Two-Dimensional Computer Modeling of Pomme de Terre River at Highways 12 and 22 in Minnesota

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This paper investigates two-dimensional flood simulation modeling of the Pomme de Terre River at Highways 12 and 22 in Minnesota, using FESWMS-2DH. A one-dimensional modal, WSPRO, was initially used by Minnesota Department of Transportation to calculate hydraulic characteristics such as water surface elevations and profiles and flow velocities at the floodway and floodplain. The two-dimensional model was used to undertake a more realistic analysis of flow behavior in the channel with particular interest in flow characteristics at the bridge opening. This paper analyzes the results of model simulations. Particular attention was paid to the abutment scour prediction using Young's equation. The results were compared with HEC-18 approach.

Introduction

Highways 12 and 22 have scour problem during 100-year flood. One-dimensional modeling can not simulate and compute the flood delineation and the scour depth in details. The Federal Highway Administration (FHWA) requested further investigation of the above sites. To investigate a more accurate flow depth and potential scour at the bridge, Finite Element Surface-Water Modeling System, FESWMS, was implemented. It was intended to simulate the two-dimensional flood flow for different flood scenarios and was highly recommended by FHWA. The advantages of the two-dimensional model are in better depiction of complex flow regimes. Some situations are simply too complex for effective use of one-dimensional models. In some cases such as bridges with multiple piers, more detailed and accurate data are obtained from a two-dimensional model that can yield significant design cost savings.

Highway 12 bridge is located 10.7 miles west of Danvers, Minnesota. Constructed in 1933, it is a single span, steel truss structure with a span length of 88.3 ft. This bridge has vertical wall abutments with wing walls resting on concrete footings supported on timber pilings(1). The pile depths are 35.9 ft and 32.3 ft at the west and the east abutment, respectively. The bridge Scour Investigation report for Highway 12 indicates that there is no riprap or scour protection for these abutments (1). The field investigation reveals significant scour at the abutment face. The mean diameter of field sample is 0.00049 ft (d_{50}).

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The Highway 22 bridge is located about 10.5 miles northwest of Holloway, Minnesota. This bridge consists of three 40-ft pre-stressed concrete beam spans with a 36-ft roadway. The bridge abutment has 2:1 slope at each side of the bridge. Two pier piles are located 40 ft apart.

Computer Model

A two-dimensional hydrodynamic model is used for flood analysis. Developed by the USGS and FHWA, FESWMS is a two-dimensional computer simulation model for use of steady and unsteady flow. It uses finite element techniques to solve sets of equations that describes two-dimensional depth averaged surface-water flow in a horizontal plane (2). FESWMS supports both super and sub-critical flow analyses including area wetting and drying. This model can be used to simulate flow in rivers and floodplains where vertical velocities are small in comparison to horizontal velocities. FESWMS has been developed primarily to simulate complex hydraulic conditions at highway river crossings where conventional analysis based on one-dimensional flow calculations cannot provide the needed level of solution detail. The effect of bed friction and turbulent stresses are considered and water column pressure is hydrostatic. Clear water general scour can be calculated along with local scour at bridge piers. An in-house mesh generator program was used for this study to develop the element networks for Highways 12 and 22.

Flood Analysis (Highway 12)

The network mesh for Highway 12 consists of 320 elements and 1354 nodes. Figure 1 shows the network mesh for Highway 12 used in FESWMS. The initial conditions such as inflow and water surface elevation were set for the upstream and the downstream boundaries of the river. Setting the inflow at the upstream and the water surface at downstream of the bridge is the most common and essential approach in defining the regular boundary conditions (2). The 100-year inflow of 5745 ft^3/s was set at the upstream boundary of the channel. The initial water surface elevation used in this simulation is 993.0 ft. The downstream boundary of the channel was set for outflow only with small fluctuations allowed in water surface elevation. This boundary was set as a natural boundary condition. Wind effects were assumed to be zero. Slip condition was applied at all solid boundaries. Appropriate Manning roughness coefficients were applied for the floodway and the floodplain area. Water density was assumed to be 1.94 $slug/ft^3$.

Figure 2 shows velocity vectors for the 100-year flood. The thick solid line shows the floodplain boundary for the 100-year flood flow. This figure indicates that the highest flow velocity occurs in the middle of the bridge opening. Looking upstream, the water velocity is slightly higher at the right abutment than at the left abutment. An area with higher flow velocity has a greater chance of scour than a location with lower flow velocity. The average velocity in the vicinity of the bridge opening is about 3.70 ft/s.

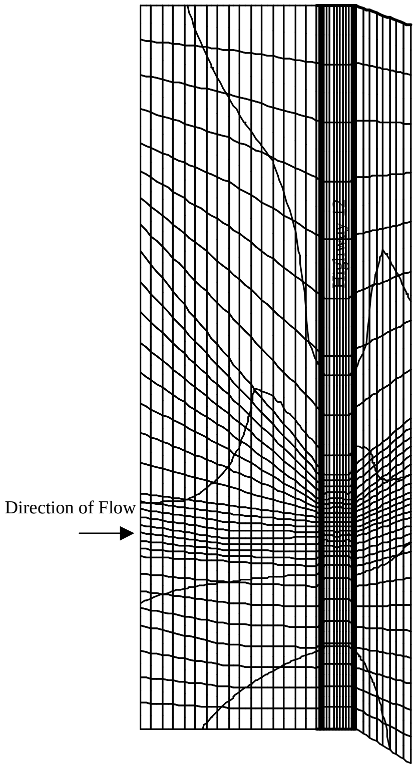

Figure 1. Network mesh for Highway 12.

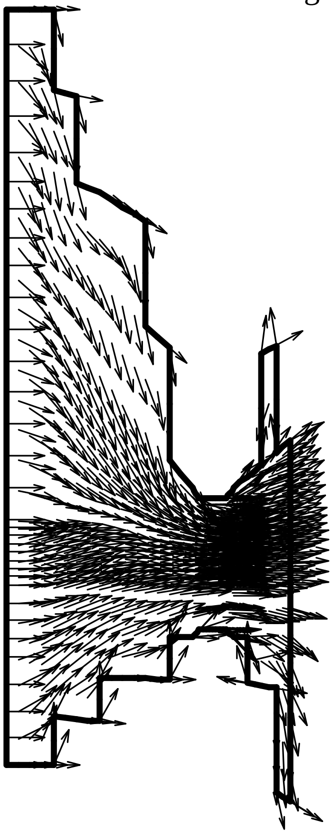

Figure 2. Velocity vectors for 100-year flood.
The thick line is flood delineation boundary.

Figure 3 shows water surface elevation contours that represents the base flood elevation, BFE, as defined by FEMA's flood insurance study program. The 100-year water surface elevation is lower than the bridge elevation, therefore, no overtopping or pressure flow occurs during the 100-year flood event.

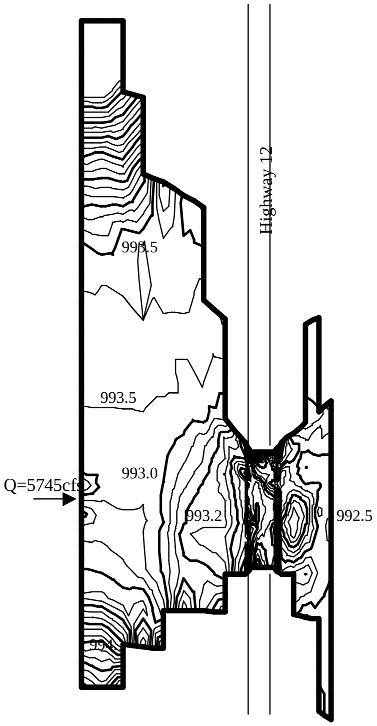

Figure 3. Water surface elevation representing Base Flood Elevation, BFE.

The above model was simulated again, this time for the 500-year flood event. Flow discharge for this event is 7530 ft^3/s and the initial water surface elevation was set to be at 995.0ft (1). The rest of the model's parameters such as water density and Manning roughness coefficients were kept the same as those in the 100-year run. Figure 4 shows the resulting of velocity magnitudes and velocity vectors. The floodplain delineation zone was expanded for this flood scenario. The highest velocity is again in the middle of the bridge opening. The flow velocity has increased throughout the floodplain area. Further analysis in water surface elevation for the 500-year flood event shows that the overtopping occurs at the bridge crossing. The Bridge Scour Investigation report for Highway 12 indicates that overtopping occurs for any frequency above 390-year event.

Flood Analysis (Highway 22)

The network mesh was generated using the longitudinal cross-sections at 50 ft and 70 ft upstream and at 50 ft and 100 ft downstream from the bridge. Other cross section data, such as those at the vicinity of the bridge were also used to lay out a more defined network mesh. The model network mesh was refined into smaller elements for more accurate simulation. The refinement is the linear interpolation of elements between the X and Y coordinates. The network mesh of Highway 22 only covers a small area upstream and downstream from the bridge. The mesh layout consists of 911 elements and 3803

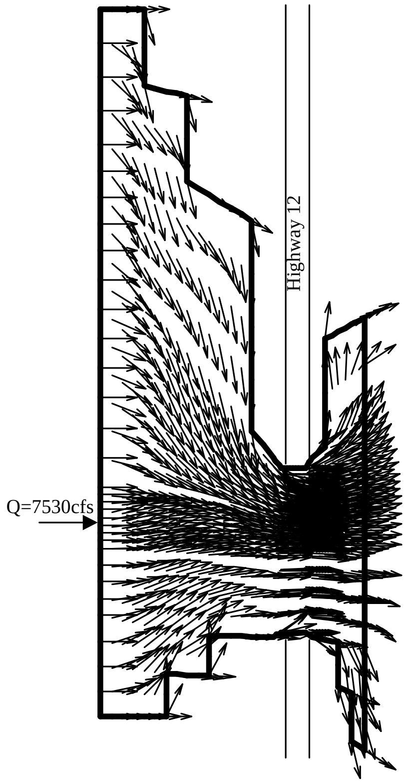

Figure 4. Velocity vectors for 500-year flood.

nodes. The elements are very fine at the river-bridge intersection to allow a more detailed analysis. The 100-year flood was simulated for a discharge of 5153 ft^3/s with water surface elevation at 1040.57 ft. This water surface elevation was assigned at the downstream of the river as a boundary condition. Water density used in this simulation is 1.94 $slug/ft^3$.

Figure 5 shows the velocity vectors during 100-year flood. The velocity vectors show direction and the intensity of the flow. The velocity vectors at the left abutment show a circular motion of water creating a small eddy that causes the lower water surface elevation. The 100-year flow has it highest velocity in the middle of the bridge piers.

The flood discharge for the 500-year flood is 7530 ft^3/s. The starting water surface elevations for Highway 22 was set at 1043.2 ft. The initial analysis by the Minnesota Department of Transportation indicates that there is overtopping that results in pressure flow for any flood event higher than 390-year. For the 500-year flood the water surface elevation is higher than the bridge elevation. Figure 6 shows the water surface elevation contours with the flood delineation for the same flood event. Similar to the results from the 100-year simulation, a lower water surface elevation exists at the upper face of the left abutment and right face of the left bridge pier. The flood delineation zone has expanded due to higher flood scenario. The island downstream from the bridge has remained as a no-flood zone.

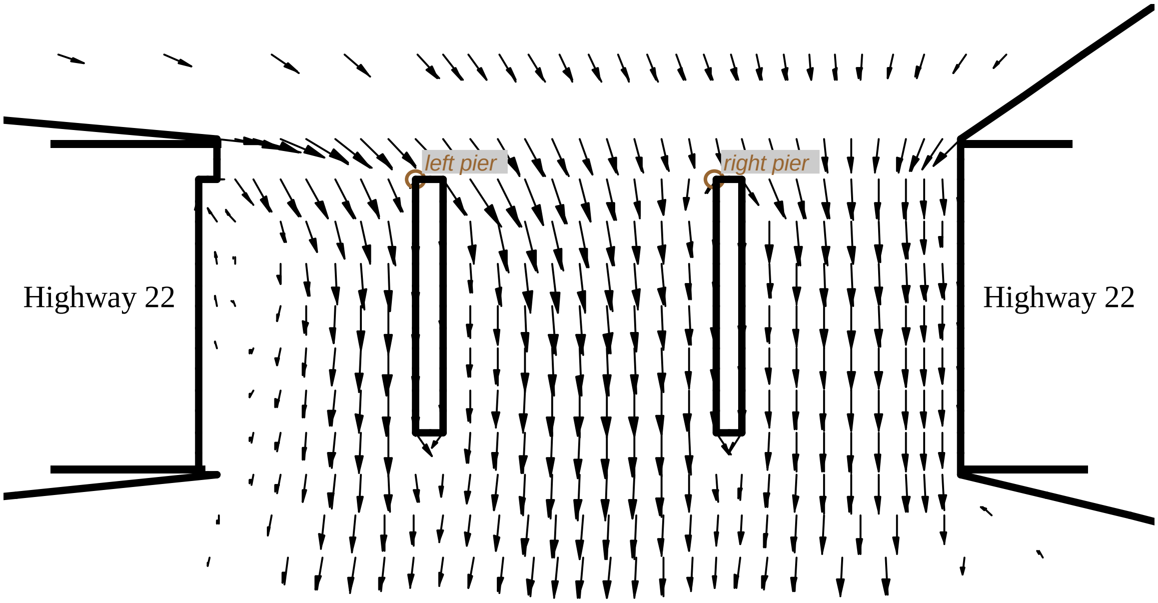

Figure 5. Velocity vectors during 100-year flood.

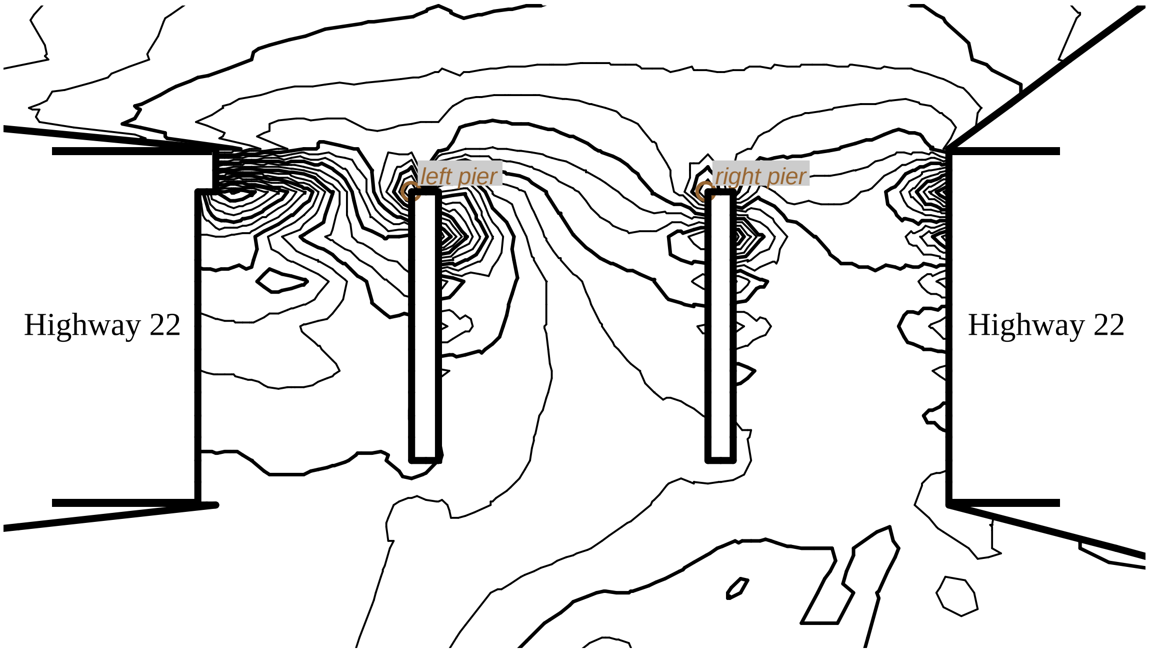

Figure 6. Base flood elevation for 100-year flood.

Results from the Highways 12 and 22 computer simulations show capability of the numerical modeling when appropriate parameters and accurate data are used. The two-dimensional model has a great edge over one-dimensional model such as HEC-RAS and WSPRO because it helps users to analyze results in more detail. The advantages of one-dimensional models are relative ease of use. Less experience, time and data are required to develop one-dimensional models. Tables 1 through 4 summarize the two-dimensional modeling results for water surface elevations and flow velocity for both sites and two different flood events.

Table 1. FESWMS results for water surface elevation (Highway 12, looking up-stream)

Flood Event	*Discharge ft^3/s*	*Initial Water Surface Elevation WSE, (ft)*	*Left Abutment WSE (ft)*	*Right Abutment WSE(ft)*	*Channel Opening WSE (ft)*	*Up-Stream WSE (ft)*	*Down-Stream, WSE (ft)*
100-year	5750	993.1	992.3	992.7	992.9	993.4	992.5
500-year	7530	995.0	994.7	995.0	994.8	995.2	994.5

Table 2. FESWMS results for velocity magnitude (Highway 12, looking up-stream)

Flood Event	*Discharge ft^3/s*	*Left Abutment Velocity VEL (ft/s)*	*Right Abutment VEL (ft/s)*	*Channel Opening VEL (ft/s)*	*Up-Stream VEL (ft/s)*	*Down-Stream VEL (ft/s)*
100-year	5750	2.76	2.63	4.86	1.97	4.46
500-year	7530	3.06	2.53	4.78	2.00	4.53

Table 3. FESWMS results for water surface elevation (Highway 22, looking up-stream)

Flood Event	*Discharge ft^3/s*	*Initial Water Surface Elevation WSE (ft)*	*Left Abutment WSE (ft)*	*Right Abutment WSE (ft)*	*Channel Opening WSE (ft)*	*Up-Stream WSE (ft)*	*Down-Stream, WSE (ft)*
100-year	5150	1041.20	1040.97	1041.27	1041.22	1041.72	1041.12
500-year	7530	1043.20	1042.90	1043.40	1043.90	1044.20	1043.22

Table 4. FESWMS results for velocity magnitude (Highway 22, looking up-stream)

Flood Event	*Discharge ft^3/s*	*Velocity VEL At piers (ft/s)*	*Left Abutment VEL (ft/s)*	*Right Abutment VEL(ft/s)*	*Channel Opening VEL (ft/s)*	*Up-Stream VEL (ft/s)*	*Down-Stream VEL(ft/s)*
100-year	5150	4.50	3.50	4.00	6.00	2.50	4.50
500-year	7530	5.03	3.55	4.45	7.50	2.74	5.30

Scour Analysis

Scour analyses were performed to calculate scour depth at the abutments for Highways 12 and 22. Field investigation of Highway 12 shows no indication that the river is either aggradating or degradating. There is a high possibility for aggradation and degradation at these sites for floods higher than 100-year flood event.

Highway 22 abutments have a 2:1 slope and the abutments apparently are protected by ripraps. If this is the case, the scour depth should be less than Highway 12. The abutment scour depths are calculated for Highway 22. There is no information on whether the abutments are protected or not. Abutment scour for Highways 12 and 22 was calculated using Young's equation (3).

$$y + d_s = K\,[n^2 / (S(SG-1)d_{50})]^{3/7}\,(\,yV_r\,)^{6/7} \qquad (1)$$

Where

V_r = Resultant velocity adjacent to the tip of the abutment,
n = Manning friction coefficient,
S = Shields' parameter,

Shields parameter is based on Kilgore's (4) relationship involving Froude number (Fr), and it is given as;

$$S = [\tan\,[88.05-4.37\,(Fr)^2\,]\,]^{-1} \qquad (2)$$

SG = specific gravity for sediment,
d_{50} = median particle size,
y = approach depth,
d_s = scour depth,
K = Correction factor.

Equation (1) was derived based on numerous laboratory experiments and it was used for comparison and testing using Lim's S11 experiment (3). This equation depends on the approach velocity and depth. The resultant velocity, V_r, and the approach depth were computed by FESWMS-2DH. These values were picked up from FESWMS outputs. Shield's coefficients were computed using Froude Number values that were computed by FESMWS. Young's equation was used to compute the scour depth at the bridge abutments. The abutment scour depth for Highways 12 and 22 were calculated using the following parameters:

n = 0.020 for organic silty sand, fine grain gravel,
S = Different values for different Froude Numbers,
d_{50} = 0.0005 ft,
SG = 2.65,
y = approach depth at the approach section over floodplain,
K = 1.0

Tables 5 and 6 show the computed and measured abutment scour depth as well as the HEC-18 approach (Equation 28, Page 48) for both Highways. The measured scour depths for 500-year flood was not available.

Table 5. Abutment scour depth for Highways 12(looking up-stream)

Flood Event	*HW12 Left Abutment Scour Depth (ft)* ***Computed***	*HW12 Left Abutment Scour Depth (ft)* ***Measured***	***HEC-18*** *(ft)*	*HW12 Right Abutment Scour Depth (ft)* ***Computed***	*HW12 Right Abutment Scour Depth (ft)* ***Measured***	***HEC-18*** *(ft)*
100-year	17.42	14.6	17.33	10.48	13.0	19.52
500-year	26.35	N/A	24.83	18.54	N/A	19.60

Table 6. Abutment scour depth for Highways 22(looking up-stream)

Flood Event	*HW22 Left Abutment Scour Depth (ft)* ***Computed***	*HW22 Left Abutment Scour Depth (ft)* ***Measured***	***HEC-18*** *(ft)*	*HW22 Right Abutment Scour Depth (ft)* ***Computed***	*HW22 Right Abutment Scour Depth (ft)* ***Measured***	***HEC-18*** *(ft)*
100-year	13.10	12.0	27.95	9.49	8.10	19.39
500-year	22.06	N/A	35.24	18.40	N/A	24.16

Results show that the Young’s prediction scour depths are within a reasonable range of the measured values. Scour equations are highly sensitive to certain parameters such as resultant velocity, approach velocity and the flow depth in the floodplain.

The model networks were developed based on available limited number of cross-sections that do not completely represent the exact geometry of the stream and the floodplains particularly at the vicinity of the bridge. Therefore, highways 12 and 22 numerical results are only considered as examples to test equation 1.

Conclusions

The following are our findings regarding the use of advanced numerical model such as FESWMS-2DH, which is used in evaluation of scour depths and floodplain delineation.

1- The two-dimensional model showed better and more accurate results than one-dimensional model.
2- Young's equation prediction of scour depth for abutments is within good range.
3- Correction factor, K, was derived from a non-dimensional relationship of velocity and area.

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