocity of 32.6 cm/s. The gray shaded area represents the pile, while the color map indicates the velocity magnitude (cm/s). Vectors indicate velocity and are scaled by the single vector appearing in the upper left-hand corner of the image representing a 40 cm/s velocity.**



**Figure 6. The (right panel) initial and (left panel) final bed profile offshore of a vertical pile as measured with the PIV system during the CROSSTEX experiment. The bed elevation is indicated with the bright light reflected from the bed. The pile is indicated as the dark gray area on the right of each image. The red dashed line indicates the position of the initial bed elevation.**



**Figure 7. The final scour depth (non-dimensionalized by the pile diameter) versus the Keulagan-Carpenter number, where  $KC=UT/D$ .**

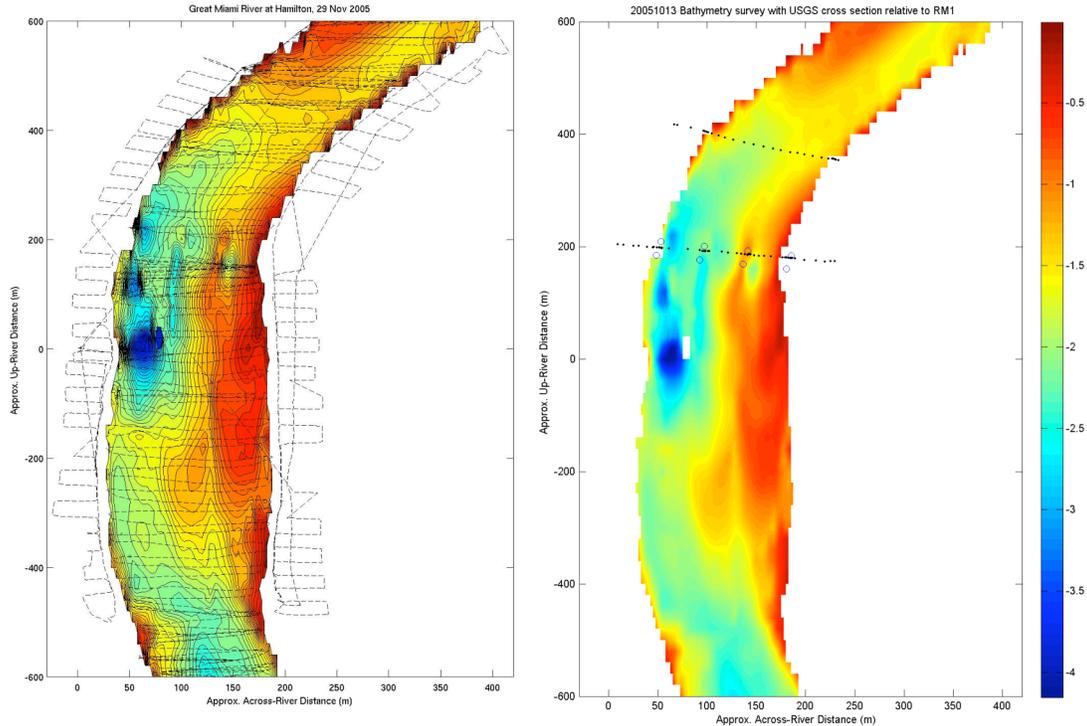
### *Field*

Figure 8 shows images of our waverunner survey of the Great Miami River at Hamilton obtained on 30 November 2005. Both figures show color contours of the bathymetry, with the left panel showing the survey tracks from the waverunner as well as a walking GPS survey of the river banks. The right figure shows the location of the pier piling edges (as circles) and the locations of cross-river transects where comparisons to a USGS 1999 survey can be done. The elevations of the river banks in the plots are omitted because the high elevation of the banks obscures the details of the subsurface river topography.

The horizontal ( $x, y$ ) coordinates are in meters relative to our established GPS base position. North is toward the top of each figure. The vertical elevations (given by the color contours defined by the scale on the right-hand-side of the figures) is also in meters relative to the mean waterline elevation observed by the waverunner averaged over the whole survey length. The elevations were transformed in this manner so that the approximate water depths are given. The actual coordinates before transformation are in the ITRF00 reference frame. Note that the cross-river and along-river scales are not the same, with the cross-river scales exaggerated by a factor of 2 for visual clarity.

The survey spans about 1.2 km along the river, and was done over 2.5 hrs with about 60 cross-river transects spaced every 20 m. We were also able to get close to the river's edge owing to the relatively steep banks. The bridge where the Imagenex sonar was deployed (see Figure 4) is located about  $y = 200$  m in the plot. There is a gap in the tracks where the bridge is located as we were only able to get within about 10 m or so of the bridge before the GPS satellites were blocked. The raw survey data were smoothed onto an evenly spaced grid and interpolated beneath the bridge; however, the accuracy of the water depths under the bridge is not known owing to potential largish changes right by the bridge pilings. Techniques are presently being developed that will allow for accurate surveys everywhere beneath the bridges (based on dead-reckoning navigation of along-river waverunner transects).

The river bed topography shows significant variability. For example, about 200 *m* downstream (south) of the bridge there are deep holes (up to 4.5 *m* depths) on the west side of the river, whereas on the east side there is a shallow bar that extends toward the middle as you move downstream. The cross-river gradient is about 1:20 at about  $y = 0$  *m*. There also appears to be a shallow bar on the western bank toward the northern end of the survey (about 400 *m* upstream of the bridge) and a general deepening of the river toward the south (about 600 *m* downstream of the bridge).



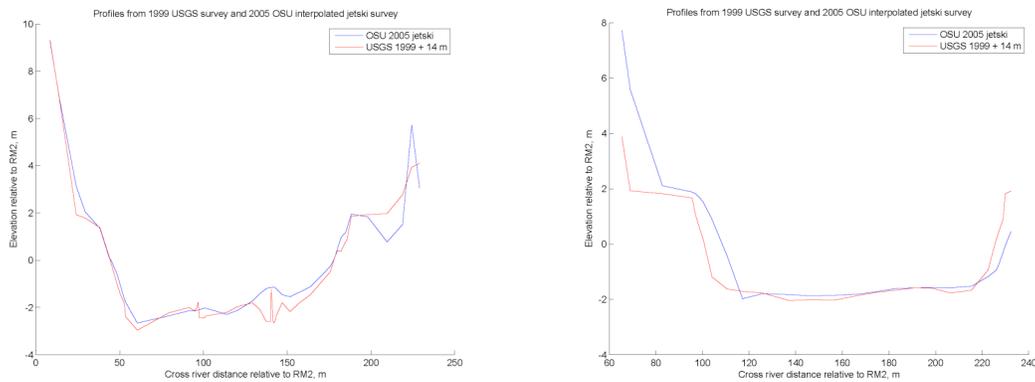
**Figure 8. Bathymetric survey of the Great Miami River in Hamilton, OH, conducted on 29 Nov 2005. The depths are shown in meters as color contours relative to the approximate mean water level at the bridge (located at about  $y = 200$  *m* in the figure). The horizontal coordinates are in meters relative to our GPS base position. The bridge pilings are shown as circles in the right-hand panel located an across-river distance of approximately  $x = 130$  *m*. The survey tracks are shown as dashed black lines in the left panel. The riverbanks exceeding 6-8 meters above water level were surveyed with differential GPS manually (*e.g.*, walking) but are omitted from the plot so that the river topography can be seen more clearly. The location of cross-river transects compared with USGS surveys (Figure 9) is shown in the right-hand panel.**

It would be expected that highly variable flow over the inhomogeneous river topography would result in significant changes in the river morphology over time, with inter annual variability approaching meter scale in some instances. Limited survey data exists to compare with our surveys, particularly of the dense grid scales obtained with our state-of-the-art survey system. Still, in 1999, two cross-river transects were conducted by the USGS. A comparison between these data and our 2005 survey is shown in Figure 9. Owing to uncertainties in the USGS vertical origin, the USGS data is offset 14 *m* vertically in the figures. Although there is some cross-river depth variation observed between 1999 and 2005, the general characteristics of the profile are retained. The general agreement in

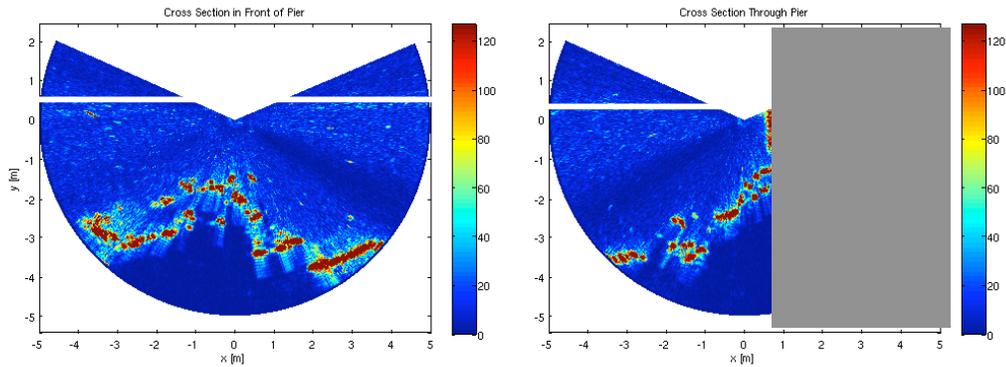
location of the river banks at the edge of each survey indicates that the vertical offset applied to the USGS data is reasonable, and that changes to the river bed topography have not been substantial. As no surveys were done downstream of the bridge, no comparison to the downstream profiles can be made with the 2005 survey. Plans to resurvey this section of river periodically are under way and a part of ongoing research efforts.

The river bed geometry just upstream of one of the pier pilings was observed with the Imagenex sonar system for about a 2 *hr* period on 30 November 2005. Figure 10 shows sample acoustic slices taken over a 5 *m* radius across the river (left panel) and along the river (right panel). In 4 *m* of water, the images show 1.5-2 *m* of deposition upstream of the pier, with maximum deposition right at the piling. Interestingly, these steady river flow observations with no apparent surface wave energy are in contrast to that observed by the steady flow numerical simulations and laboratory wave flume observations obtained under strong surface wave action. These results suggest that deposition and scour around bridge piles in riverine flow may be significantly altered by the presence of large debris (e.g. trees limbs) hitting the stagnation point on the upstream side of the pier.

In future studies, the numerical model geometries matching the observed field observations will be initialized with observed mean surface flow fields obtained with *in situ* and remote sensing systems deployed concurrently at the field site. This work is part of ongoing research.



**Figure 9. Comparison of 2005 across-river topography obtained by our GPS-based waverunner survey system with a 1999 survey conducted by the USGS. The locations of the transects are shown in Figure 7. Owing to uncertainties in the origin of the USGS survey, the coordinates for the USGS surveys were offset vertically 14 *m* to approximately match that of the waverunner surveys. After adjustment, little change in the river topography upstream of the bridge was observed in the 6 years between surveys. Note that no USGS surveys were done downstream of the bridge so no comparisons with our 2005 survey could be done.**



**Figure 10. The 5 m radius cross sections of local bathymetry obtained in front of and perpendicular to the pier (left) and upstream of and in line with the pier (right). The colors indicate backscatter intensity with hot colors showing the high return of the bottom and the cool colors showing the low return of the water column. The white bands indicate approximate position of the water surface. The gray rectangle indicates the approximate location of the bridge pier. These images show a 2 m high deposition present upstream of the bridge pier that is consistent with the waverunner surveys.**

### Significance

Thus far, 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 (Smith and Foster, 2005). 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. In addition to clear applications to pipelines and buried or unburied objects on the sea bed, this work sets the groundwork for looking at flows around vertical piles and bridge piers relevant to the present research. 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 (Smith and Foster, 2006). 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.

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.

Ongoing research efforts will utilize *in situ* acoustic observations of the river bed topography evolution, and surface remote sensing techniques to measure the surface flow fields, to initialize and verify the numerical model (verified with laboratory observations) to predict bed changes under a variety of flow conditions.

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## Publications resulting from this work

- Hatton, K.A., D. L. Foster, P. A. Traykovski, P.A., and H. D. Smith, 2006, Scour and Burial of Submerged Mines in Wave Conditions, *IEEE-Journal of Ocean Engineering*, in press.
- Smith, H. D., and D. L. Foster, D.L., 2005, Modeling the Flow around a Cylinder above Scoured Bed, *ASCE Journal of Waterway, Port, Coastal and Ocean Engineering*, 131(1), 14-24 (2005).

## Abstracts of Work Presented at National and International Meetings

- Hatton, K. A., and D. L. Foster, 2004, Scour and Burial of Submerged Mines in Wave Conditions, *Eos Trans. AGU*, 85(47), Ocean Sci. Meet. Suppl., Abstract OS21B-1222.
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