TIDAL SCOUR ANALYSIS - WILLIS AVENUE BRIDGE, NEW YORK CITY, NEW YORK

SERKAN MAHMUTOGLU

Earth Tech, 500 Southborough Drive
South Portland, Maine 04106, USA

RYAN M. EDISON, P.E.

Earth Tech, 500 Southborough Drive
South Portland, Maine 04106, USA

This paper discusses the analysis of navigational velocities, scour and recommended countermeasures at Willis Avenue Bridge in New York City. The bridge crosses the Harlem River and serves as one of the major commuter routes into Manhattan Island. Today, this historic, swing span bridge is being replaced. During the proposed construction of the new bridge, the navigational channel will see varying levels of obstruction that will increase the local current velocities through the piers. This increase in velocities poses potential problems for safe navigation and increased risk of bridge scour. To characterize the very complex tidal dynamics of the project site, a 2D hydrodynamic model was calibrated and verified, prior to analyzing both the maximum expected velocities through the piers and the depth of the associated bridge scour for various construction phases. The results were used to map navigational velocities, design a semi-permeable fender system, calculate scour depths, and to design temporary scour countermeasures.

1 Introduction

The Willis Avenue Bridge, opened in 1901, is located at the southern end of the Harlem River in New York, connecting Manhattan Island to the Bronx. It is a swing bridge that carries four lanes of one-way traffic with a daily load of 70,000 vehicles from Manhattan Island to the Bronx. Today, this historic bridge is being replaced with a similar type of structure to improve geometry for vehicle/pedestrian traffic, reduce accidents, increase loading capacity, and to eliminate the present structural and seismic issues.

The Willis Avenue Bridge is located in an area that experiences complex tidal dynamics; an area where the Hudson River, Atlantic Ocean, and Long Island Sound (LIS) all have a dynamic influence. During the proposed construction of the new bridge, the navigational channel will see varying levels of obstruction that will increase the local current velocities through the piers. This increase in velocities poses potential problems for safe navigation during construction and the increased risk of bridge scour.

This study was performed in order to analyze the navigational velocities, bridge scour, and design scour countermeasures. Three construction phases of the proposed new bridge (existing, interim, and final) were evaluated at a typical tide, the 10-, 100-, and 500-year storm events. Construction of a 2D, numerical hydrodynamic model, which was calibrated and verified with Acoustic Doppler Current Profiler (ADCP) and tidal gage monitoring data, provided the tidal velocities that were used to map navigational velocities, design a semi-permeable fender system, calculate scour depths, and to design temporary scour countermeasures.

1.1 Project Location

The Willis Avenue Bridge crosses the Harlem River just north of the Bronx Kill and the Triborough Bridge, near Randall's Island. The Harlem River flows between the Hudson River to the north and the East River to the south. The Hudson River flows to the Upper Bay of the New York Harbor, south of Manhattan Island, at which point the East River connects the Upper Bay with the LIS (Figure 1).

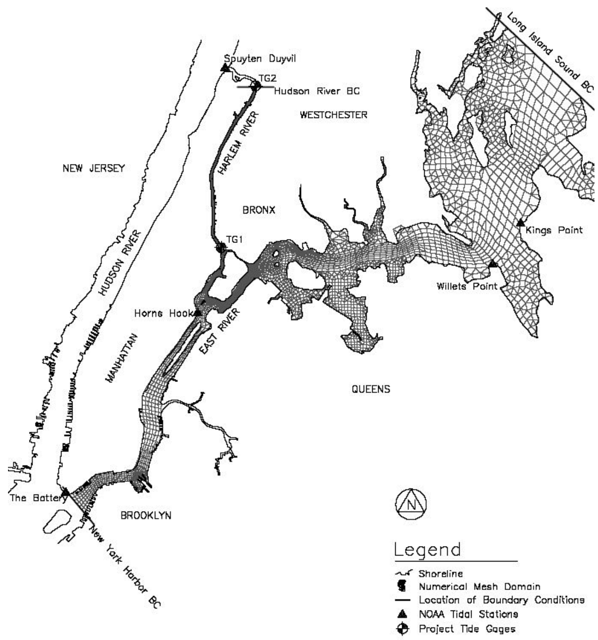

Figure 1. Location Map

1.2 Project Background

The existing Willis Avenue Bridge is being replaced with a proposed off-line swing bridge shifted slightly to the southeast of the existing bridge. This results in a shifting of the current navigational channel further to the east. It is estimated that the proposed replacement of the bridge will occur over a 28-month period and involve eight navigational stages of construction.

The bridge is located in a tidally dominated area that is known to have a strong circulation pattern and a complex semi-diurnal tidal response due to the out-of-phase responses of the Atlantic Ocean and the LIS. In a 1999 NOAA report the Mean Flood Current (MFC) and the Mean Ebb Current (MEC) at Hells Gate, located on the East River, were predicted to be 5.50 and 7.65 feet per second (fps), respectively.

The June 1997 Bridge Reconstruction Project Report (BRPR), concluded that "the existing Willis Avenue Bridge is low risk with regard to scour and [that] the Harlem River in the vicinity of the bridge is vertically and laterally stable." The BRPR indicated that the existing bridge has no past or present history of scour problems. However, it was noted that design engineers at the Third Avenue Bridge reconstruction (e.g., located directly north of the Willis Avenue Bridge) did observe a 3.9 feet scour hole at the Manhattan side rest pier.

2 Methods of Study

2.1 Data Gathering

Prior to modeling, data and information was collected from a variety of sources. Geographic data sources included nautical charts, site plans, aerial photos, shoreline vectors and hydrographic/topographic surveys. Tidal records were obtained from NOAA tidal stations (Willets Point, Kings Point, The Battery, Horns Hook and Spuyten Duyvil). Upon review of the data, additional water surface elevation and velocity information were needed at the vicinity of the bridge for model calibration and verification. A data survey consisting of water surface elevation monitoring (6 min. interval), ADCP transects (upstream, downstream and at the bridge) and in-situ ADCP (bottom mounted upward looking at 6 min. interval) was performed May 14-16, 2003 (Figure 1).

2.2 Hydrodynamic Modeling

In order to determine the site-specific hydrodynamics at the Willis Avenue Bridge a numerical model was developed. Due to the 2-dimensional nature of the tidal flow in this area, which was verified with the ADCP survey data, RMA-2 V4.35 was chosen as the hydrodynamic engine. The Surface Water Modeling System (SMS) version 8.0 was used as a pre- and post processor to RMA-2.

2.2.1 Numerical Mesh Generation

The numerical mesh was developed based upon vectorized NOAA shoreline files and USGS ortho images. Both the mesh density and the level of shoreline detail increased with proximity to the Willis Avenue Bridge (Figure 1). The approximate number of elements in the model ranges from 5,700 to 8,000 depending on the modeled bridge construction phase and configuration.

2.2.2 Boundary Conditions

Based upon a review of the literature, it was determined that the Harlem River was a “tidally dominated” (i.e., Willets Point) to “mostly tidal” (i.e., The Battery and Hell’s Gate) area. This allowed forcing of water surface elevations at each of the three boundary locations: Hudson River - Spuyten Duyvil NOAA tidal station (No. 8518903) and TG 2, New York Harbor - The Battery NOAA tide station (No. 8518750), and LIS - The Kings Point and Willets Point NOAA tide stations (Nos. 8516945 and 8516990 respectively).

2.2.3 Calibration and Verification

The RMA-2 model is calibrated with two parameters: the Peclet Number (Pe) and the Manning Roughness Coefficient (n). The point in-situ ADCP and the project’s Tide Gage No. 1 (TG 1) were used to compare the actual data with the model results (Figure 1). In order to determine a “best-fit” to the measured data, 25 runs were set-up with varying Pe and n values. Using Peclet Number of 20 and a Manning’s Roughness Coefficient of 0.02 resulted in Root Mean Square (RMS) error values, between the measured and predicted values, of 0.14 and 0.17 for velocities and water surface elevations, respectively (Figure 2). Verification of the model was performed by comparison of the results with the ADCP transect data at the maximum ebb conditions, and comparison of the water surface elevation at the Horns Hook NOAA tidal station for the typical tide conditions. The results of the verification indicated that no further calibration was required.

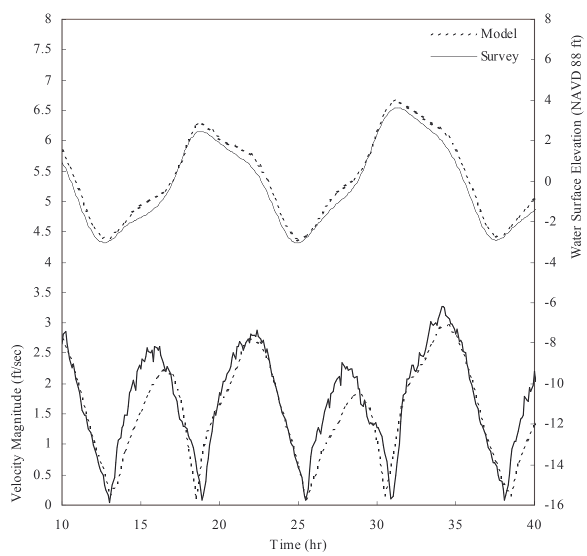

Figure 2. Survey versus Model Water Surface Elevation and Velocity Magnitude Results

2.2.4 Hydraulic Events Modeled

Once the model was calibrated and verified, four flow scenarios were developed: a typical tide; the 10-, 100-, and 500-year storms.

The typical tide was defined as the tidal condition at, or near, the project site that followed the NOAA established tidal datums (MHHW, MHLW, MLHW and MLLW). The tide was selected by analyzing the closest NOAA station to the bridge, which was Horns Hook (Figure 1).

Upon establishment of the typical tide, design storms were developed using ADCIRC hurricane data summarized in the Pool Funded Study that was coordinated by the SCDOT. From this study, using ADCIRC station (No. 368) located in LIS, peak storm surge values (Sp) of 2.78 and 4.43 meters were obtained for the 100- and 500-year events respectively. The shape of the synthetic storm surge hydrograph was developed from the normalization of ADCIRC hurricane data as presented in the Pool Funded Study. The recommended half storm duration of 2 hours was used. Because the 10-year storm was not included in the Pool Funded Study, the 10-year water surface elevation of 10.1 feet (NGVD 29 datum) was taken from the USACE "Tidal Flood Profiles" at Willets Point. Using Microsoft Excel's spreadsheet solver, a corresponding Sp value of 1.91 meters was determined.

These hurricane hydrographs were then combined with the typical tide at LIS. The timing of the storm with the typical tide was determined by using Microsoft Excel's spreadsheet solver to maximize the water surface elevation at LIS, as the higher velocities at Willis Avenue tend to follow the LIS tide closely.

2.3 Scour Analysis and Countermeasure Design

The scour analysis and countermeasure recommendations were done in accordance with the guidelines set forth in the most current editions of the Federal Highway Administration's HEC-20 (Stream Stability at Highway Structures), HEC-18 (Evaluating Scour at Bridges), and HEC-23 (Bridge Scour and Stream Instability Countermeasures). The calculations for contraction and local scour were performed with spreadsheets, and required hydraulic parameters were extracted from the RMA-2 model.

Soil grain size diameters (e.g., D_{50}) were determined from a sieve analysis. These sieve analyzes were taken from five borings located along the alignment of the proposed bridge.

The Modified Laursen's equation was used in its clear-water formulation for calculating the contraction scour, the Froelich's equation for local abutment scour, and the CSU equation for the local pier scour. The correction factor for wide piers in shallow flow conditions was applied as needed based upon the criteria outlined in HEC-18.

It was initially conservatively assumed that the solid piers and fender systems were, allowing zero flow through the fender system. While this is true for the existing conditions, it was later determined that a 30 percent open area would better represent the proposed semi-permeable pier and fender system.

Upon review of the proposed fender system, it was determined by both Earth Tech and Hardesty & Hanover that the fender width should be used in the local pier scour equations. While this decision results in conservative scour depths, it was determined to be warranted given: 1) the close proximity of the fender to some of the bridge supporting piles, 2) the lack of research for wide piers and fender systems, and 3) high traffic volumes and functional importance of the Willis Avenue Bridge.

3 Results

3.1 Hydraulics

During the monitoring period, the maximum tidal range recorded at the Willis Avenue Bridge (TG 1) was 6.77 feet and current magnitudes as high as 3.78 fps were recorded during the ebb tide. Also, the influence of the Triborough Bridge's pier alignment was noticed by the presence of an eddy during ebb tide. This eddy zone, which was also confirmed by the model, reduces the channels conveyance capacity during ebb tide. A jetty on the Bronx side and a 90-degree seawall bend located just north of the bridge further limits the bridge's conveyance capacity.

It was found that the Interim and Final conditions have higher velocities than the existing bridge. This is caused by a 11.5 feet increase in the new center pivot pier, and the shifting of this pier towards the Bronx side of the channel, which encroaches on the main conveyance channel. The Interim bridge conditions saw the largest velocities due to the widest effective bridge footprint. By using semi-permeable fenders, additional runs showed a reduced channel velocities for the Interim and Final conditions (Figure 3).

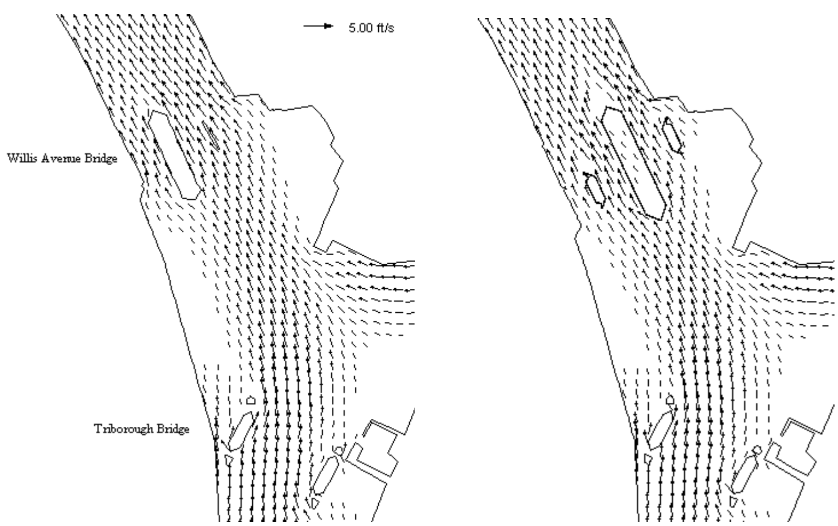

Figure 3. Existing (left) and Final (right) Conditions Depth averaged Velocities at Maximum Ebb of Typical Tide Event

3.2 Scour

Upon review of the site's recent bathymetric survey an existing scour hole of 4.9 feet deep was noted on the southeastern side of the center pivot pier. This coincides well with the predicted local scour depths at the existing center pivot pier for the typical tide conditions of 5.9 feet. This configuration of a scour hole on the ebb side and the local aggradation at the northern tip, indicates the site's dominant ebb tide.

For both the Existing and Final bridge conditions, the predicted scour hole bottom elevations are above the bridge footing bottom elevations or pile tip elevations. However, if no scour countermeasures are installed during the Interim conditions, the foundations of the existing center pivot pier and the existing east rest pier would be undermined during the 500-year event.

The increased predicted scour depths from the Existing to the Final bridge conditions are a result of a wider bridge substructure unit in the Final design. As such, the final bridge is exposed to larger angles of attack and increased channel velocities. For example, the predicted total scour increased by approximately 30 percent for the 10-year storm. However, by using a semi-permeable fender system in the Final conditions, the scour depths are predicted to decrease by approximately 14 percent from the original proposed Final Conditions. With the improvements made to the Interim and Final Conditions, the 10-year contraction scour is reduced by 6.5 feet for the Interim Conditions, and by 4.3 feet for the Final Conditions.

3.3 Countermeasures

During the various construction phases of the bridge replacement, predicted scour depths may exceed the embedment depths of temporary bulkheads, foundations of the existing bridge, sheet piling, etc. Because of this finding, it was recommended that either all structures be designed to account for the predicted scour depths, or that standard riprap be placed around these structures as a temporary countermeasure during construction.

Riprap was sized based upon HEC-18 (Third Edition) guidelines for abutments and piers, equations 8.1 and 8.3. The riprap D_{50} is 1.0 ft. In addition to any riprap, it is also recommended that diving inspection be performed after a 10-year (or greater) storm, that routine diving inspections are continued once the proposed replacement bridge is finished, and any ice and debris build up be removed.

4 Discussion

The average flow velocities through the bridge for the typical tidal conditions were estimated as: 1) Existing Conditions – 2.1 fps, 2) Interim (w/ semi-permeable fender) Conditions – 2.5 fps, and 3) Final (w/ semi-permeable fender) Conditions – 2.2 fps. In general, channel velocities at the Final Willis Avenue Bridge will be larger than the Existing conditions due to the Final bridge's wider center pivot pier and the shifting of the bridge's substructure unit further out into the main conveyance channel. However, the improvements made by the new fender system design serve to decrease the channel velocities, making the average channel velocities similar to those observed at the existing Willis Avenue Bridge, thus decreasing the scour depth. Average channel velocities through the Existing Willis Avenue Bridge during typical tidal conditions are approximately 30 percent lower than at the Third Avenue and Madison Avenue Bridges.

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