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Modeling and Monitoring Scour during Bridge Replacement with Multi-dimensional Modeling and Repeated Multi-beam Surveys at the Tanana River near Tok, Alaska

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ABSTRACT

The Alaska Highway near Tok, Alaska crosses the Tanana River via a 288 m truss bridge constructed in 1944. Due to age, damage from a 2002 earthquake, and extensive pier scour, the bridge is being replaced in 2009-2010. Since it was originally constructed, the angle of approaching flow to the bridge has changed and currently approaches the right-bank pier at 45 degrees creating a large scour hole around the pier. The new bridge is being constructed 75 meters downstream of the existing bridge and a temporary construction causeway was built in 2009 upstream of the new bridge alignment. The effect of the causeway on the channel hydraulics at the existing bridge are of concern to ADOT&PF. Several potential causeway geometries and their corresponding affect on the angle of flow approaching the existing bridge pier were simulated with a multi-dimensional model. Modeled flow angles, depths, and velocities immediately upstream of the pier did not vary significantly between the modeled scenarios, but a monitoring schedule was put in place to insure the safety of the structure until the new bridge is completed. Four multi-beam surveys completed during the summer of 2009 documented the dynamic nature of the streambed. The largest scour depths were consistently at the nose and along the right-bank side of the caisson where the flow was attacking the pier. Model results and repeated high accuracy surveys allow the state to continue operation of the bridge and avoid installing scour countermeasures until construction of the new bridge is completed.

INTRODUCTION

The Alaska Highway, which is Alaska's main land arterial with Canada and the contiguous United States, crosses the Tanana River near Tok, Alaska, via a bridge that is nearly 60 years old. Age, a narrow bridge deck, damage from an earthquake, and observed streambed scour at the bridge have led to the Alaska Department of Transportation and Public Facilities' (ADOT&PF) decision to replace the structure. The new bridge is being constructed 75 m downstream of the existing structure.

The Tanana River near Tok drains an approximately 17,600 km² glaciated basin north of the Alaska Range. At and near the study reach, the river is extensively braided and carries a high suspended-sediment load. The riverbed is composed of silt and sand, and dune movement has been observed over a range of stages. The riverbanks are

composed of unconsolidated silt and sand, with the exception of the right bank that is composed of granitic bedrock from the existing bridge to the downstream extent of the study reach. Overbank vegetation is predominately dense spruce and willow. The existing bridge is located where the river enters a natural constriction that is controlled by the bedrock along the right bank. As the river approaches the bridge on the right bank, it is directed by the bedrock at an angle to the long axis of the pier. This flow angle of attack on the pier has been observed to be approximately 40 to 45 degrees at a streamflow of $725 \text{ m}^3/\text{s}$. The high angle of attack on the pier and position of the bridge at the head of a natural constriction, where flow velocities and sediment transport capacity are the highest, make this structure particularly susceptible to streambed scour.

The existing bridge, ADOT&PF bridge number 505, is located at mile marker 80.5 of the Alaska Highway. It is 288 m long, 7 m wide, and was constructed in 1944. Two sloping sharp-nosed piers that are surrounded by sheet pile caissons support the bridge. The piers are 2.4 m wide and 15.8 m long. The caisson surrounding the piers is 7 m wide, 20 m long and extends above the water surface at medium flows. The new bridge is being constructed from temporary earthen and pile supported causeways (Figure 1). The causeways were constructed in September 2009 and are scheduled to be removed by April 2010 before the spring breakup. The left causeway extends approximately 30 m from the left bank and is connected to an approximately 110 m long center causeway located on a natural bar that is exposed during low flows. Cylindrical piles support two bridge decks, one connecting the two causeways and another extending from the center causeway into the channel toward the right bank.

FIGURE 1: Upstream view of the two causeways and bridge 505 near Tok Alaska. Photographed on October 9, 2009 at a streamflow of $112 \text{ m}^3/\text{s}$.

The U.S. Geological Survey (USGS) collected continuous daily streamflow information at the bridge (gaging station No. 15472000) from 1950 to 1953 (U.S. Geological Survey, 1951-1954). The mean annual streamflow of the Tanana River near Tok Junction during that period of data collection was $197 \text{ m}^3/\text{s}$. During late May or early June, a period of high flow associated with snowmelt runoff begins. High flow persists typically through July and August reflecting glacial melt and periods of rainfall. High flows also result from intense rainfall in the late summer and low flows precede freeze up in late October to early November. Annual peak flows from 1950 to 1953 were 889, 889, 796, and $988 \text{ m}^3/\text{s}$, respectively. The slope of the river through the bridge is 0.0002 m/m . The USGS surveyed water depths and velocities in August 2002 to develop and calibrate a multi-dimensional flow model for simulating high-flow water-surface elevations and velocities (Conaway and Moran, 2004).

Annual channel cross sections have been surveyed at the bridge since 2002 and scour depths at the right bank pier have extended to the base of the caisson. The susceptibility of this pier to scour prompted an analysis using a multi-dimensional flow model to simulate the potential backwater effects of the caissons 75 m downstream of the bridge. In addition to the modeling effort a monthly channel surveying schedule was established to track channel changes around the scour-critical pier during construction. Scour monitoring was chosen instead of installing scour countermeasures for a bridge that is scheduled for replacement.

SURFACE WATER MODELING

The USGS Multi-Dimensional Surface Water Modeling System (MD_SWMS) (McDonald and others, 2005) was used to simulate the initial conditions and the potential causeway geometries to determine the effects on velocity and depth at bridge 505. MD_SWMS is a generic interface developed by the USGS for hydrodynamic models. FaSTMECH, one of the computational models within MD_SWMS (Nelson and McDonald, 1997), is a 2-dimensional, vertically-averaged, steady state model that was selected for this study. The initial conditions scenario was created with bathymetry data collected in 2002 (Conaway and Moran, 2004) and updated with bathymetry collected in 2009 at the bridge. The model was calibrated with water-surface elevations, flow velocities, and flow directions collected at a streamflow of $725 \text{ m}^3/\text{s}$ when the 2002 bathymetry was collected (Conaway and Moran, 2004). A second scenario was modeled with the bathymetry from the initial conditions and was modified to reflect the elevation and extents of the two causeways.

Four streamflows; $300 \text{ m}^3/\text{s}$, $425 \text{ m}^3/\text{s}$, $566 \text{ m}^3/\text{s}$, and $866 \text{ m}^3/\text{s}$ (2-year recurrence interval flow) were simulated with each model. These flows represent the range of streamflows that could be expected during the life span of the project. At $300 \text{ m}^3/\text{s}$, the river is divided into two channels through the bridge reach and the only effect of the causeways is the constriction of flow between them along the left bank. At $425 \text{ m}^3/\text{s}$, the right bank portion of the channel becomes constricted by the causeway and simulated

velocities are increased in that area. The effects of the channel constrictions become more pronounced at $566 \text{ m}^3/\text{s}$. Velocities on the downstream side of the left bank pier are reduced in the causeway simulations because more flow is diverted to the right bank portion of the channel by the center causeway. The causeways are completely overtopped at $866 \text{ m}^3/\text{s}$. The likelihood of this streamflow occurring during the lifespan of the causeways is extremely low because high flows have historically occurred only in July and August.

To evaluate potential impacts at the right bank pier of the existing bridge the predicted depth, velocity, and Froude number were extracted from both models along a cross section immediately upstream of the pier. The results were similar for all simulations except at the highest streamflow. The predicted depths were up to 0.4 m higher to the left and the right of the pier for the causeway scenario (Figure 2). Velocities and Froude numbers were not however significantly different. The increased depths are the result of more flow being distributed to this portion of the channel as a result of the center causeway.

The modeling results from the two scenarios do not indicate that the causeways will have an impact on conditions that cause scour at the right bank pier. Predicted flow depths were greater for the causeway scenario at the highest streamflow, but not immediately upstream of the pier, only to the left and right of the pier. Pier scour was computed for both scenarios using the CSU pier scour equation with the bed armoring coefficient (Richardson and Davis, 2001) (Table 1). The scour computations were made using the geometry of the caisson because only a small portion of the pier stem is in the water column. The angle of attack for the approaching flow, 45 degrees, was the same for both scenarios. Predicted scour only increased by 0.1 m for the causeway scenario.

TABLE 1: Computed pier scour from modeled values for the initial conditions and causeway scenario.

	Initial Conditions	Causeway
Froude number	0.19	0.20
Angle of Attack	45	45
Pier Shape	Round	Round
Pier Width (m)	7.01	7.01
Pier Length (m)	19.81	19.81
Depth (m)	6.07	6.08
Velocity (m/s)	0.98	1.01
D50 (mm)	9.10	9.10
D95 (mm)	41	41
Bed Armoring (k4)	0.4	0.4
Computed Pier Scour	5.49	5.61

Figure 2: Model results from both the initial and causeway scenarios for a cross section immediately upstream of the right-bank pier.

STREAMBED SCOUR MONITORING

An analysis of streambed scour potential by Heinrichs and others (2001) estimated 8.5 m of pier scour for the 100-year recurrence interval streamflow. Cross sections along the upstream side of the bridge and profiles along the right bank pier have been surveyed annually since 2002 (Figure 3). Several of these surveys indicated that the bed elevations at the right bank pier were below the bottom of the caisson. The seasonality of streamflow and sediment load result in a seasonal pattern of streambed scour and fill where bed elevations rise during fall and winter and then decrease during the spring and summer. This pattern was described by Conaway (2006, 2007) in an analysis of continuous streambed elevation datasets from other glacially-fed rivers in Alaska.

Streambed elevations around the right-bank caisson were mapped four times in 2009 over a range of streamflows (6/2/09, 240 m³/s; 7/1/09, 362 m³/s; 8/5/09, 736 m³/s; 10/7/09, 112 m³/s) to monitor bed elevations. Bathymetry data were collected using a 1200 kHz acoustic Doppler current profiler (ADCP) interfaced with a differentially

Figure 3: Surveyed cross sections along the upstream side of bridge 505.

corrected GPS. The ADCP uses four transducers oriented 20 degrees from vertical to emit acoustic pulses that are scattered and reflected from particles in the water column back to the transducers. Frequency differences between the transmitted and received pulse are combined with boat speed information to resolve a 3-dimensional water velocity. The ADCP uses reflections from the stream bottom to determine boat speed and flow depth for each beam. A position was calculated for the individual beam depths using AdMap (Mueller, 2007). AdMap was also used to interpolate positioning from the ADCP bottom track data under the bridge where GPS data were invalid. These techniques allow the ADCP to be used as a multibeam sonar with a sampling rate of approximately 1 Hz.

The bathymetry data from each survey were interpolated to a continuous grid around the caisson using kriging. Vertical changes in bed elevation between surveys were quantified using surface differencing (Figure 4). The elevations from the June survey were subtracted from those of the July survey. Positive values indicate fill and negative values indicate scour. For each new survey the previous surface was subtracted to document bed elevation changes through the summer. Scour was evident along the right-bank side of the caisson nose in June. This portion of the caisson is exposed to the highest velocities. The downstream left-bank side is on the lee side of the primary flow and was the highest elevation in June. In July, the scour hole at the nose of the caisson expanded

to the left-bank side of the nose and down the length of the caisson's right-bank side. Scour at the nose was slightly greater in August when the bed elevation on the left-bank side of the pier nose was 0.8 m above the bottom of the caisson and the maximum flow depth was 14 m. The downstream left-bank side of the caisson scoured 2 m between the July and August measurements. Fill was measured around the entire pier in the October survey. Over 7 m of infilling occurred at the left-bank side of the caisson's nose between the August and October surveys. Elevations measured in October likely represent the full extent of fill because of the rapid decrease in both streamflow and sediment load in the fall. Bed elevations in October were compared to those surveyed in June and were higher in all areas except the downstream left-bank side of the caisson where the bed was 2 m lower than in June (Figure 4).

Figure 4: Plots of elevation change determined from surface differencing between surveys. Values were determined by subtracting the streambed elevations from the older survey from those of the newer. Warm colors indicate scour and cool colors indicate fill.

CONCLUSIONS

A multi-dimensional surface water model was used to evaluate the affects of two causeways in the Tanana River on streamflow hydraulics at bridge 505. This bridge is slated for replacement in 2010 because of age and streambed scour at a caisson that surrounds one of its piers. Results from four streamflow simulations did not indicate that streamflow hydraulics would be affected by the causeways located just 75 m downstream. Estimated pier scour computed from the results of the initial conditions scenario and the causeway scenario increased from 5.5 m to 5.6 m, respectively

Repeated multi-beam bathymetry surveys using an ADCP documented the dynamic nature of the streambed around the caisson. Positioning algorithms were used to accurately map thousands of bed elevation points under the bridge. These surveys tracked the streambed's response to a rising streamflow through the summer and into the fall recession. Scour was greatest along the nose and right-bank side of the caisson where flow approaches the bridge at an angle of 45 degrees. The minimum measured bed elevation in August was only 0.8 m above the bottom of the caisson. The scour hole filled as much as 7 m between August and October. The streambed likely fills to a similar elevation each fall as streamflow and sediment load decrease. This would indicate at least 7 m of scour since our observations were not continuous. The predicted scour for the caisson was 5.6 m for a 2-year recurrence interval flow. These findings are consistent with others from glacial-fed rivers in Alaska that experience seasonal bed fluctuations in excess of predicted scour for flood flows.

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