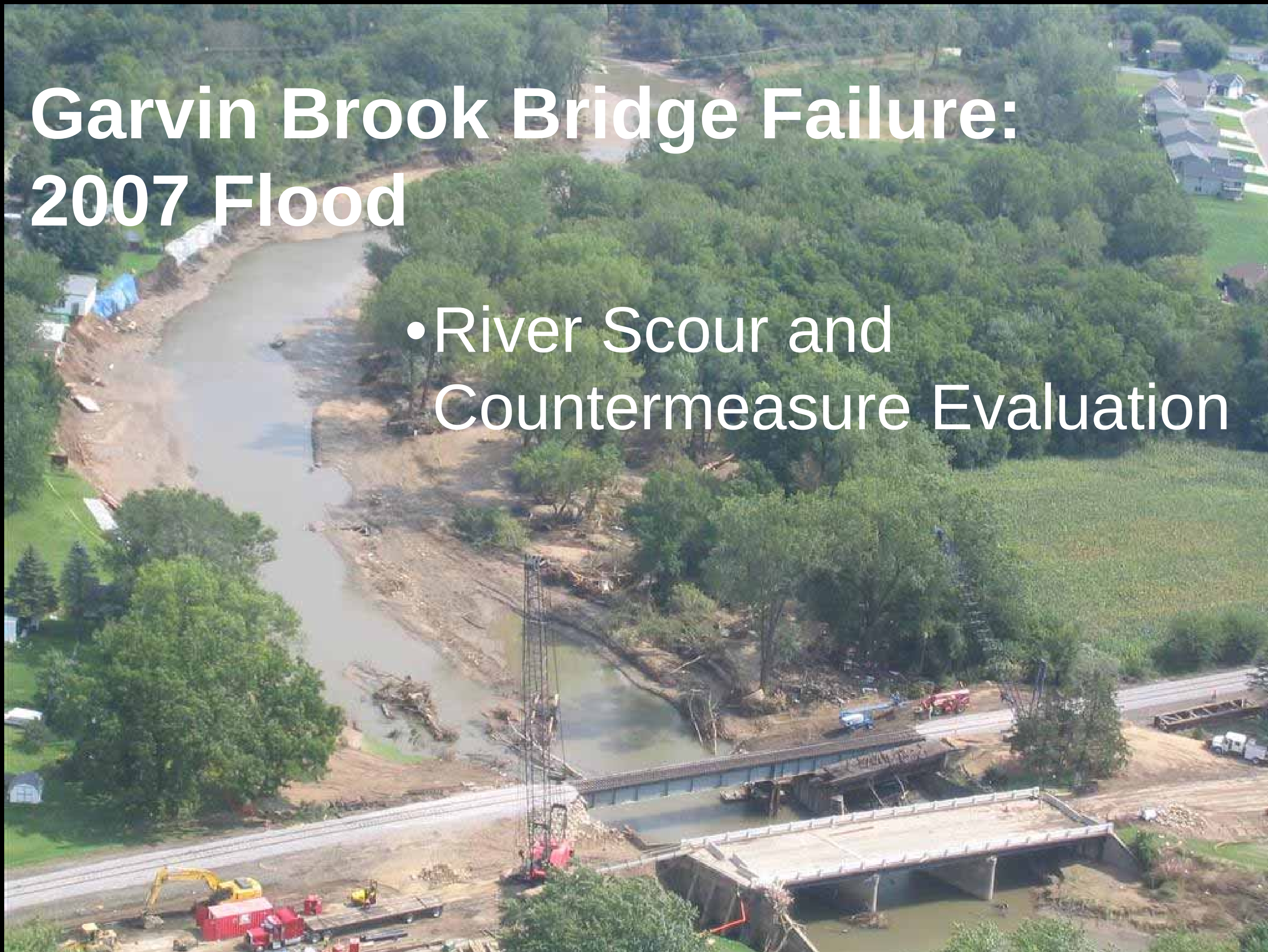
Garvin Brook Bridge Failure: 2007 Flood

- River Scour and Countermeasure Evaluation



Presented by: Bill Weaver, P.E., D.WRE

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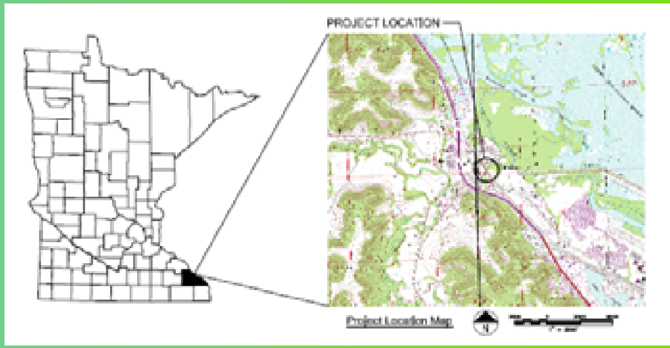
Garvin Brook Bridge Failure Evaluation Minnesota City, Minnesota



- August 2007 500 year flood caused total collapse of 150’ Span Bridge
- Original 1910 bridge washed out in 1919
- Replacement bridge lasted 87 years
- Replacement bridge designed to respect historic stream geomorphology
- New bridge scour countermeasures:
  - Lengthen bridge span to 250’
  - Design respects historic scour and stream flow patterns
  - Rip rap protection for channel, banks, piers and abutments
- Case History: Compare actual 500 year event scour to HEC-18 methods
- Discuss bridge scour countermeasures design approach

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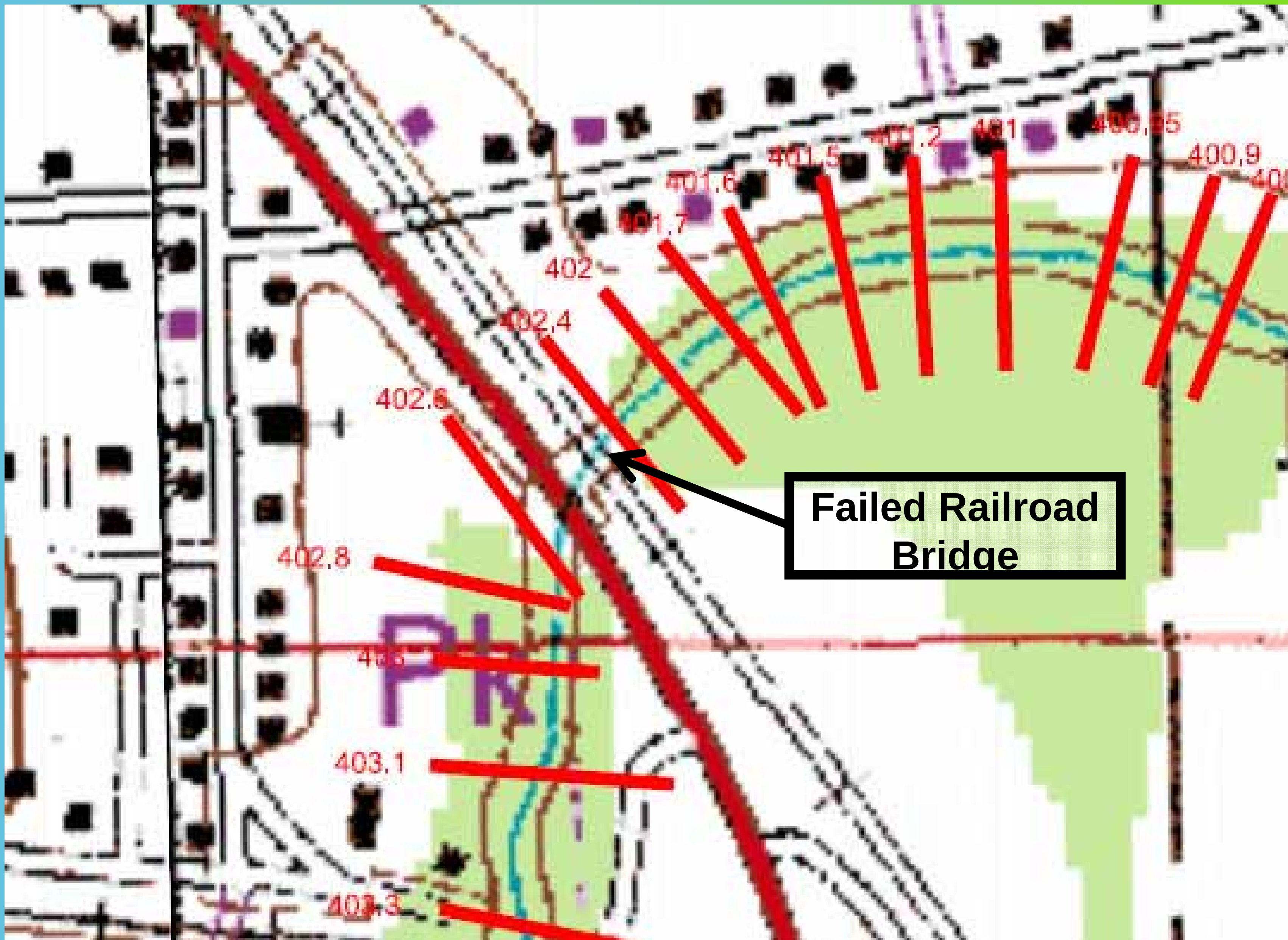
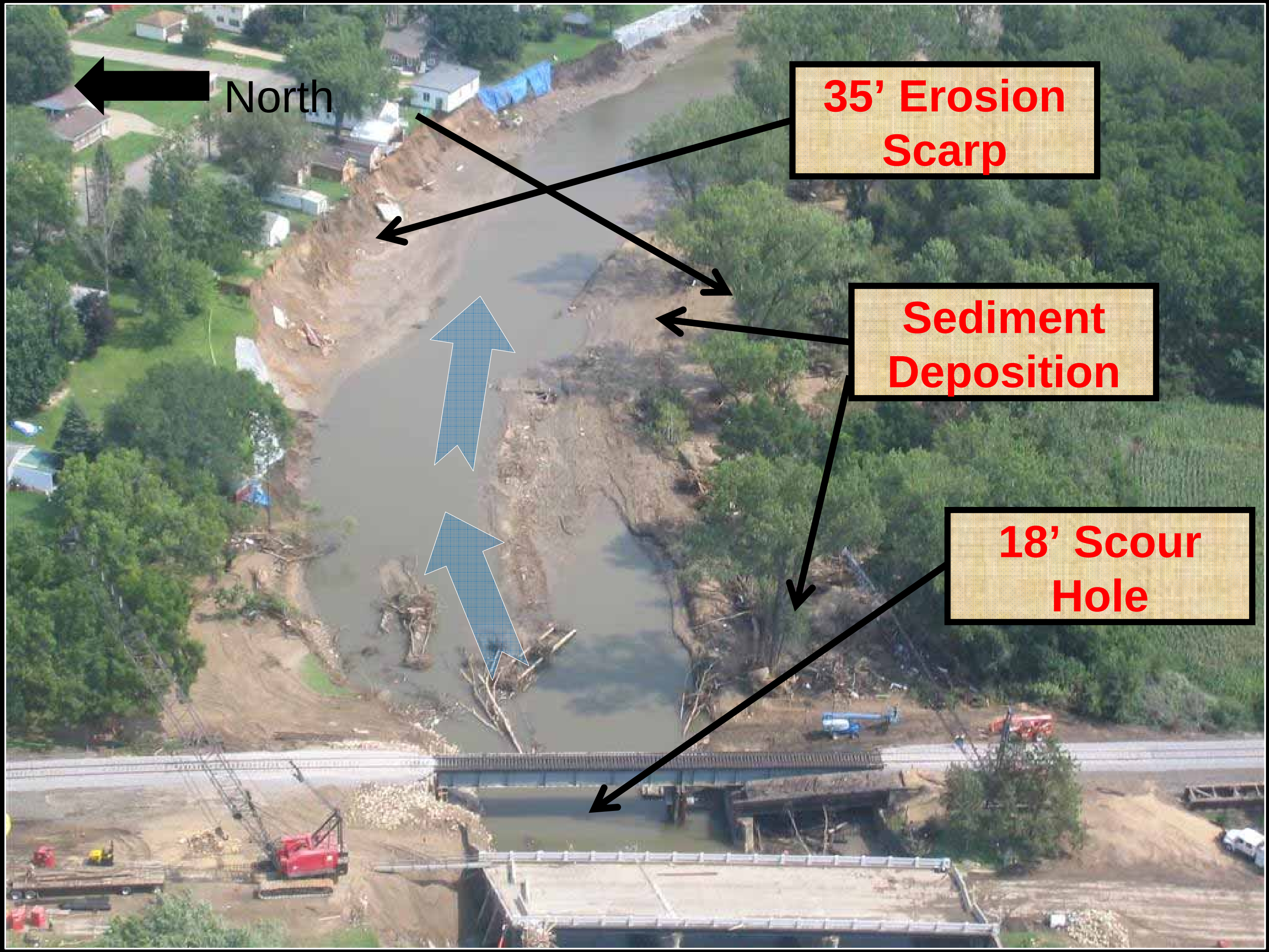
Garvin Brook Setting



Garvin Brook Railroad and Highway Bridge Failures



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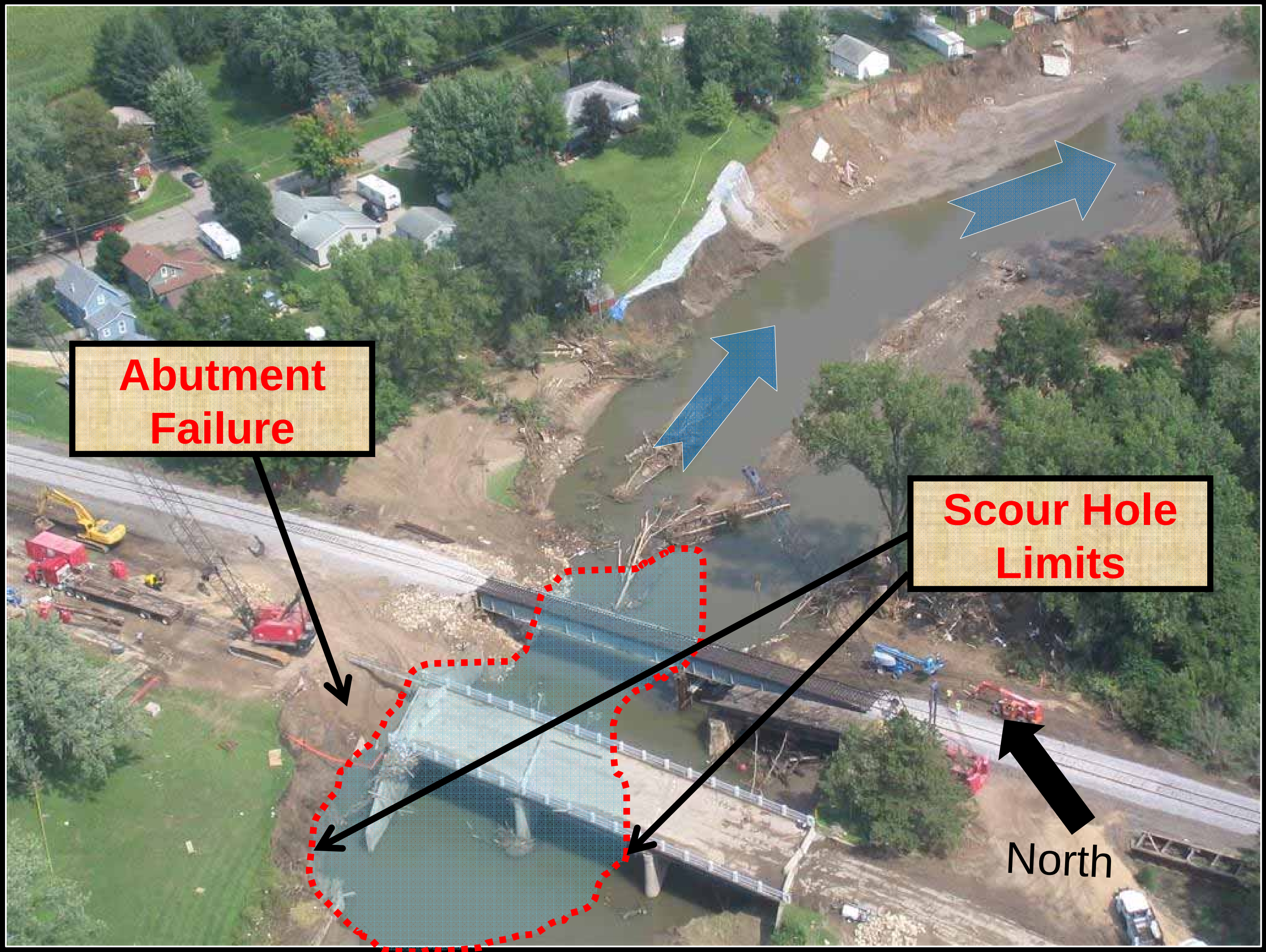
Garvin Brook Railroad and Highway Bridge Failures



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Garvin Brook Railroad and Highway Bridge Failures

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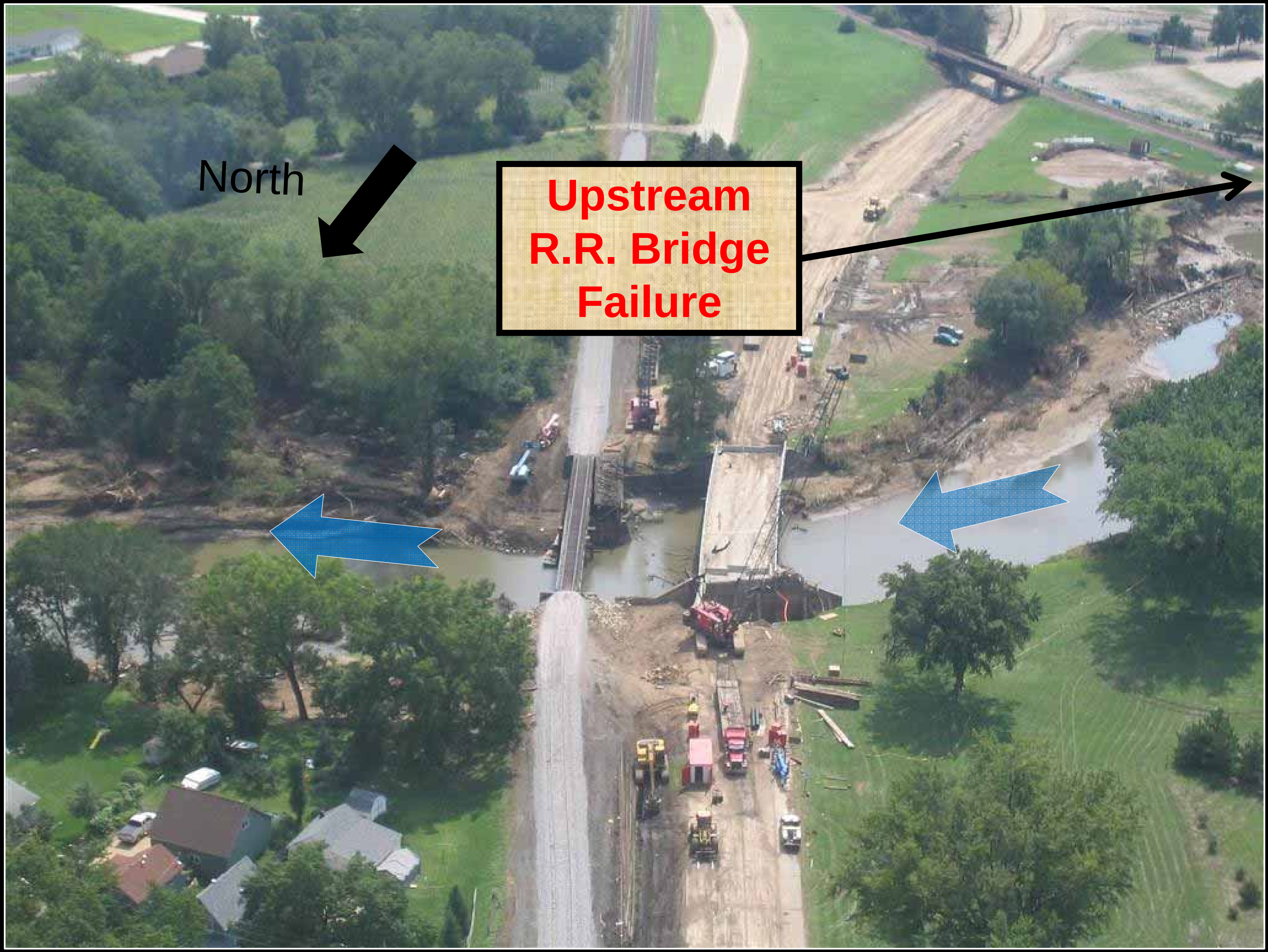

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Garvin Brook Bridge Failures

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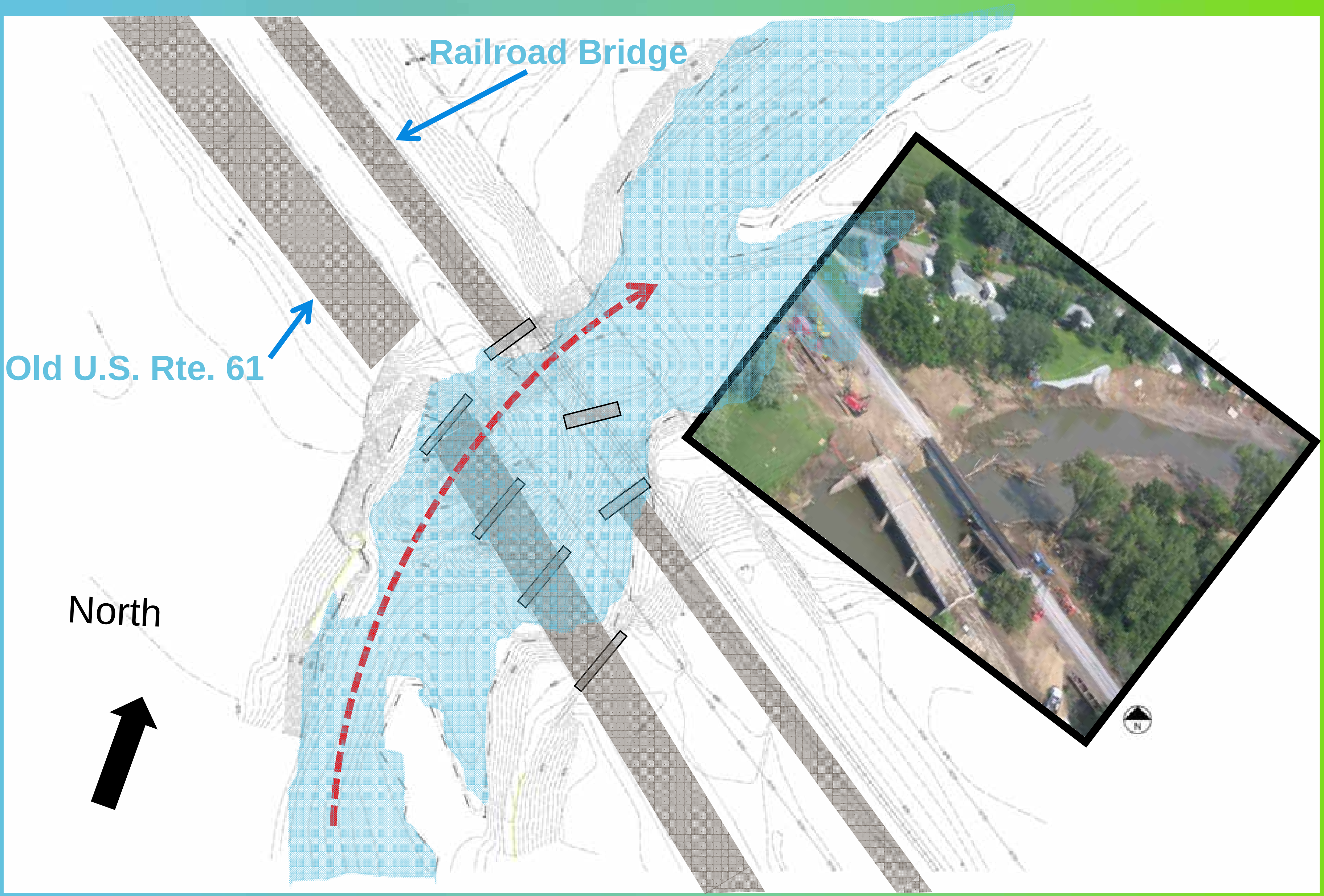
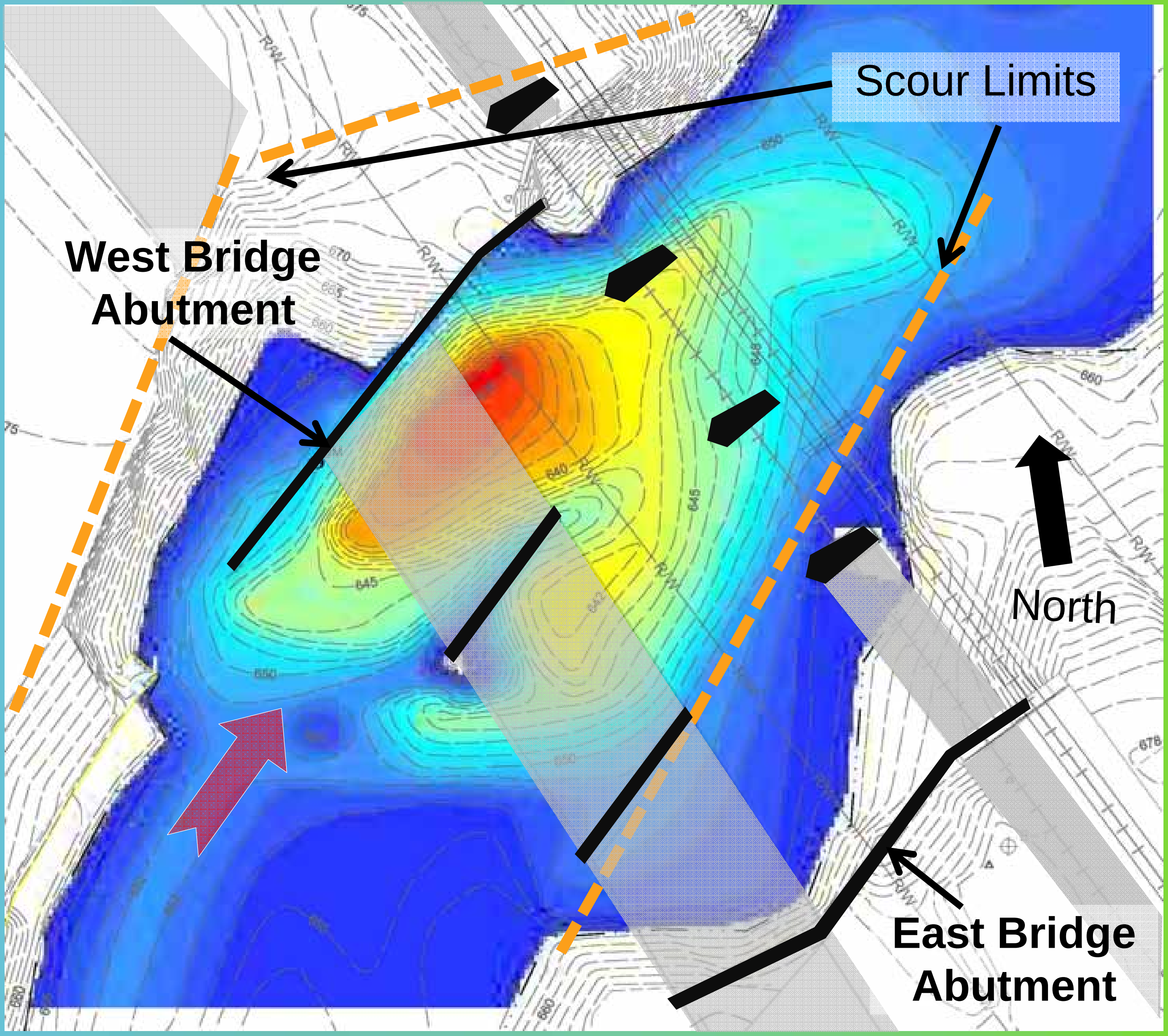
Garvin Brook Bluff Failure D/S of R.R. Bridge

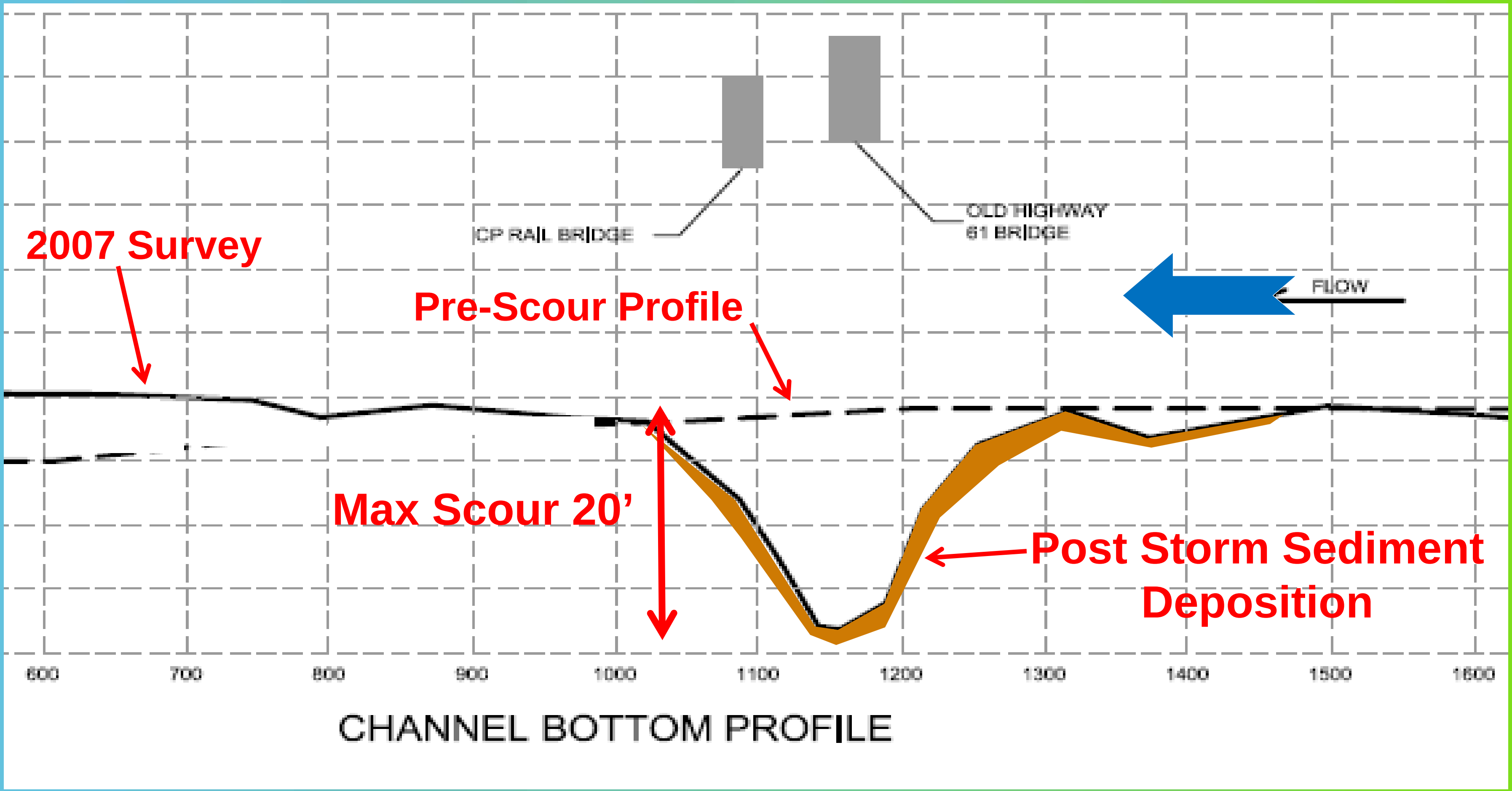
Garvin Brook Bridge Failure Site



Bridge Scour Limits



Garvin Brook Stream Profile



Flood Evaluation Summary

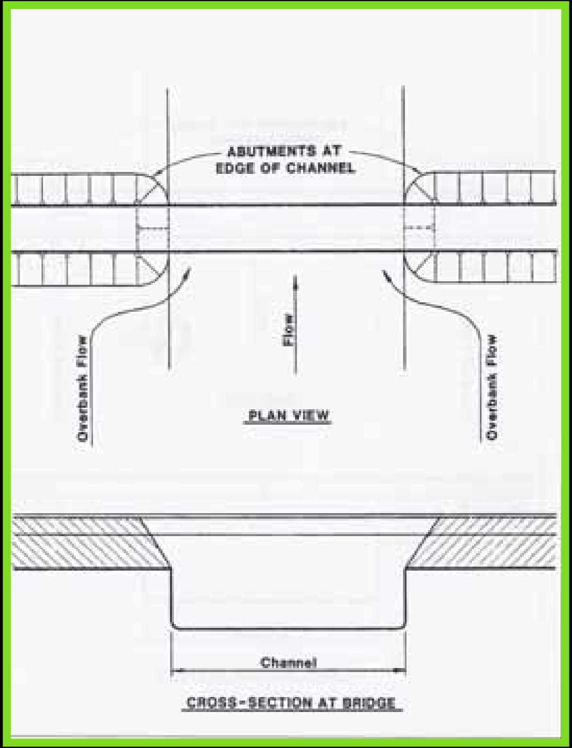
Event Recurrence Interval	Flood Discharge (cfs)	Bridge Flow Condition
10 year	6,930	Low Flow
50 year	12,350	Low Flow
100 year	15,300	Near Pressure Flow
*500 year	22,400	Pressure and Road Overflow
*Flood of Record		

Bridge Option	Flood Velocity (ft/sec)			
	50 year		100 year	
	D/S Face	U/S Face	D/S Face	U/S Face
Pre-failure	11.2	8.7	12.8	10.8
Sediment	10.7	6.3	11.5	7.1
No Sediment	9.1	5.1	10.3	5.8

Bridge Scour Evaluation (HEC-18, 2001)

Bridge Scour Components:

1. Long Term Bed Elevation Change:
   - Aggradation or Degradation of Stream Bed
2. General Scour:
   - Contraction Scour
     - Live Bed
     - Clear Water
   - Flow Around a Bend
   - Bridge Pressure Flow
3. Local (foundation) Scour:
   - Bridge Abutment
   - Pier Scour



Bridge Case 1B: abutments at edge of channel

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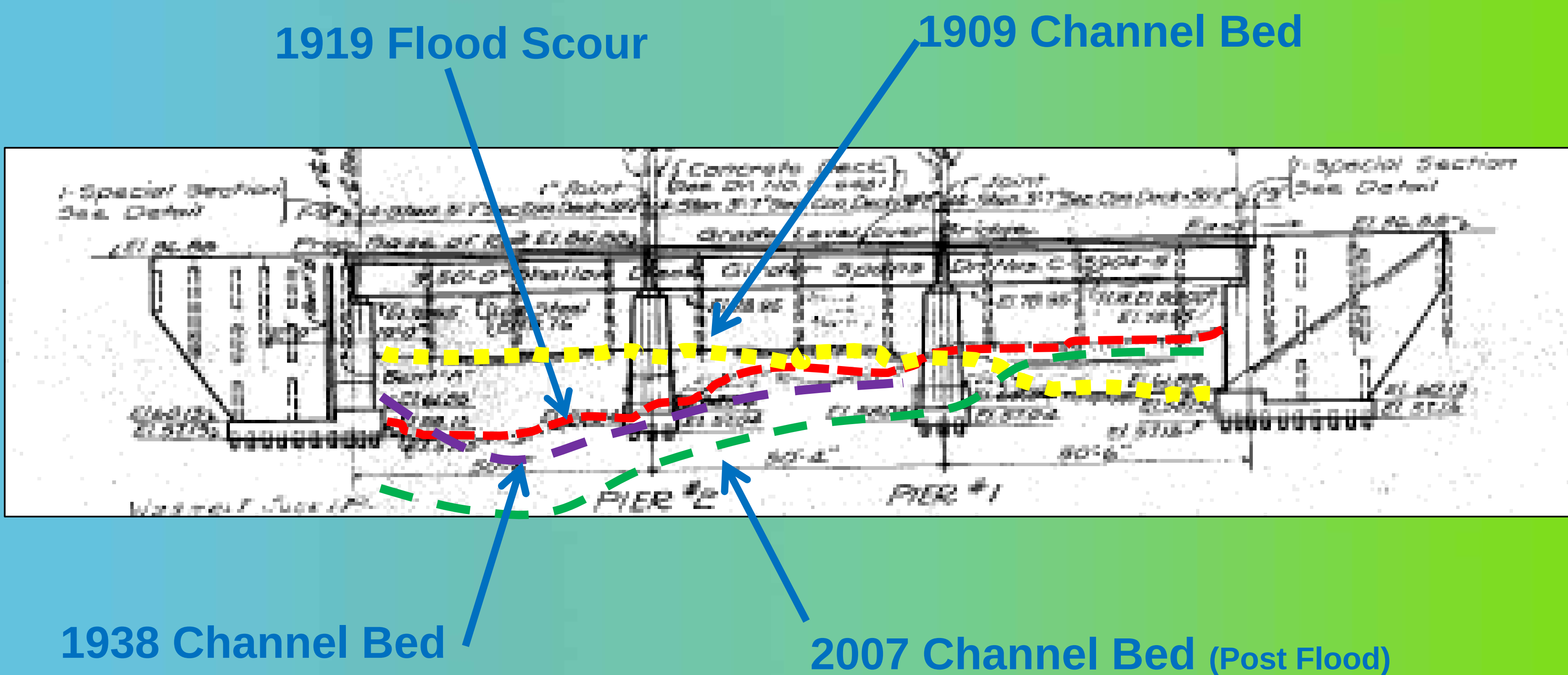
Evaluation of Long Term Stream Bed Change

1910 Bridge Section (looking D/S)



General Scour – Contraction Scour

1. Test for Live Bed or Clear Scour:

$$V_c = k_u * y^{1/6} * D^{1/3} = 1.8 \text{ ft/sec}$$

V_c = bed material critical velocity (ft/sec)

k_u = 11.17 (ft)

y = avg. approach channel flow depth (ft)

D = critical bed particle size (ft)

D_{50} = bed particle 50% smaller diameter (ft)

2. Compare Critical Velocity to Approach Velocity:
   - V_{100} approach velocity = 6.0 ft/sec >>>> V_c = 1.8 ft/sec
   - Thus – Live Bed Scour Controls

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General Scour – Contraction Scour (cont'd)

3. Estimate Live Bed Contraction Scour:

$$y_2 := \left(\frac{Q_2}{Q_1}\right)^{\frac{6}{7}} \cdot \left(\frac{W_1}{W_2}\right)^{k_1} \cdot y$$

Avg. contraction scour depth:
$y_s = y_2 - y_0$

y_2 = avg. depth in contracted section

y = avg. depth in u/s main channel

y_0 = Pre – scour water depth in contracted section

Q_2 / Q_1 = flow in contracted section / flow in u/s channel

W_1 / W_2 = bottom width of u/s channel / width of contracted section

k_1 based on: u/s shear velocity / bed material fall velocity = 0.69

RESULT: y_s = average contraction scour = 1.7 feet

General Scour – **Bend Scour**

Bridges located on stream bends:

- Complex flow patterns >> Complex scour assessment
- Flow concentration on outside of stream bend
- Non-uniform distribution of scour
- Normal analysis techniques may not apply – field inspection and interpretation required and significantly influence analysis results
- 2D analytical or physical modeling may be necessary
- Max velocities can be 1.5 to 2.0 x mean values

General Scour – Bridge Pressure Flow

Bridges flowing under pressure:

- Plunging flow under bridge >> vertical contraction
- Flow over bridge >> complicates scour formation
- Overtopping flow events can increase backwater reducing bridge flow velocity >> offsetting influence of pressure scour
- Take away – Scour analysis can be imprecise and requires considerable judgement !!

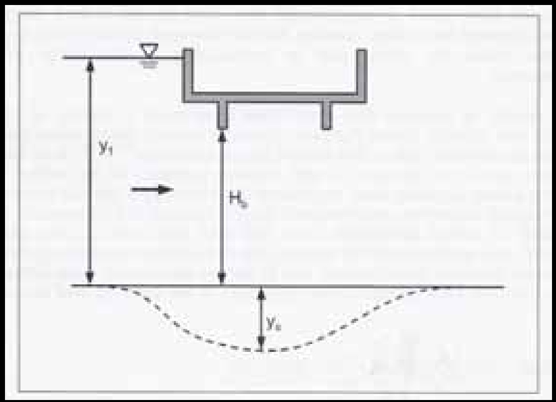

Fig 6.14 , HEC-18, 2001

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Local Scour – **Bridge Piers**

1. Estimate Pier Scour:

$$y_s := y_1 \cdot \left[2.0 \cdot K_1 \cdot K_2 \cdot K_3 \cdot K_4 \cdot \left(\frac{a}{y_1} \right)^{0.65} \cdot \left(F_{r1} \right)^{0.43} \right]$$

- y_s = scour depth (ft)
- y_1 = upstream flow depth (ft)
- K_1 = pier nose shape adjustment factor
- K_2 = angle of attack correction factor
- K_3 = bed condition adjustment factor
- K_4 = bed material armor adjustment factor
- a = pier width (ft)
- L = Length of pier (ft) [used in K_2 factor selection]
- Fr_1 = Froude # approaching pier [use mean approach velocity]
-

RESULT: y_s = pier scour = 17' to 23' [actual = 1' to 18']

Local Scour – Abutments

1. Estimate Abutment Scour:

$$y_{s1} := y_a \cdot \left[2.27 \cdot K_1 \cdot K_2 \cdot \left(\frac{L_1}{y_a} \right)^{0.43} \right] \cdot Fr^{0.61} + 1$$

- y_{s1} = scour depth (ft)
- y_a = average floodplain flow depth [A_e/L] (ft)
- K_1 = abutment shape factor
- K_2 = angle of embankment adjustment factor
- A_e = pier width (ft)
- L_1 = Length of active flow obstructed by embankment
- Fr_1 = Froude # approaching abutment
- V_8 = Q_e / A_e
- Q_e = Flow obstructed by abutment and embankment

RESULT: y_s = abutment scour = 2' to 15' [Actual = 8' to 16']

Bridge Scour Evaluation Summary

1. Long term stream bed change:
   – Channel thalweg shift from east to west
2. Contraction Scour >>>> average 1.7’
3. Bend Scour >>>> Indeterminate
4. Bridge Pressure Flow >>>> Indeterminate
5. Bridge Pier Scour >>>> 17’ to 23’ [Actual 1’ to 18’]
6. Bridge Abutment Scour >>>> 2’ to 15’ [Actual 8’ to 16’]
7. Conclusions:
   – HEC-18 scour analysis provides good insight
   – Complex Garvin Brook site scour can not rely on desktop study alone
   – 2007 500-year flood provides full scale field prototype
     » Rely on field information to influence design
   – Study results are used to influence:
     » Pier and Abutment foundation design (location and elevations)
     » Bridge widening geometry
     » Scour countermeasure design boundary conditions
   – Recommend future monitoring

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Replacement Bridge Scour Countermeasure Design

Bridge Scour Countermeasure Design

1. FHWA, USACE, State DOT's --- Most traditionally based scour countermeasures on:
   – Isbash or Sheilds: 1930's
   – Empirical methods for structures such as piers and abutments

2. American Assoc of State Highways & Transportation Officials:
   – 1962 -- AASHTO asked TRB to administer Research Program
   – 2006 – Produced NCHRP Report 568: "**Rip Rap Design Criteria, Recommended Specs, and QC**", 2006
   – Report provides history, comparisons, and recommendations

3. Recent studies recognize wide variation in methods and recommend conservative method selection

4. Garvin Creek Bridge countermeasure design discussion addresses channel, bank, pier and abutment protection

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Revetment Rip Rap Design Method Comparison
(NCHRP Report No. 568, 2006)

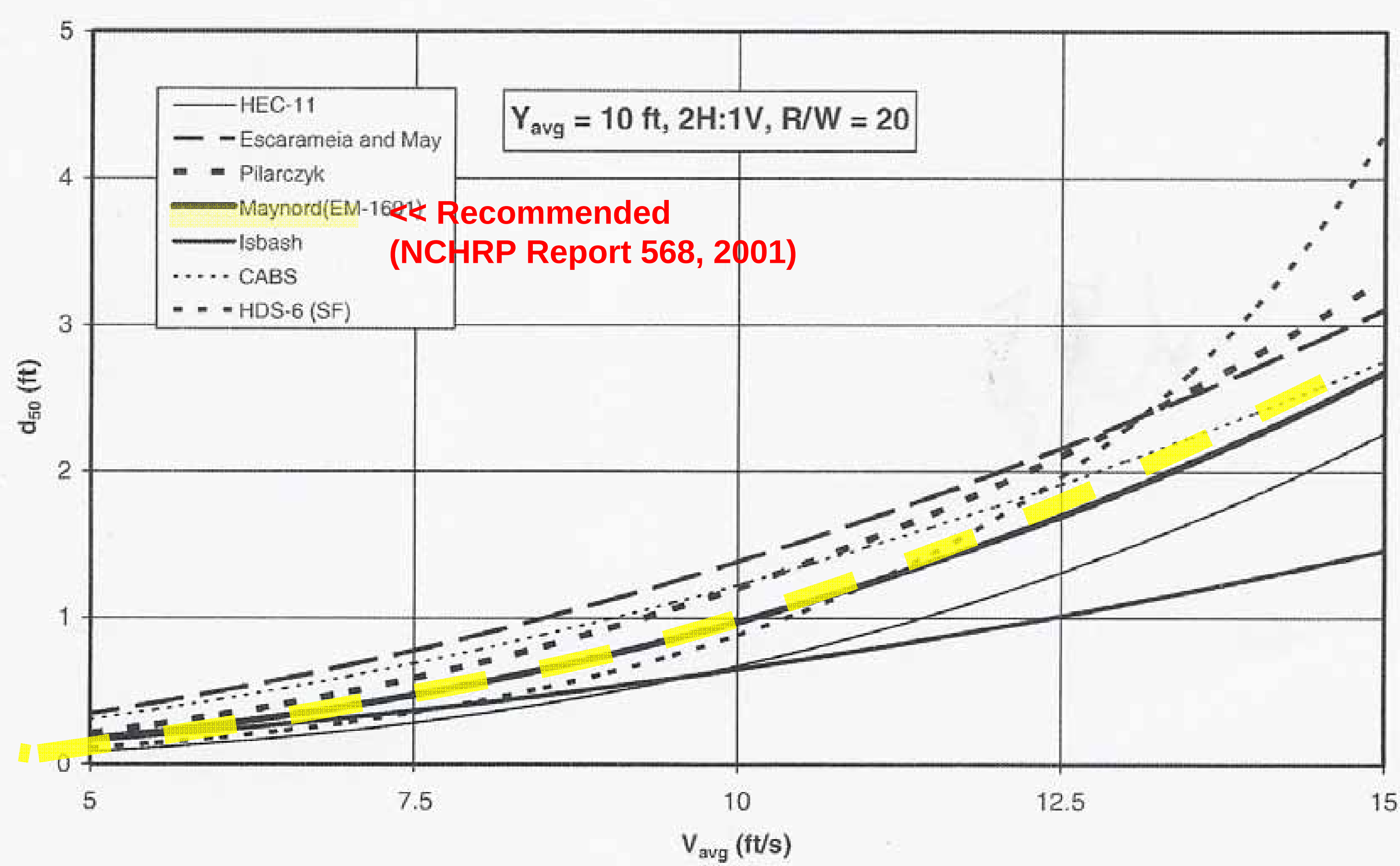

Figure 3.2. Riprap size versus velocity for mild-curvature bend.

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Bank Revetment Design

1. Maynord et al., 1989 Equation:

$$d_{30} := y \cdot \left(S_f \cdot C_s \cdot C_v \cdot C_t\right) \cdot \left[\frac{V_{ss}}{\left[K_1 \cdot \left(S_g - 1\right) \cdot g \cdot y\right]^{0.5}}\right]^{2.5}$$

d_{30} = particle size for which 30% is finer by weight (ft/)

S_f = safety factor = 1.2 | y = flow depth (ft)

C_s = stability coefficient = 0.33 [avg of angular and round stone]

C_v = velocity distribution coefficient = 1.239 = 1.283 – 0.2*log(R_c/w)

R_c = centerline Radius of Bend = 300’

C_t = blanket thickness coefficient = 1.0 [plate B-40 EM 1601]

V_{ss} = characteristic velocity = [V_{avg} (1.74 - 0.52 Log (Rc/W)] = 11.0

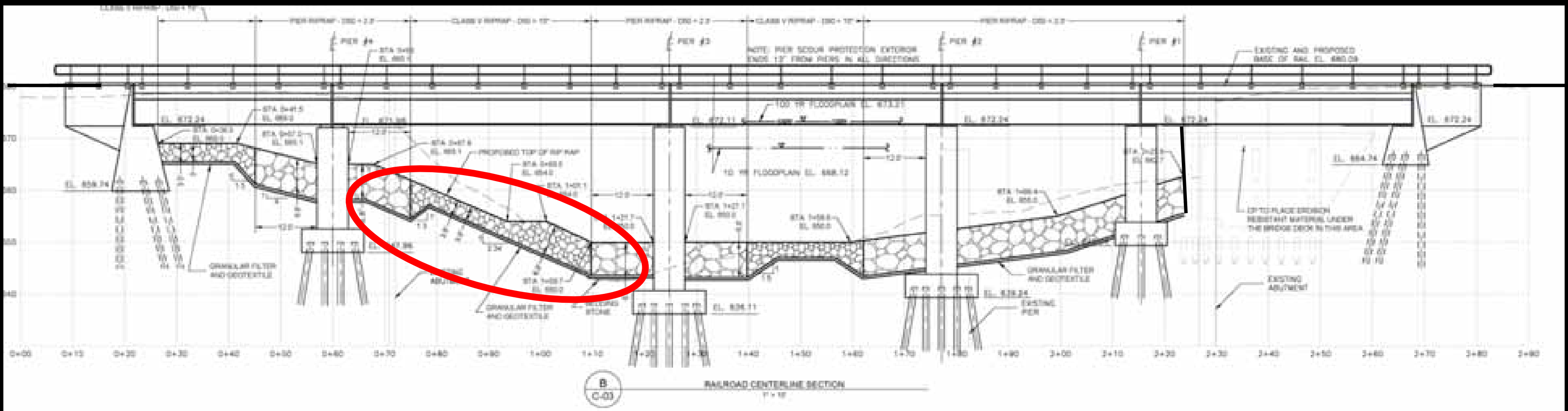
W = water surface width at u/s end of bend (ft)

K_1 = side slope correction factor = 0.924 [plate B-39 EM 1601]

2. Embankment rip rap design:

- d_{30} = 0.76’ > Use MNDOT Class V d_{50} = 15” 3’ thick layer
- Conservative sizing reflects flow complexity >>> Monitor!

Proposed Bridge Restoration – Stream Bank &Toe Protection



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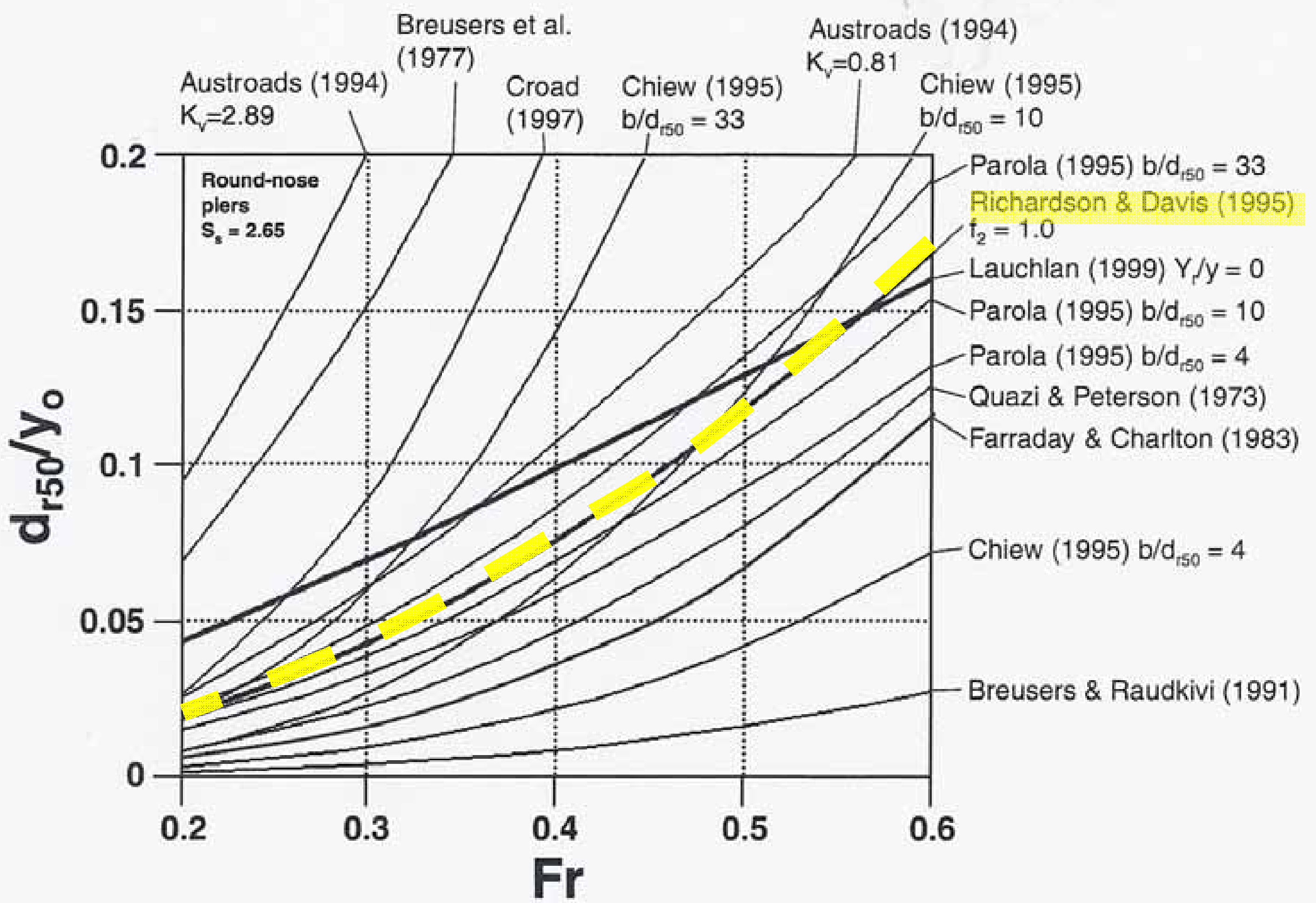
Pier Rip Rap Design Method Comparison (NCHRP Report 568, 2006)



<< Recommended (NCHRP Rpt 568, 2001)

Source: modified from Lauchlan (1999)

Figure 2.5. Comparison of equations for sizing riprap at round-nose bridge piers.

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Pier Countermeasure Design

1. Richardson and Davis, 1995 Equation:

$$V_{des} := k_1 \cdot k_2 \cdot V_{avg} \qquad V_{des} = 18.36$$

$$d_{50} := \frac{0.692 \cdot (V_{des})^2}{(S_g - 1) \cdot 2 \cdot g} \qquad d_{50} = 2.264$$

d_{50} = median stone diameter (ft)

V_{avg} = 100 year avg approach velocity on pier = 7.2 ft/sec

k_1 = round nose pier = 1.5

k_2 = for pier in main channel, sharp bend = 1.7

V_{des} = 100 year velocity on pier = 18.4 ft/sec

K_1 = side slope correction factor = 0.924 [plate B-39 EM 1601]

2. Pier rip rap design:

- d_{50} = 2.3' >>> Layer thickness = 3 * d_{50} >>> plan limits = 2 * pier width
- Recess rip rap into stream bed
- Conservative section and plan limits reflect flow complexity !!
- Recommend performance monitoring !!

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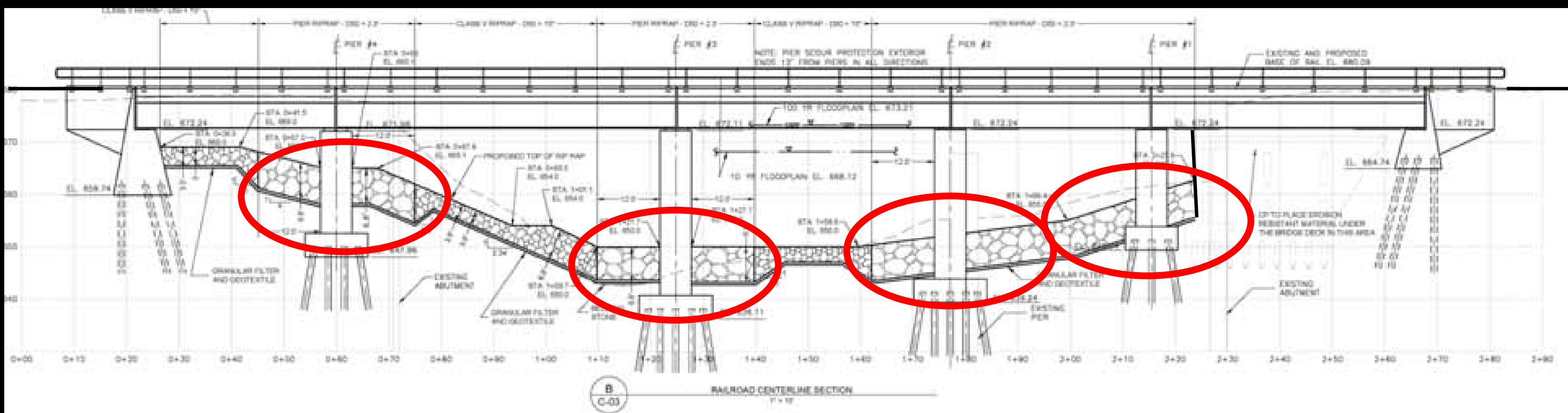
Proposed Bridge Restoration – Pier Protection



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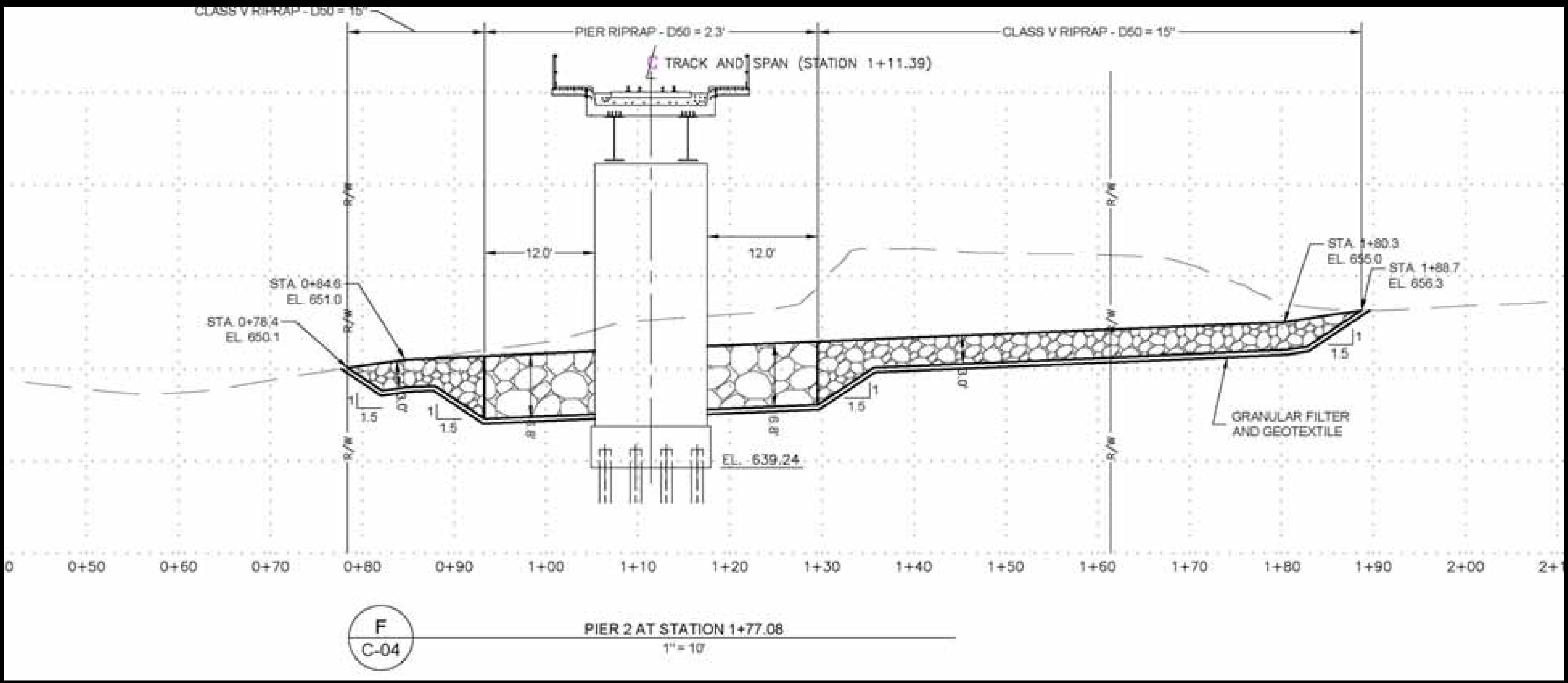
Proposed Stream Profile at Pier # 2



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Abutment Countermeasure Design

1. HEC -23 (Lagasse et al., 2001):

$$d_{50} := y \cdot \left[\frac{k}{\left(S_g - 1\right)} \right] \cdot \left(\frac{V_{avg}{}^2}{g \cdot y} \right)$$

y = flow depth in the contracted bridge opening (ft)
d_{50} = median stone diameter (ft)
V_{avg} = 100 year avg velocity in the contracted bridge opening = 7.2 ft/sec
k = 0.89 for spill through abutment

2. Abutment rip rap design:
   - d_{50} = 0.9’ >>> Layer thickness = 3 * d_{50}
   - Recess rip rap into channel bank
   - Use same geometry as revetment bank since dimensions are similar
   - Double rip rap layer thickness at toe of slope
   - Recommend performance monitoring !!

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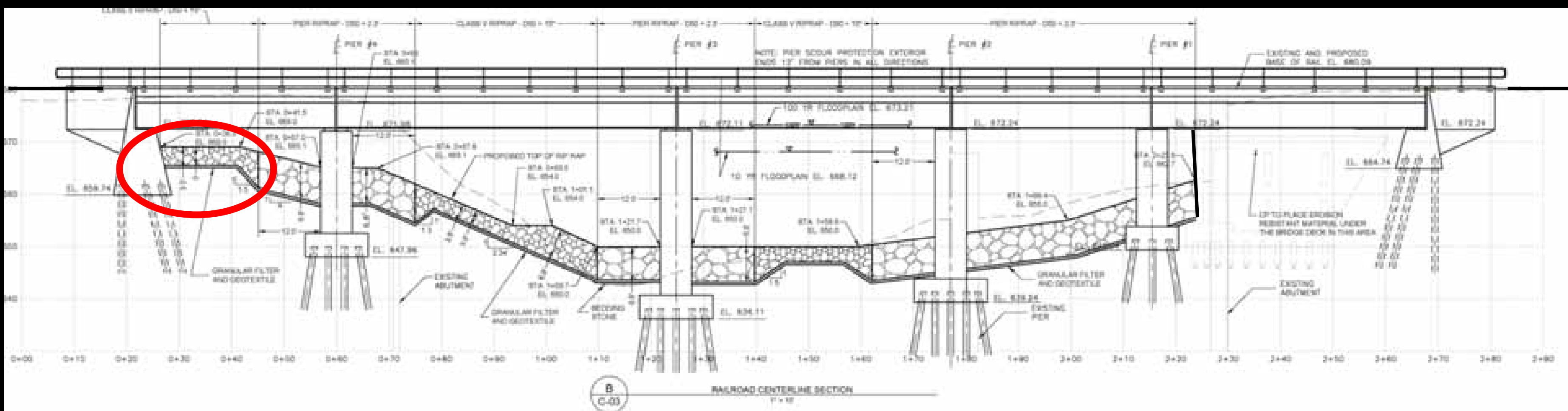
Proposed Bridge Restoration – Abutment Protection



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Garvin Brook Bridge Failure: 2007 Flood