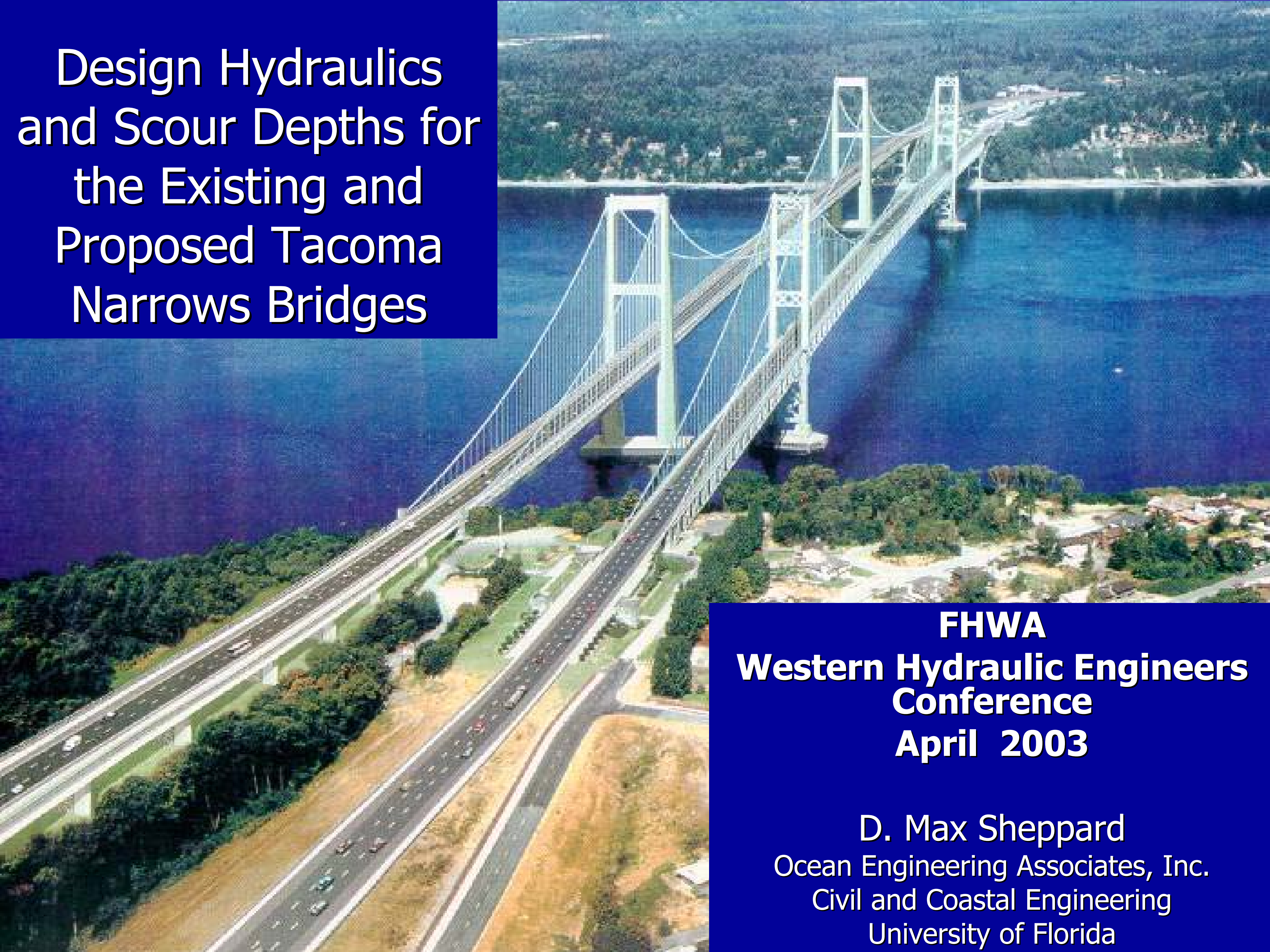


Design Hydraulics and Scour Depths for the Existing and Proposed Tacoma Narrows Bridges

FHWA
Western Hydraulic Engineers Conference
April 2003

D. Max Sheppard
Ocean Engineering Associates, Inc.
Civil and Coastal Engineering
University of Florida

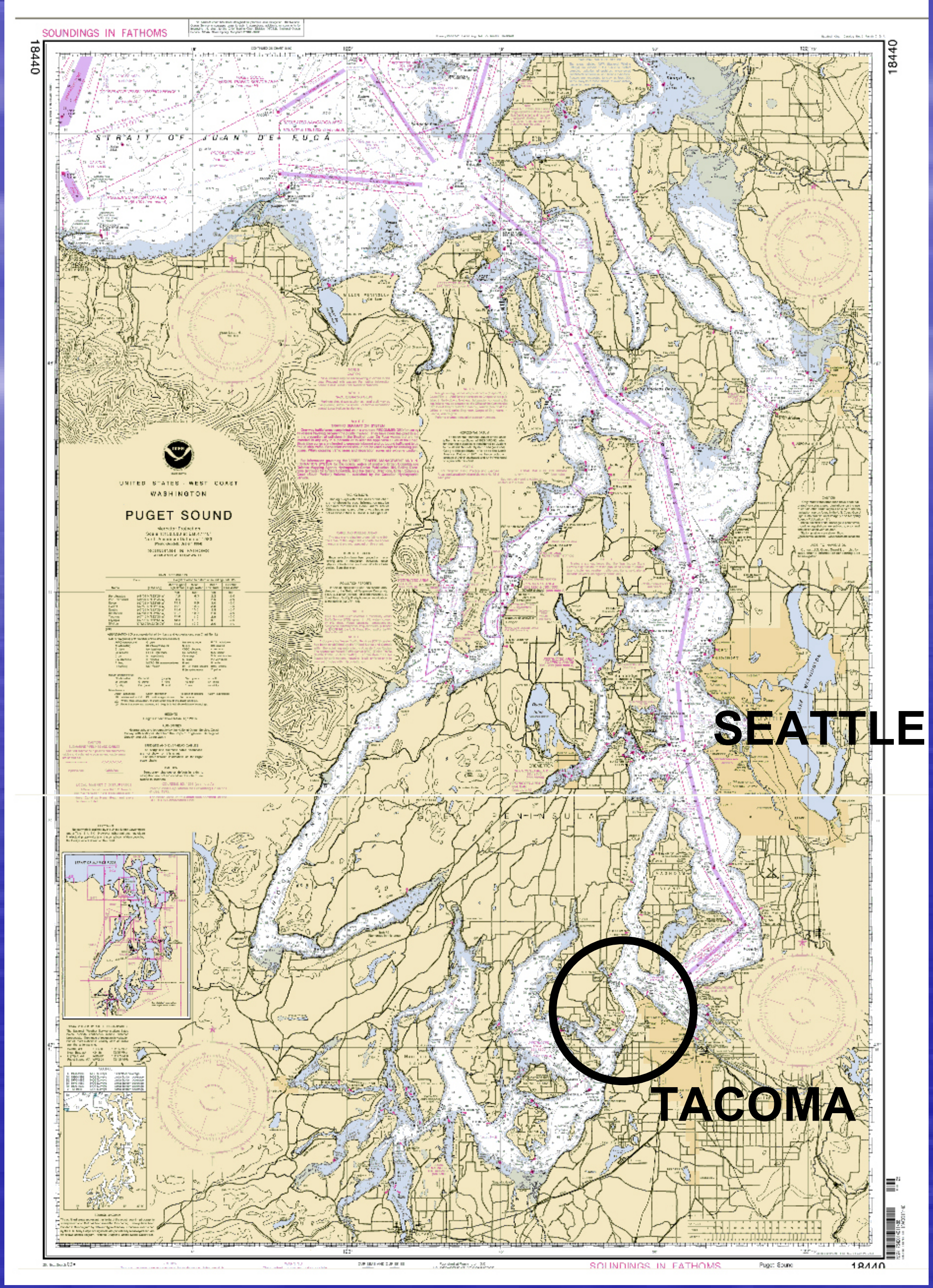
OUTLINE

- Design flow and sediment conditions
- Bridge hydraulics
  - 2D model
- Bridge scour
  - Physical model tests
  - Scour analysis
  - Design scour depths
- Summary

Unique flow and sediment conditions at site

- Design flow conditions
  - Dominated by astronomical tides
  - Large mixed astronomical tidal range
  - Site experiences near design conditions twice per month (spring tides)

Location Map



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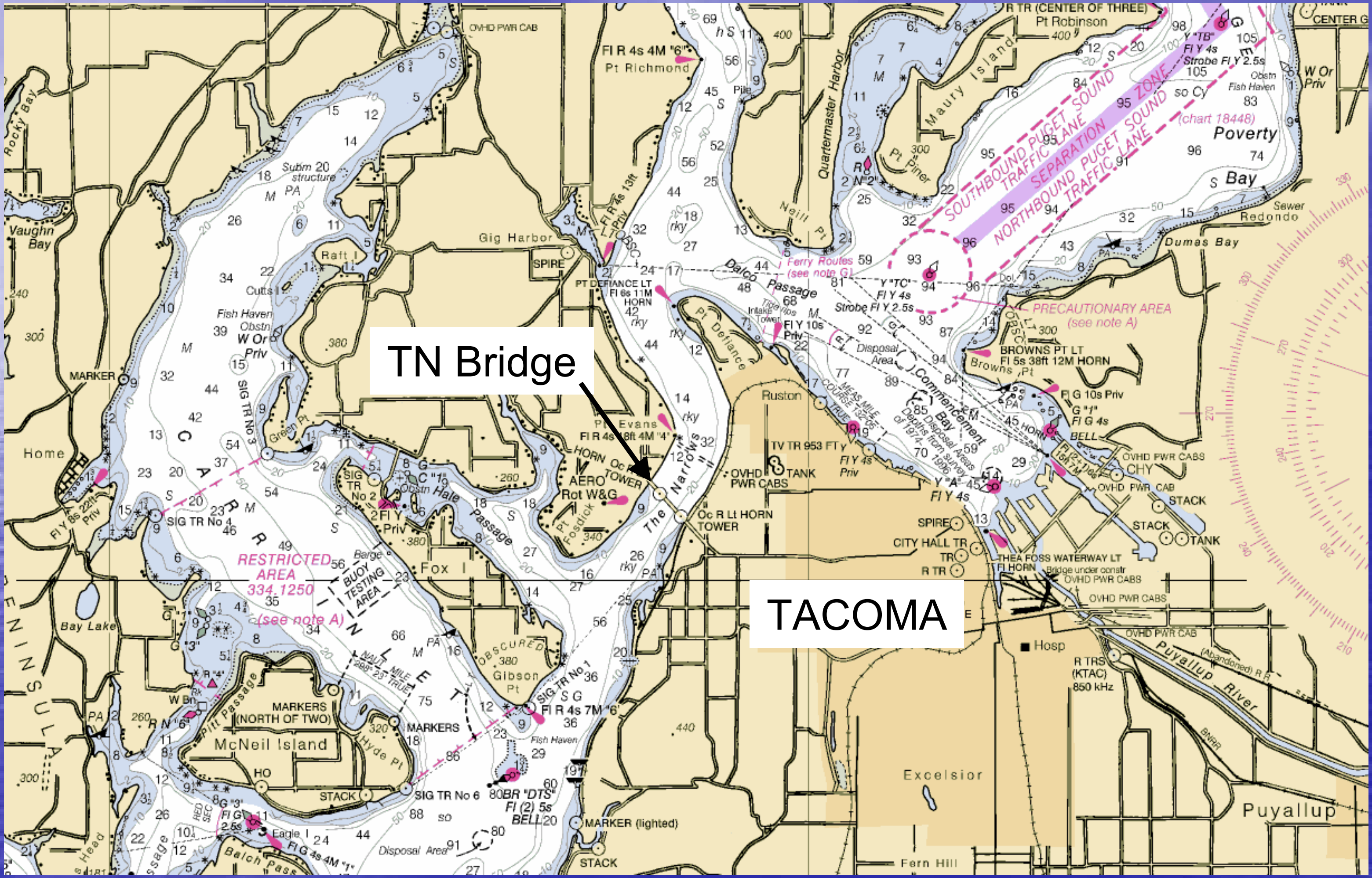
Location Map



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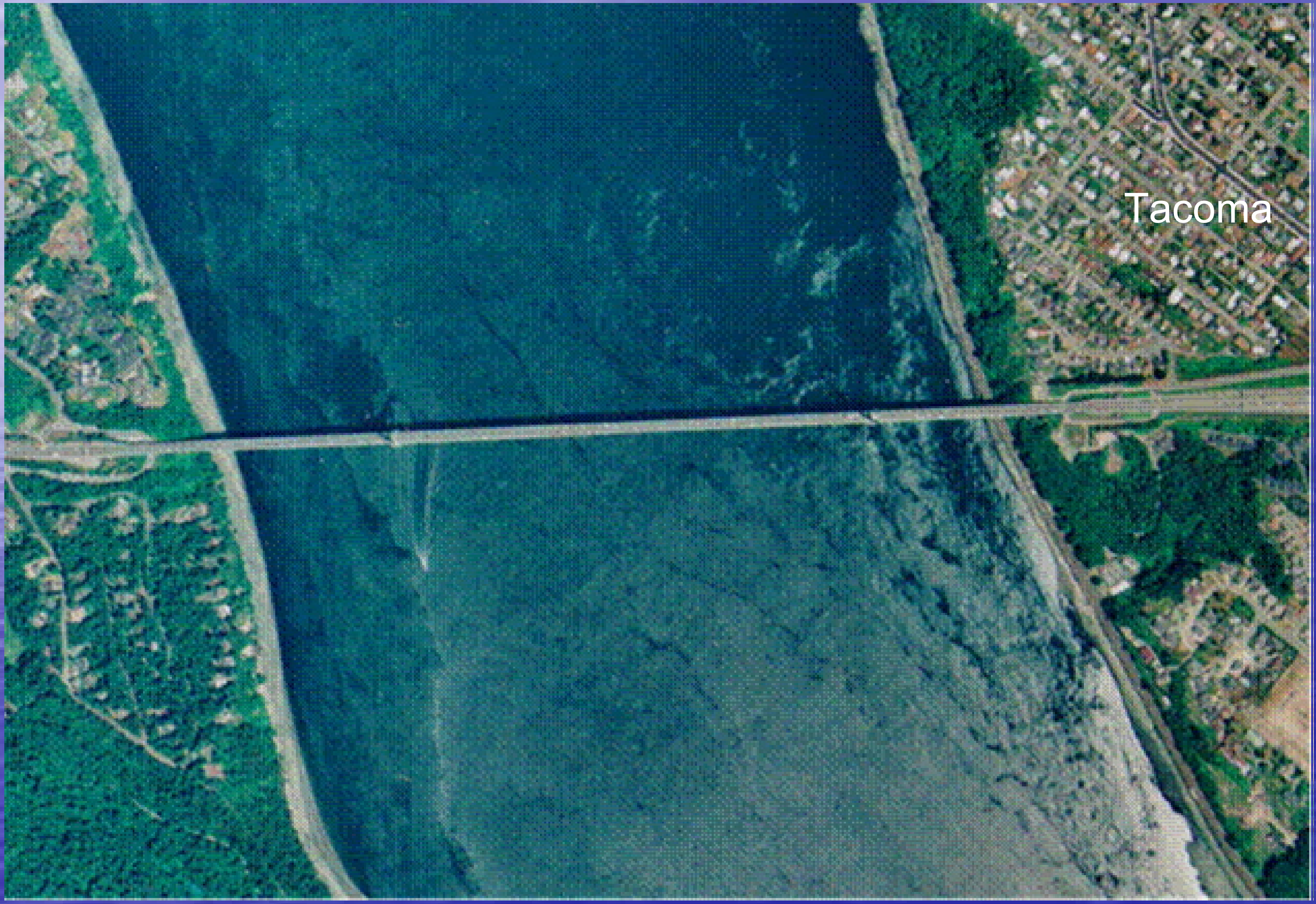
Tacoma Narrows Bridge



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Design Flows

- Astronomical tide dominated
  - Deep water near shore – small storm surge
  - Near design velocity data for model calibration
- Bathymetry-topography
  - Relatively deep channel
  - Little or no overbank flow

Design Flows

- Appropriate flow model?
  - Nearly straight channel at bridge site
  - Channel bend seaward of site
  - Channel width change landward of site
  - Bed features near site
  - Need flow direction as well as magnitude at piers
  - NOAA tide gages at Seattle and Commencement Bay

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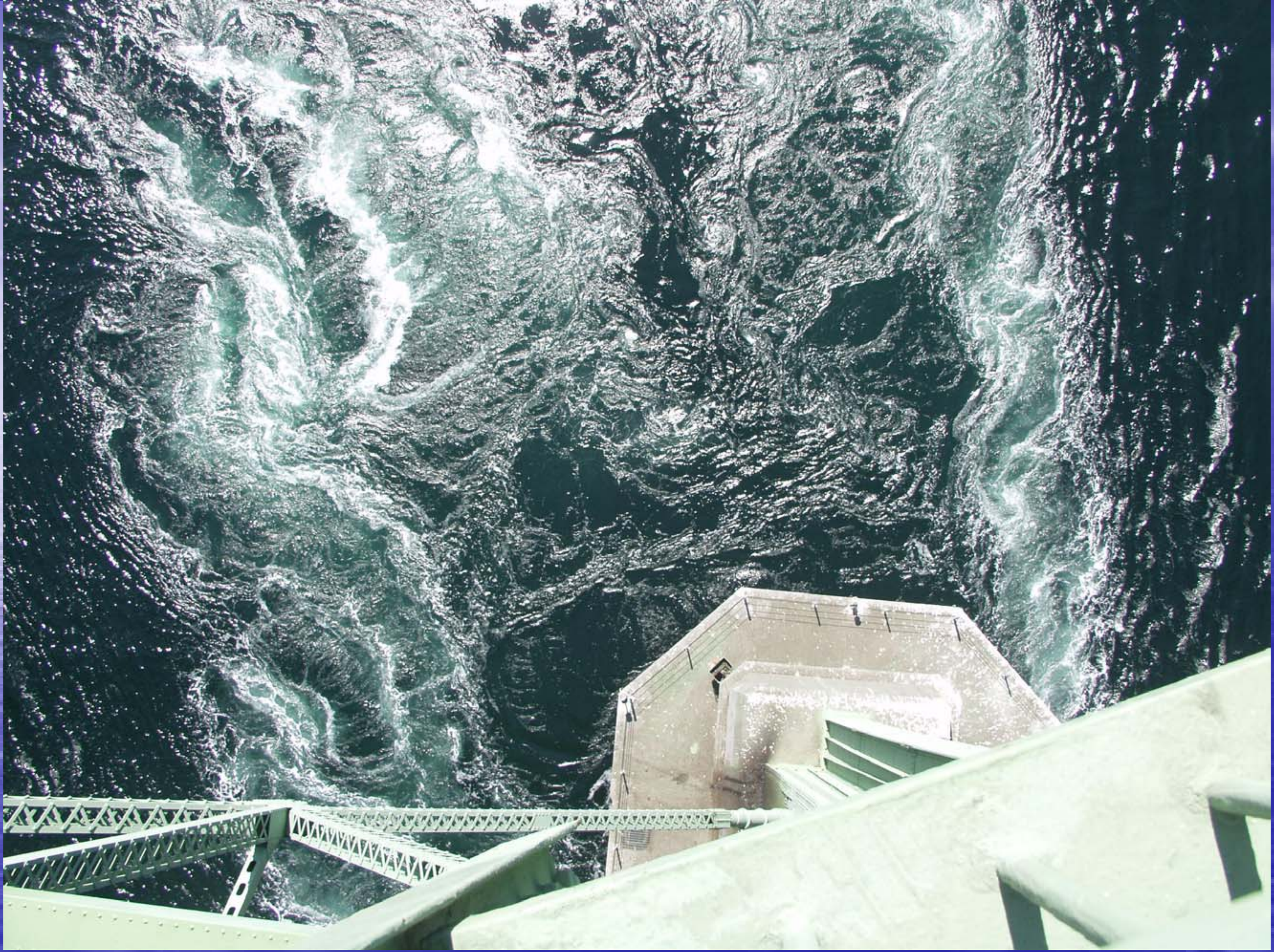

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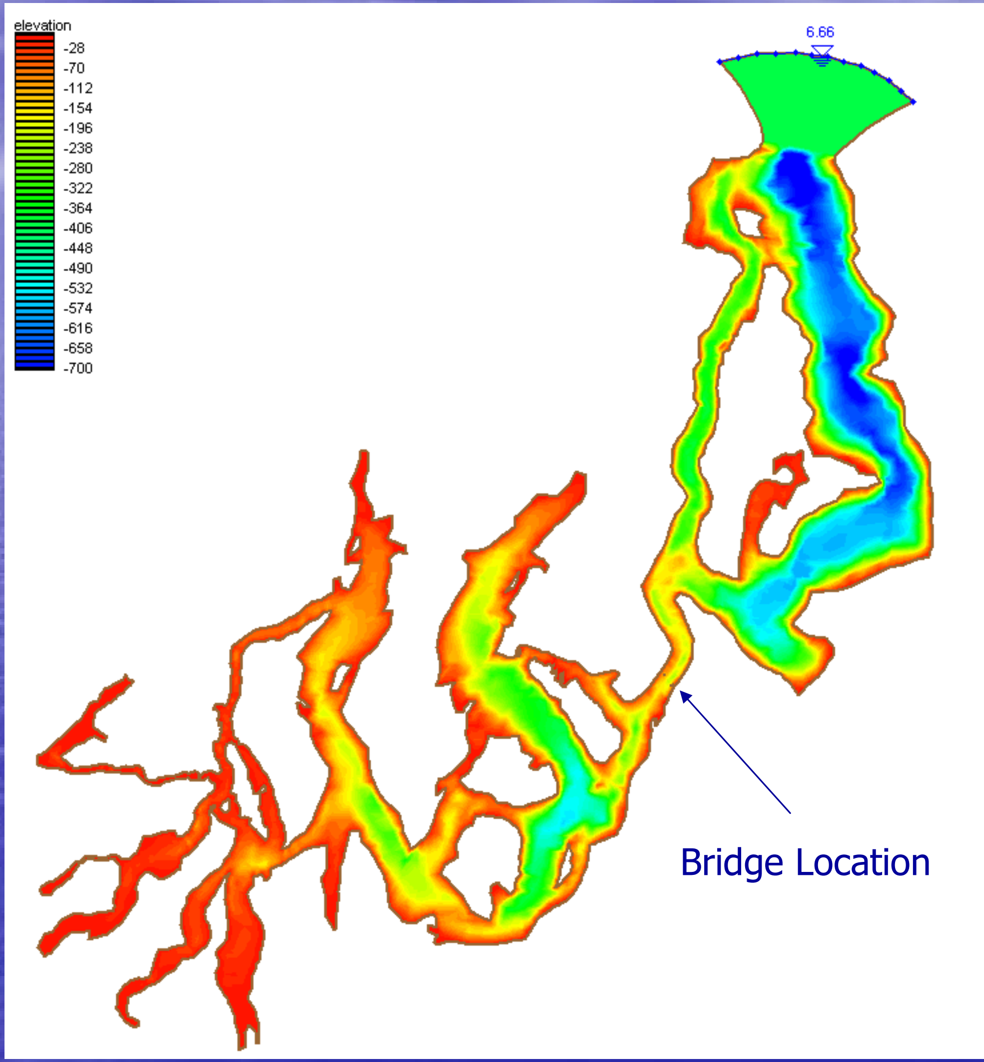
Hydraulics Models

- Both 1D and 2D (depth-averaged) models were used
- 2D Model (RMA2)
  - Mesh extends from Seattle to Olympia
  - 21,405 Nodes, 6,701 Elements
  - Element size range 200 ft^2 to 1.51 mi^2
  - Total mesh covers 297.7 mi^2
- Boundary conditions
  - Time varying water elevation at Seattle
  - Runoff discharge at 9 locations

Model Mesh



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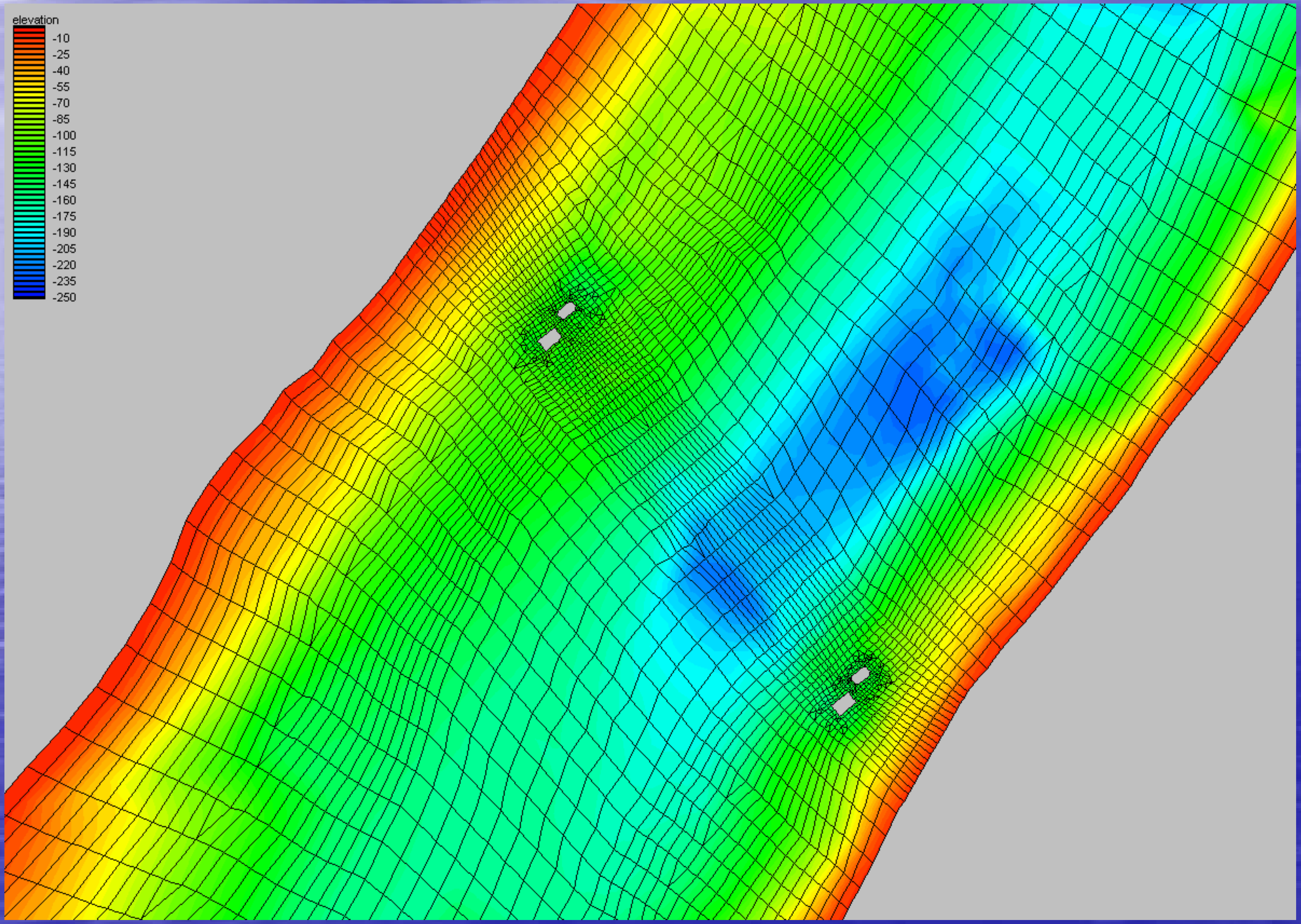
Model Mesh Near Piers



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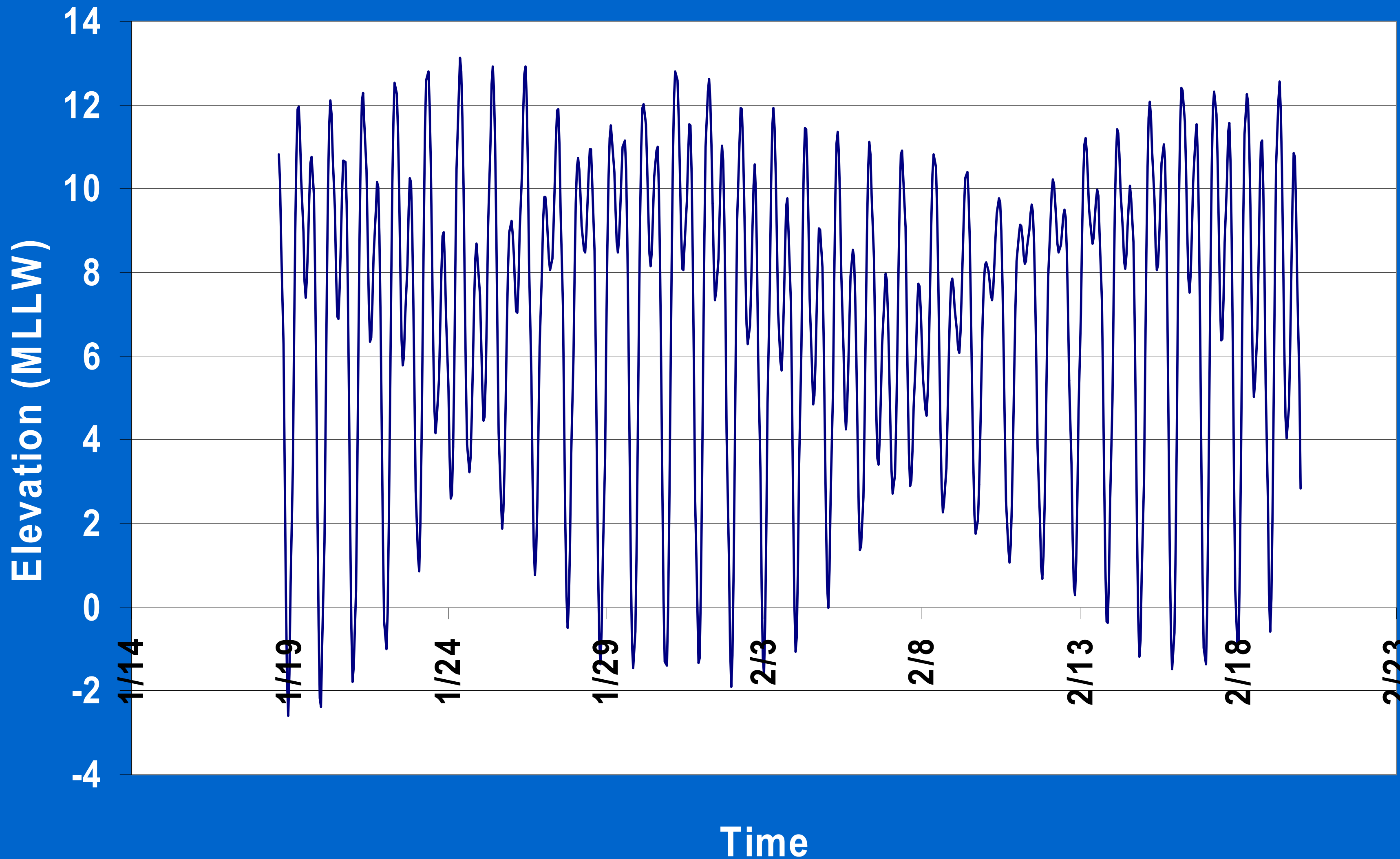
Model Calibration Data

- Acoustic Doppler Current Profiler (ADCP) data near site
  - Velocity profiles along boat path during peak spring tide flows
  - Relatively small changes in flow direction over depth above unscoured bed

Seattle Tide January 19-February 19 2003



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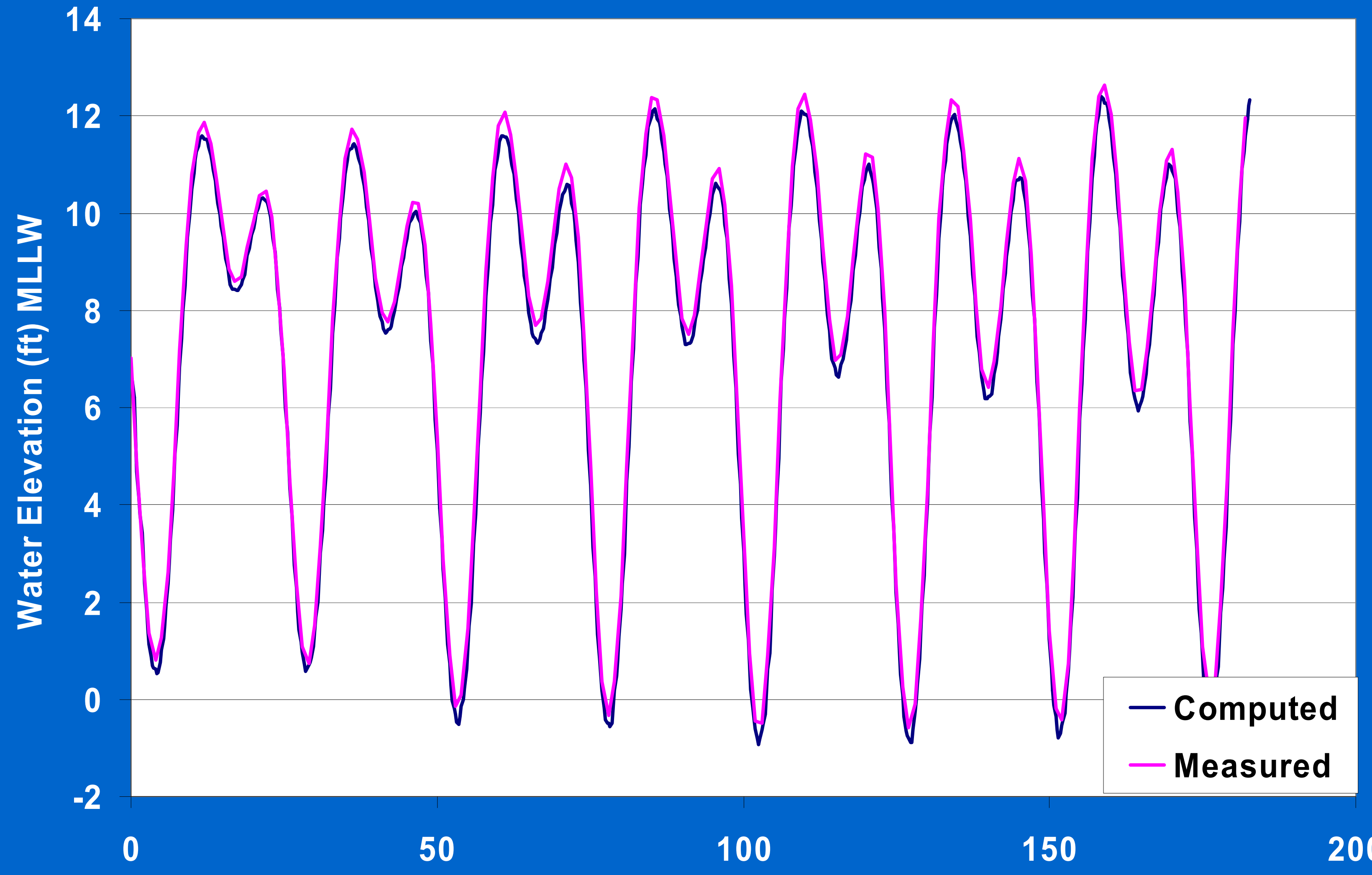
Commencement Bay Calibration



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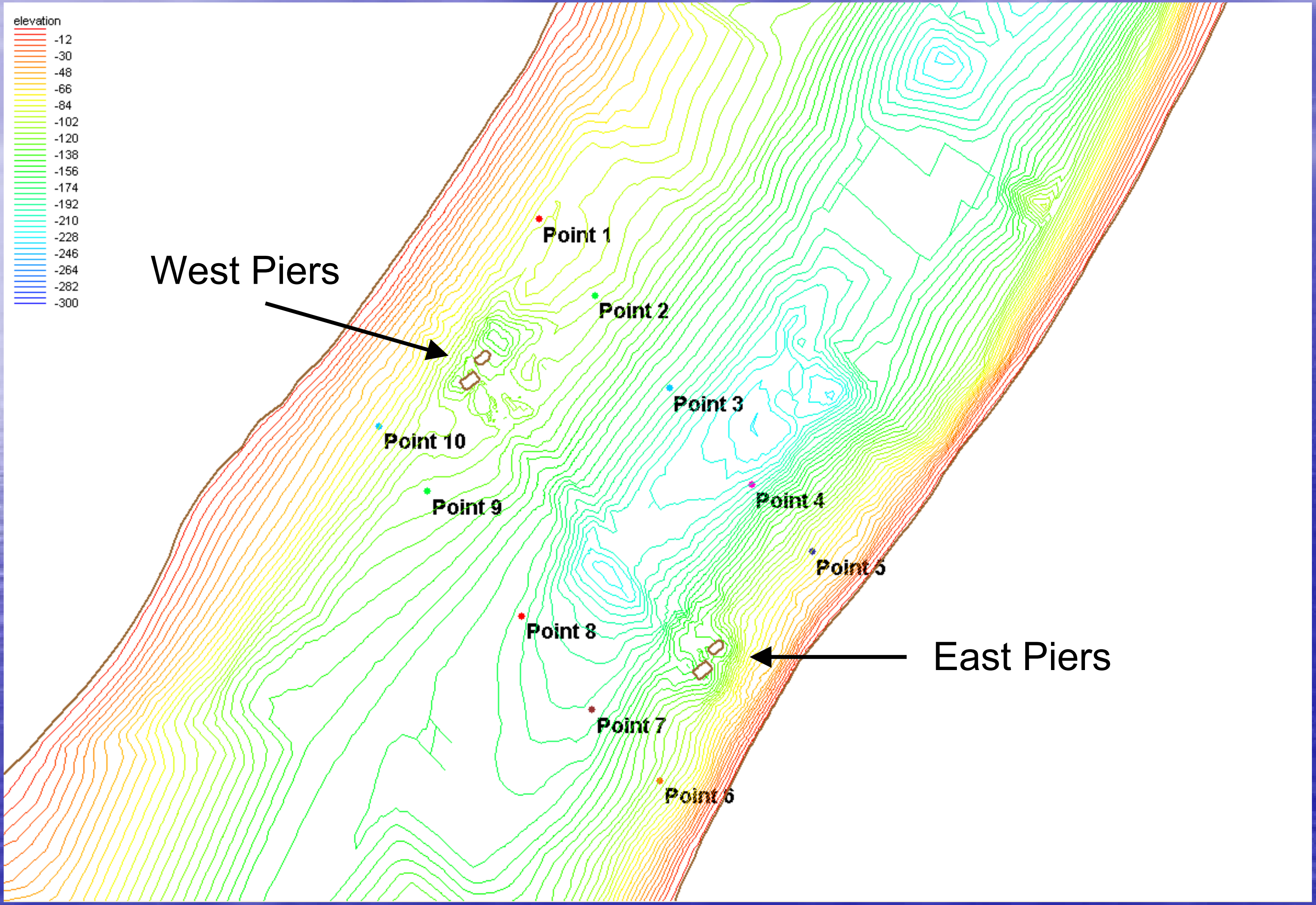
Points Used For Velocity Calibration



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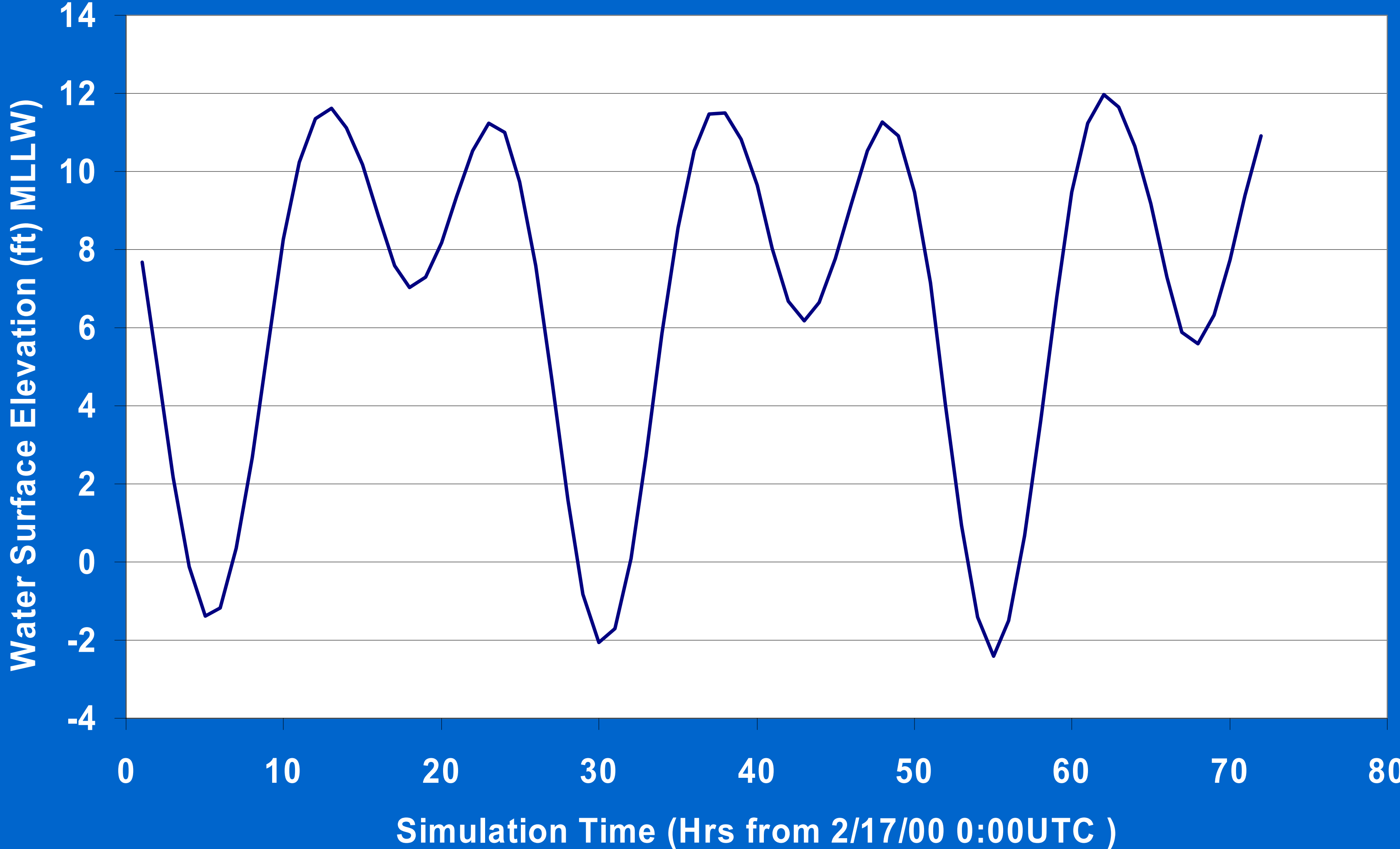
Seattle Tide
for Velocity Calibration



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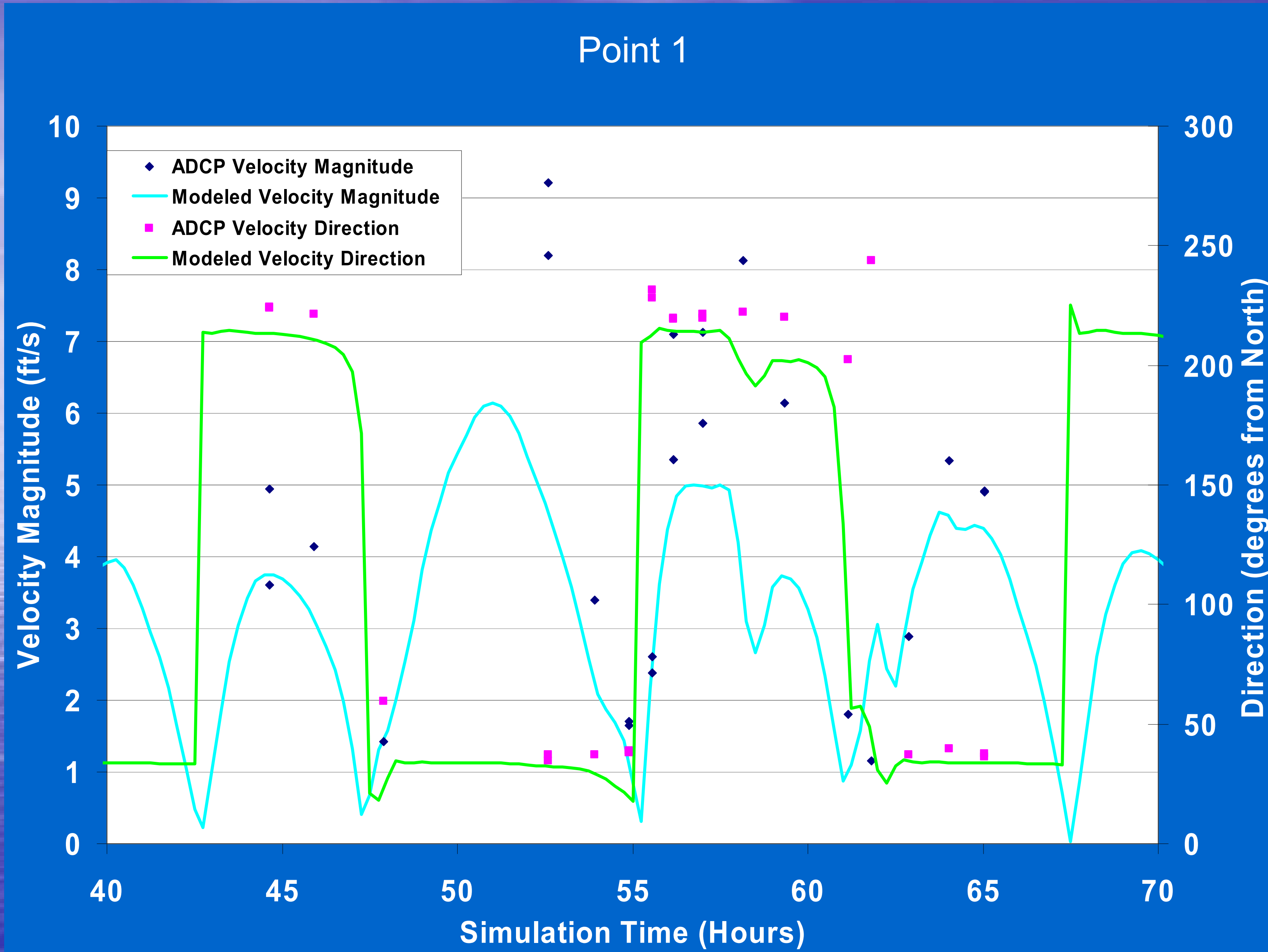

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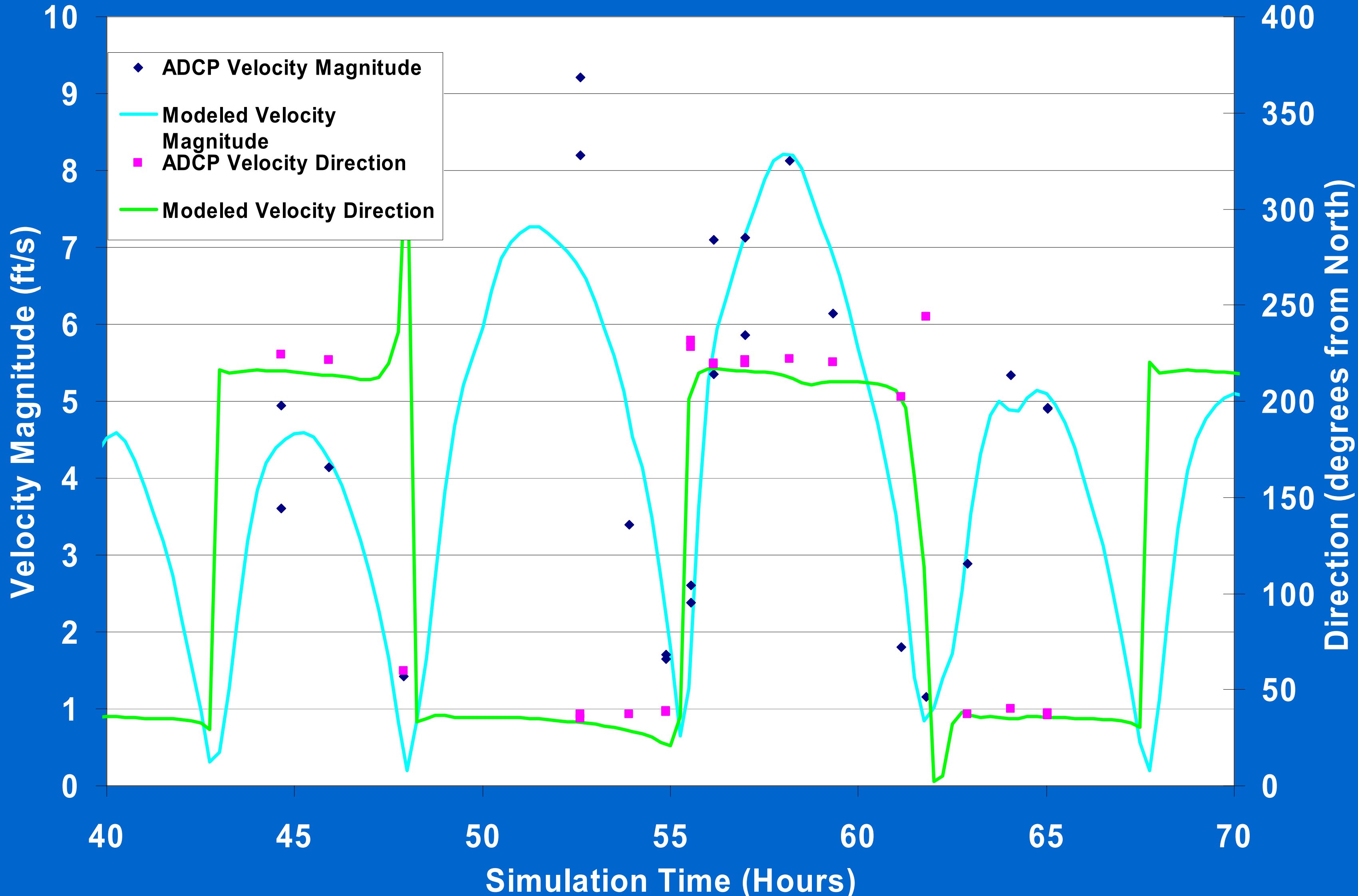
Point 2



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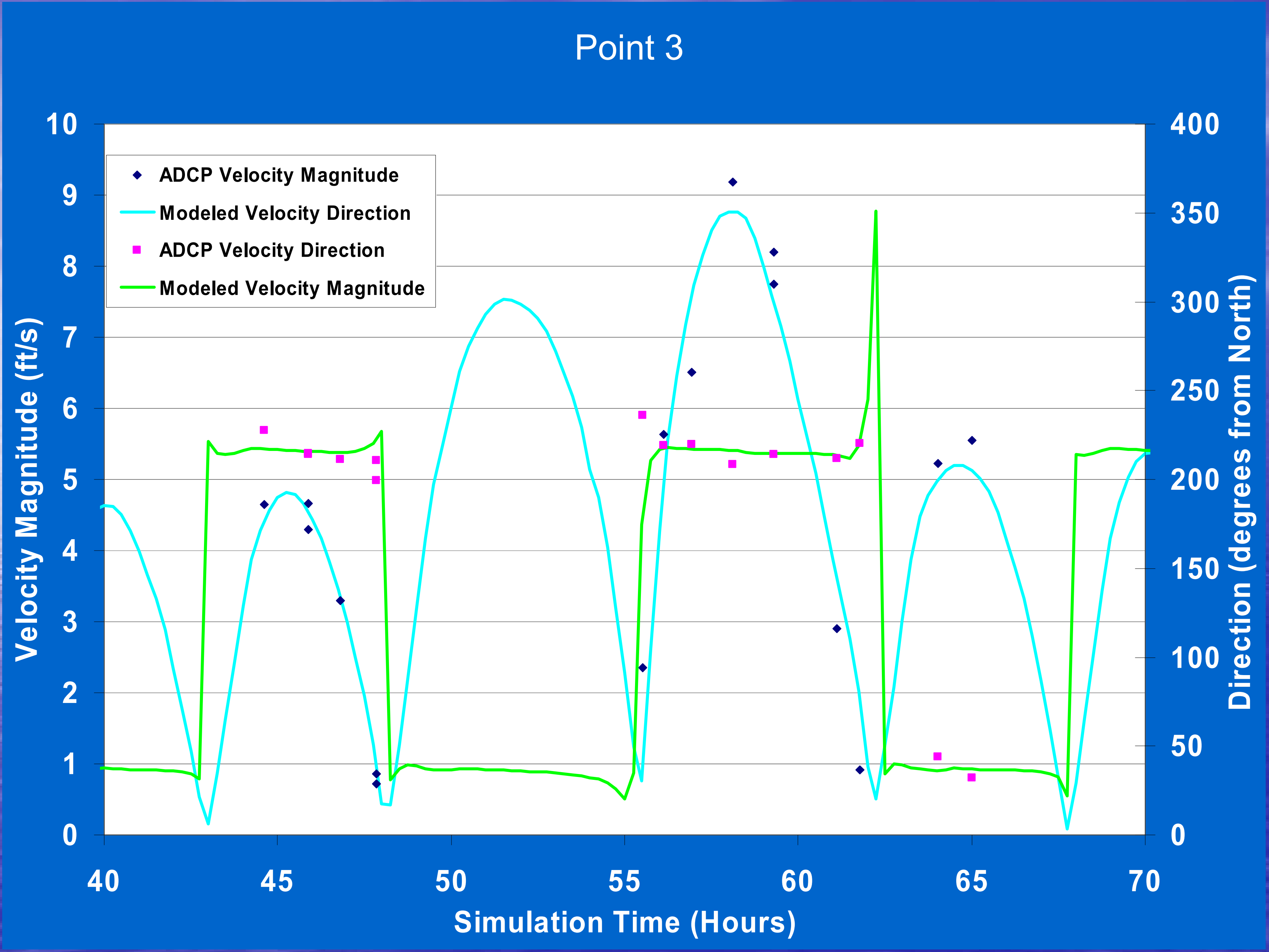

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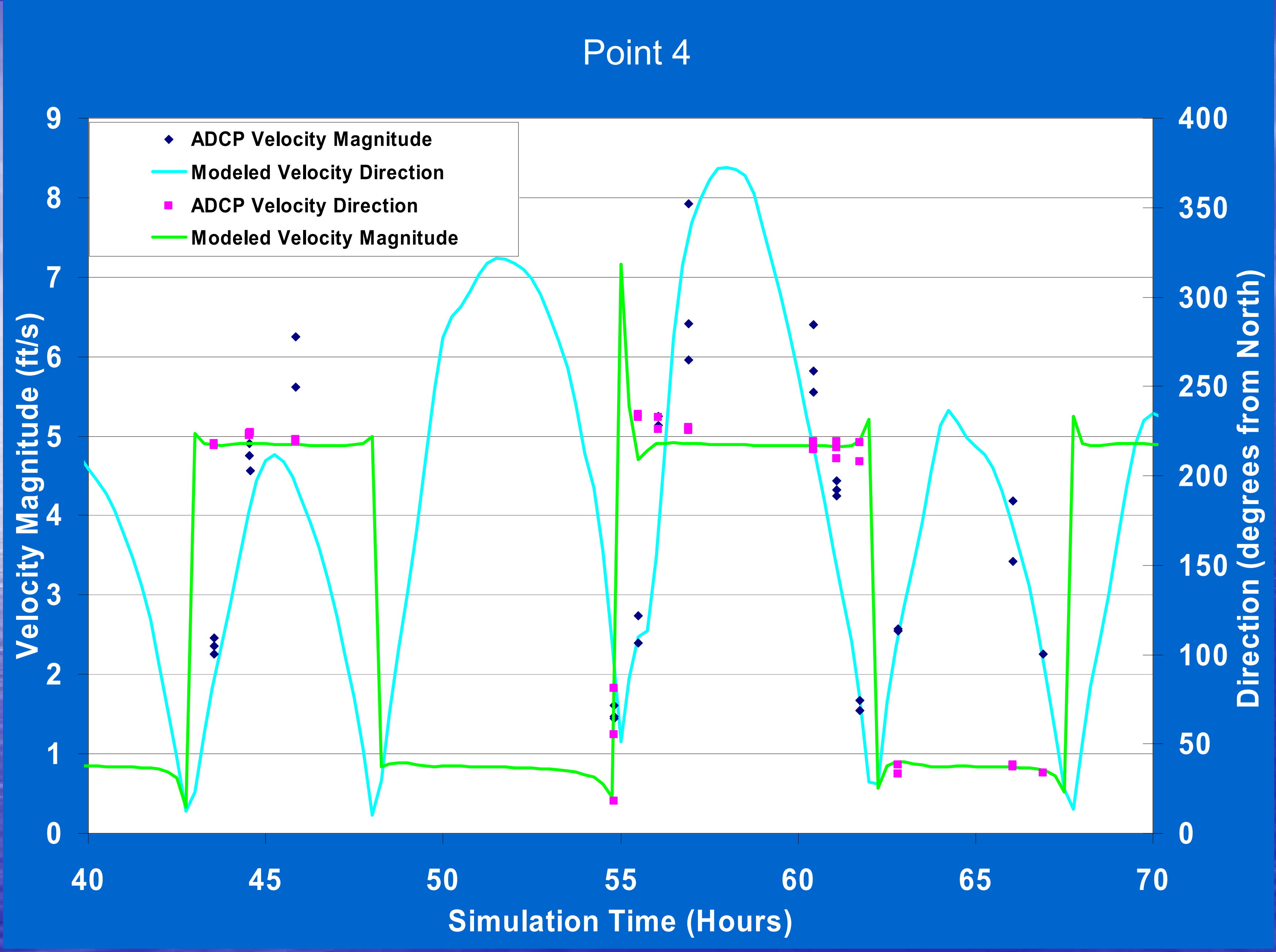

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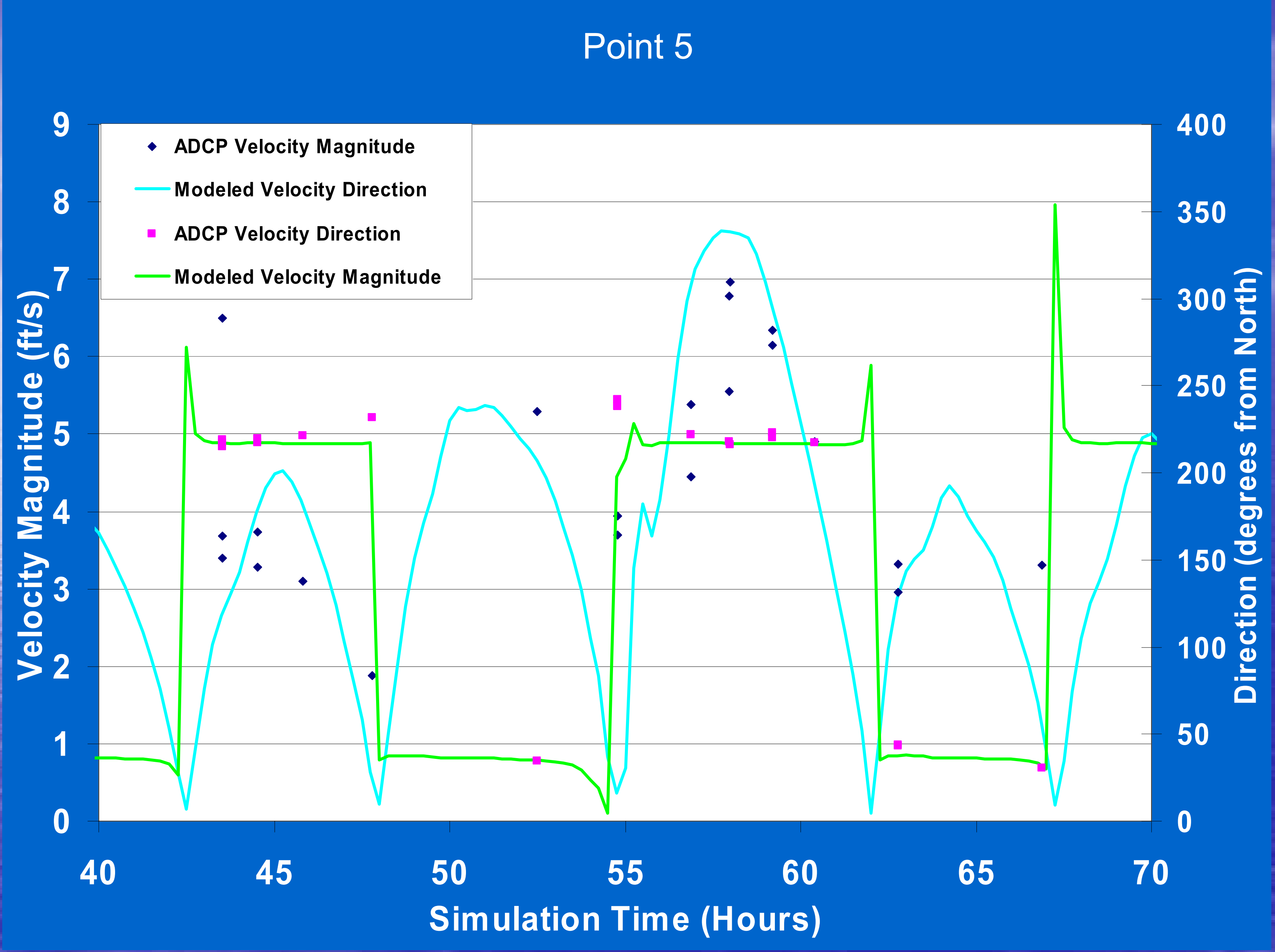

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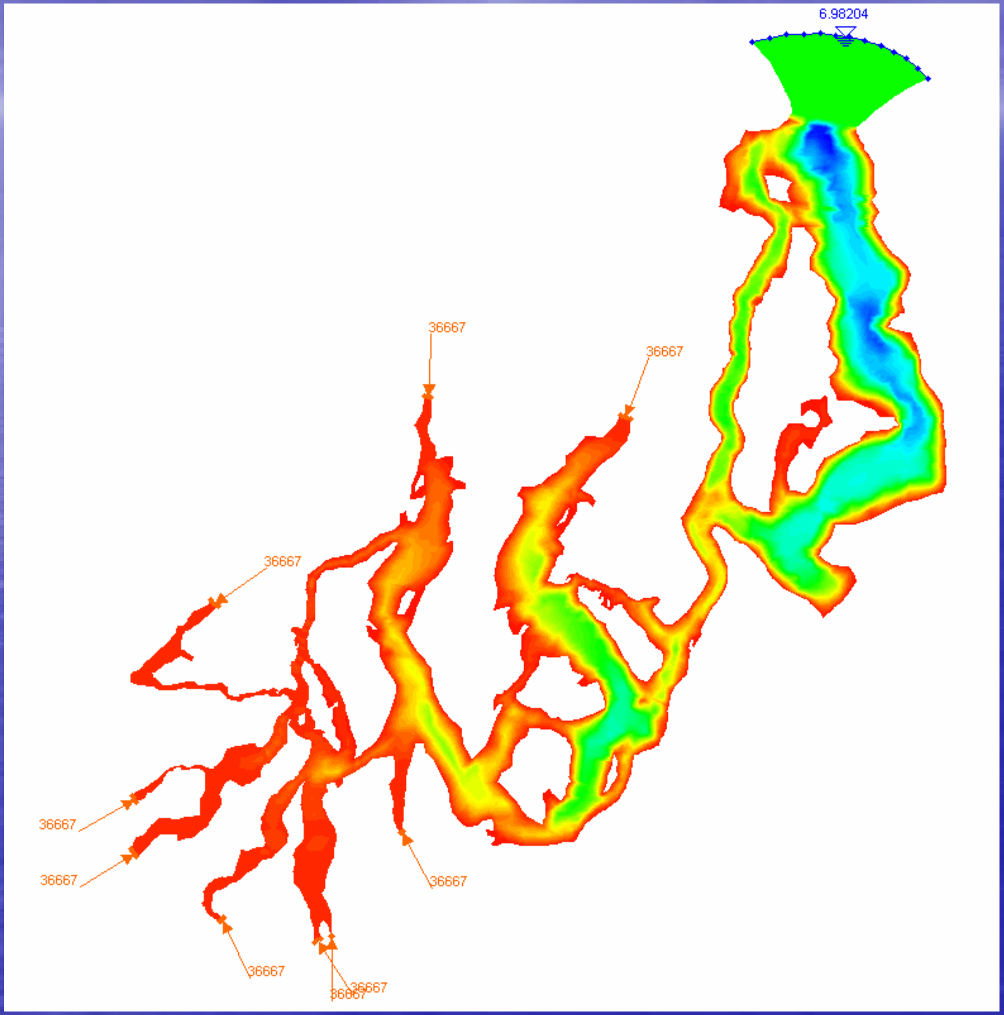
Model/Measurement Results

- Velocity Magnitude
  - Mean error -0.15 ft/s (6%)
  - RMS error 0.95 ft/s
  - Standard deviation error 18%
  - Increase computed values by 6%+18% = 24%
- Velocity Direction
  - Mean error +4.6 deg

Design Storm Water Runoff

- 100 year return interval
  - 330,000 cfs
- 500 year return interval
  - 561,000 cfs
- Discharges equally distributed among 9 locations

Mesh Boundary Conditions for Design Flows



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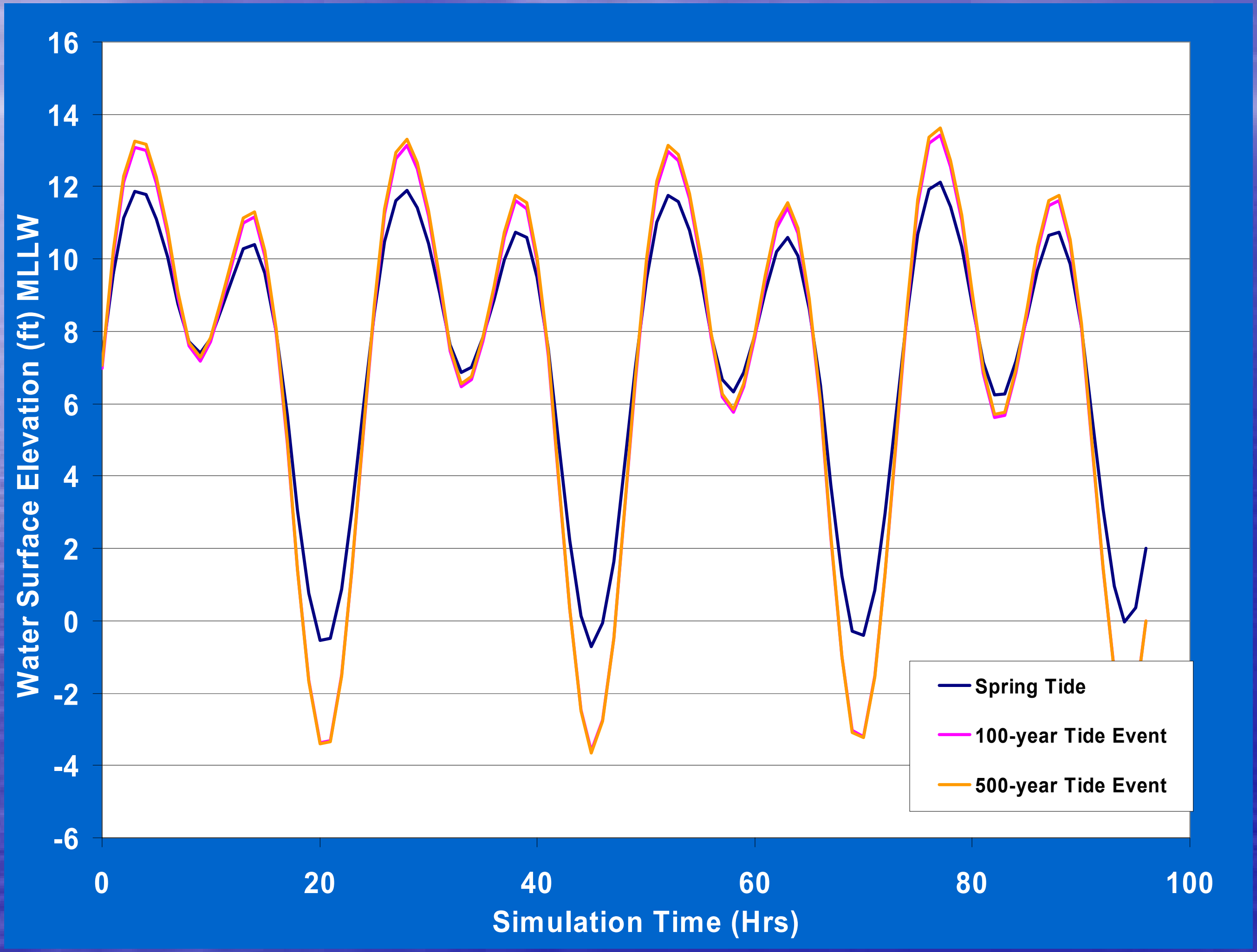
Water Elevation Boundary Conditions at Seattle



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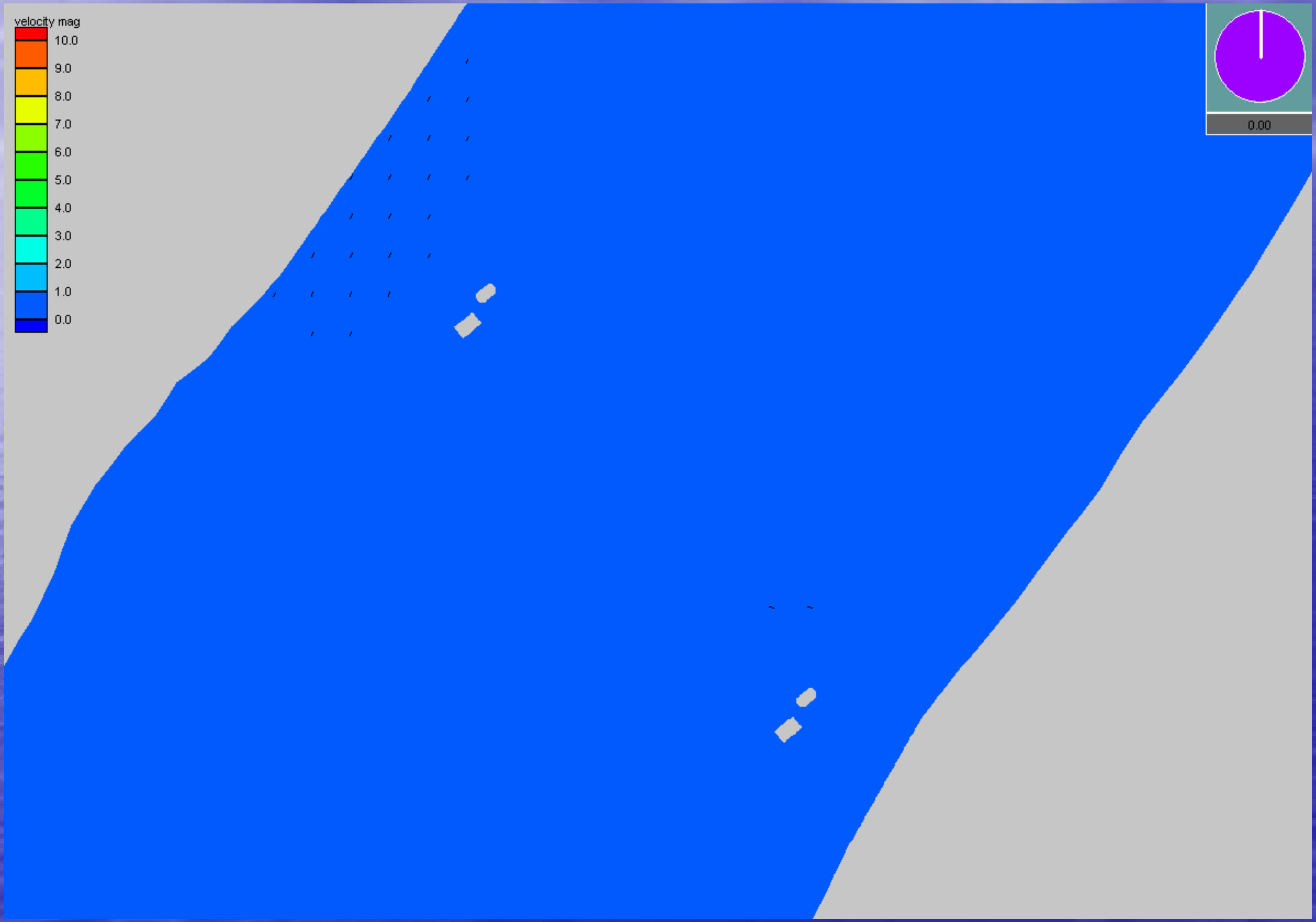
100 Year Flow Without Runoff



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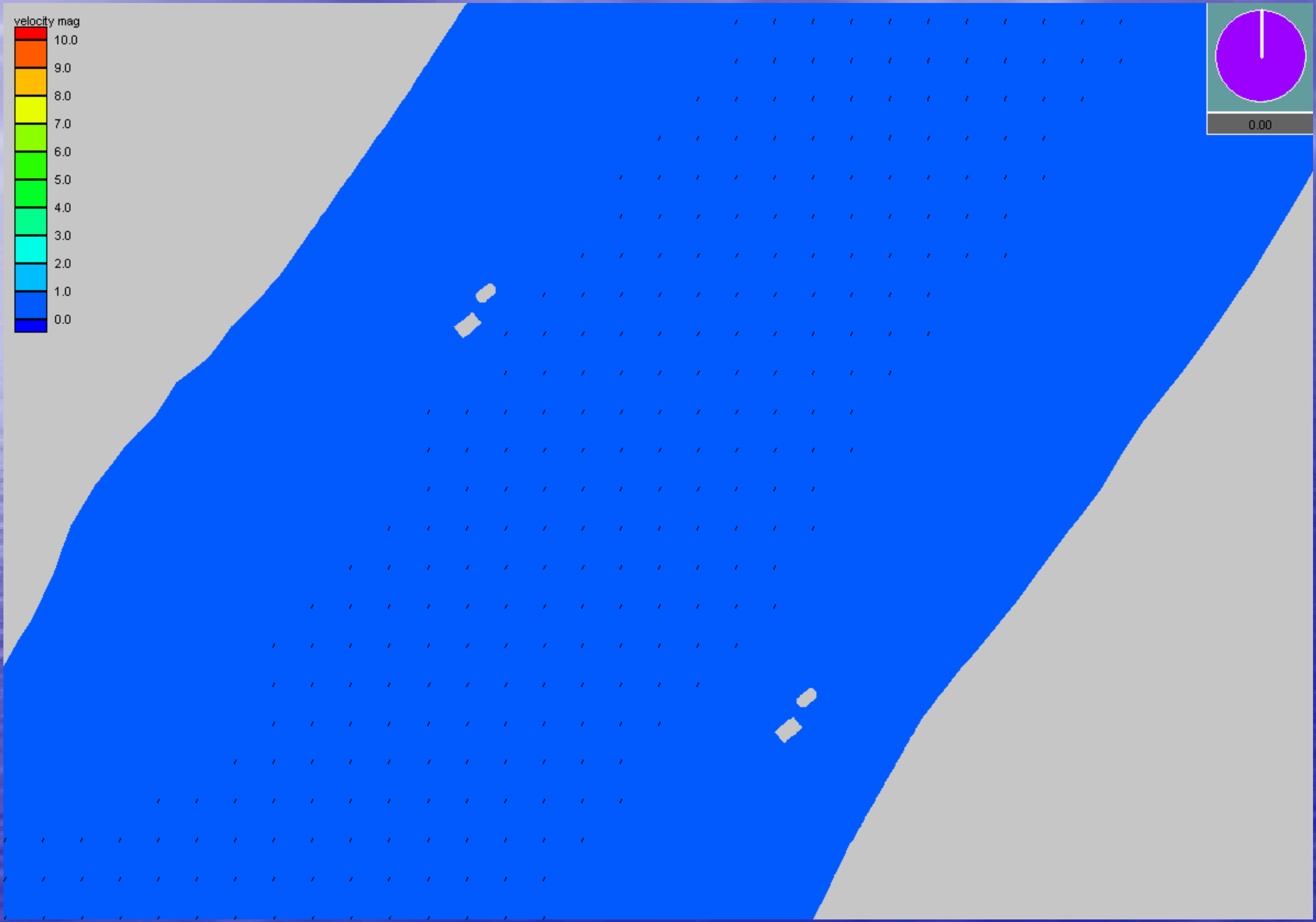
100 Year Flow With Runoff



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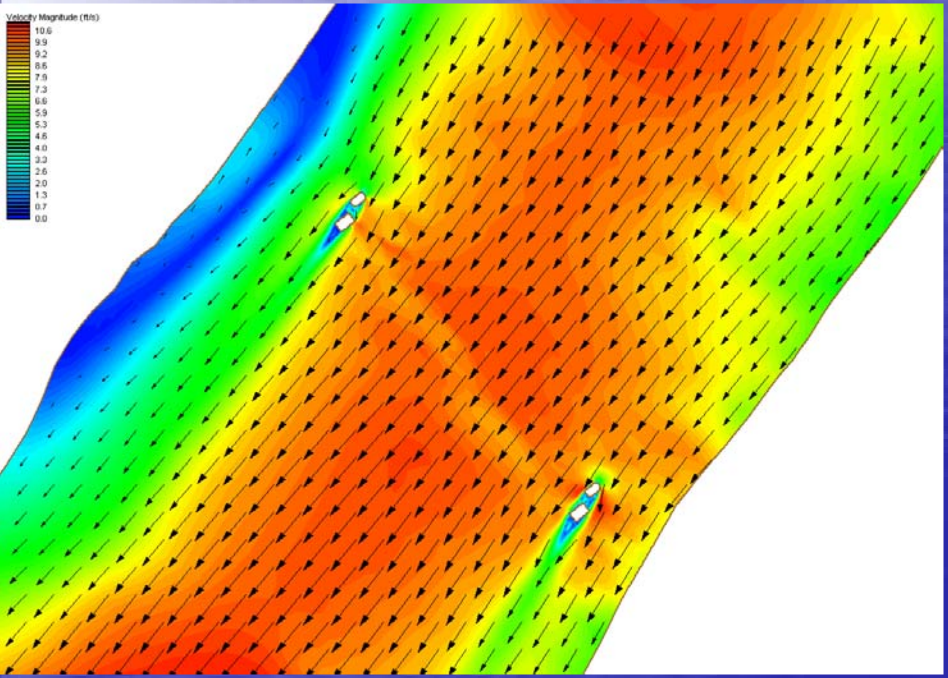
Model Results

- 100 year Storm Surge - Flood

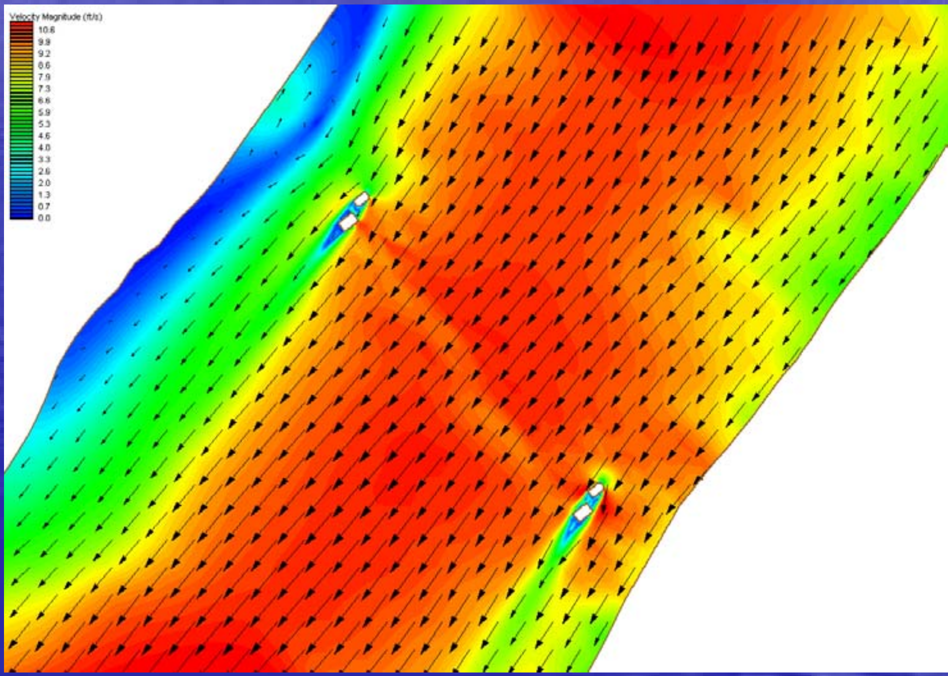
V(west) = 10.4 ft/s



V(east) =11.5 ft/s

No Runoff

V(west) = 11.3 ft/s



V(east) =12.5 ft/s

Runoff

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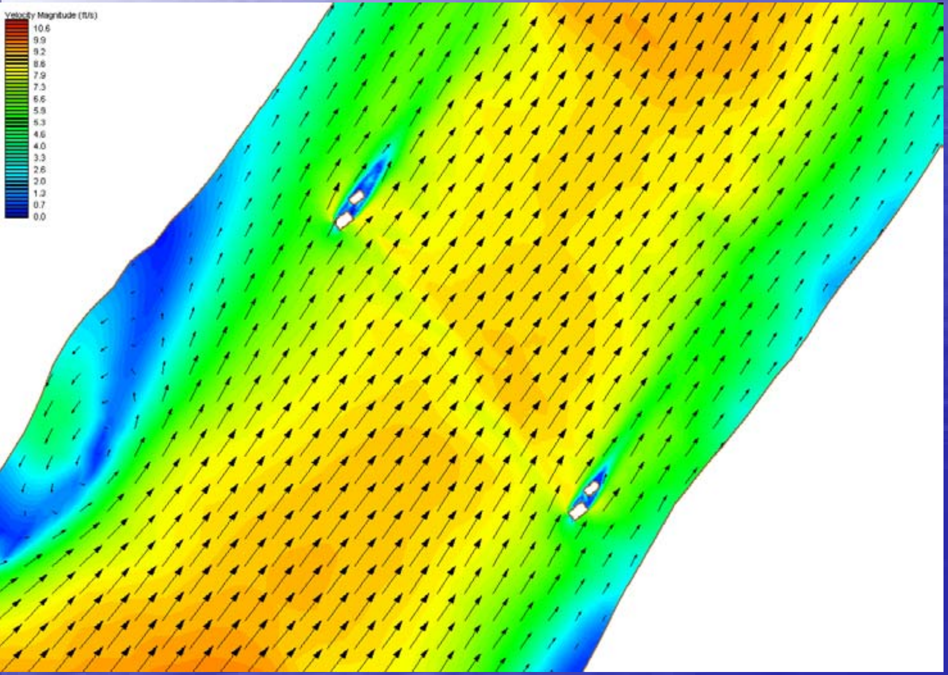
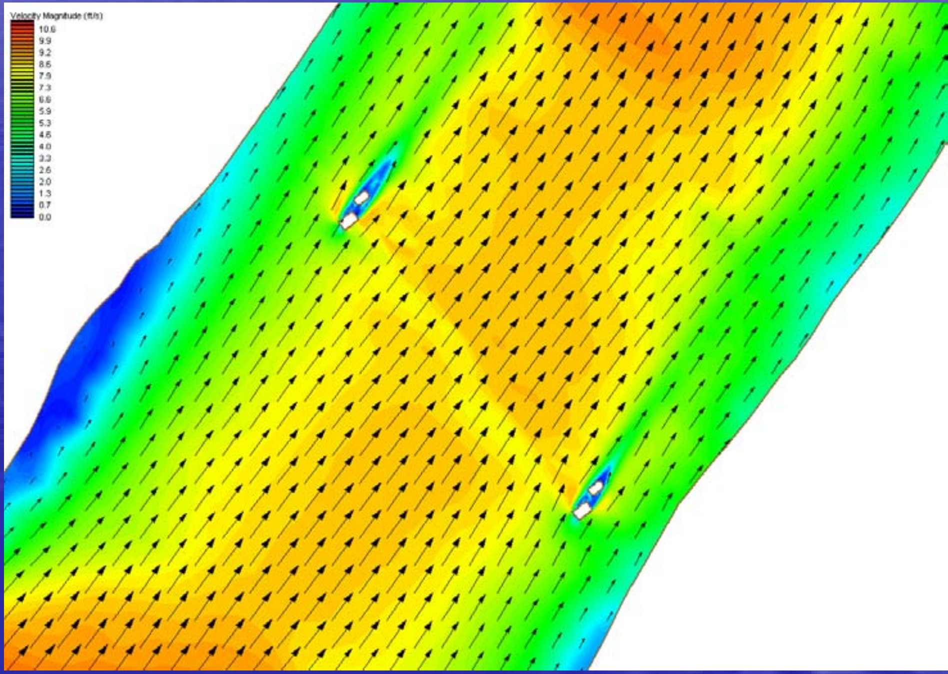
Model Results

- 100 year Storm Surge - Ebb

V(west) = 9.2 ft/s

V(west) = 9.5 ft/s





V(east) =8.6 ft/s

V(east) =9.1 ft/s

No Runoff

Runoff

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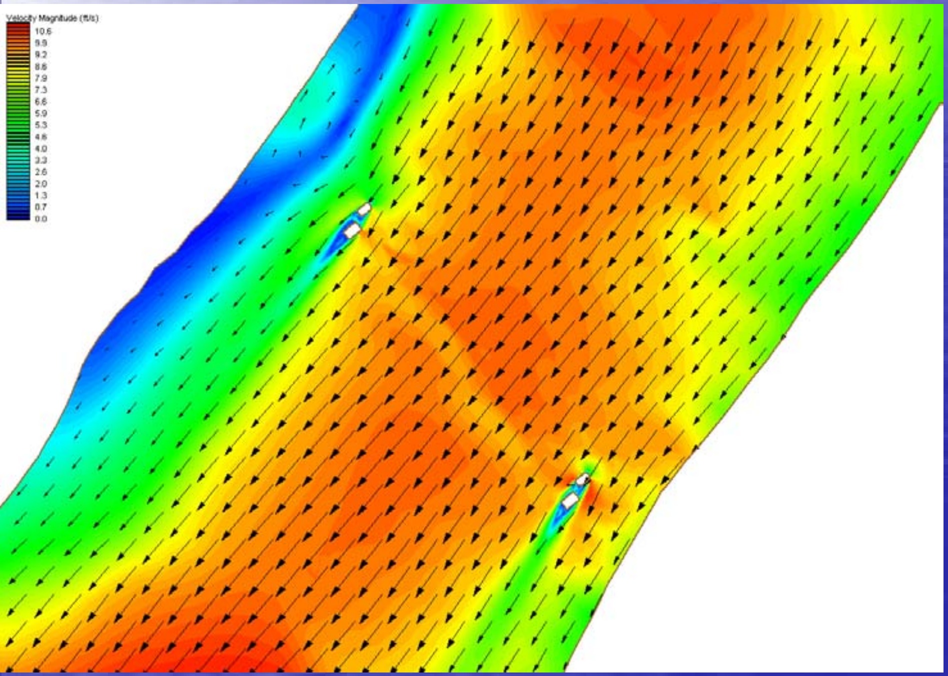
Model Results

- 500 year Storm Surge - Flood

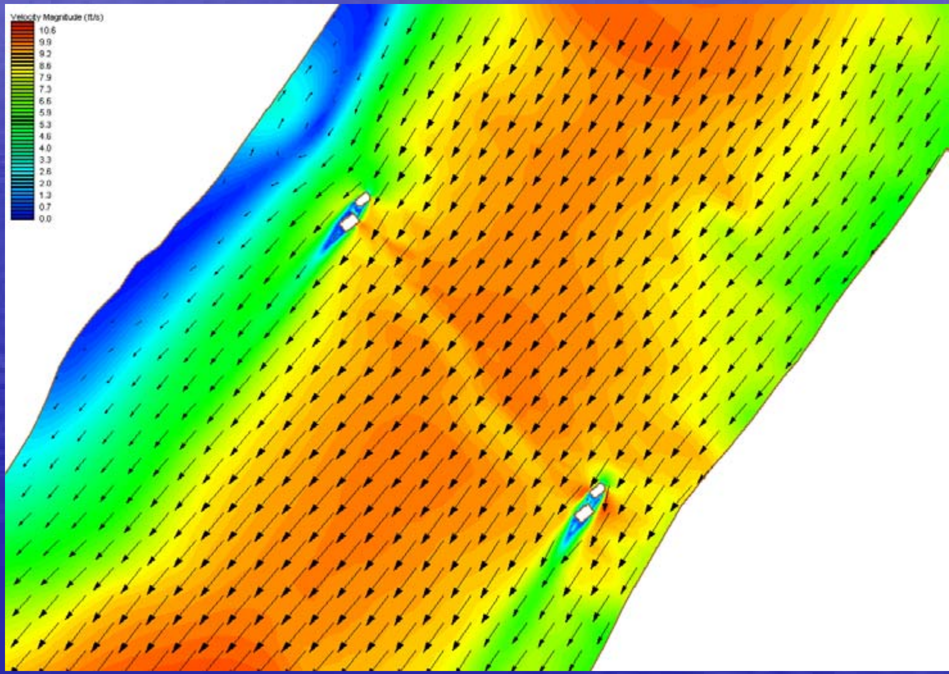
V(west) = 10.3 ft/s



V(east) =11.7 ft/s

No Runoff

V(west) = 10.5 ft/s



V(east) =11.3 ft/s

Runoff

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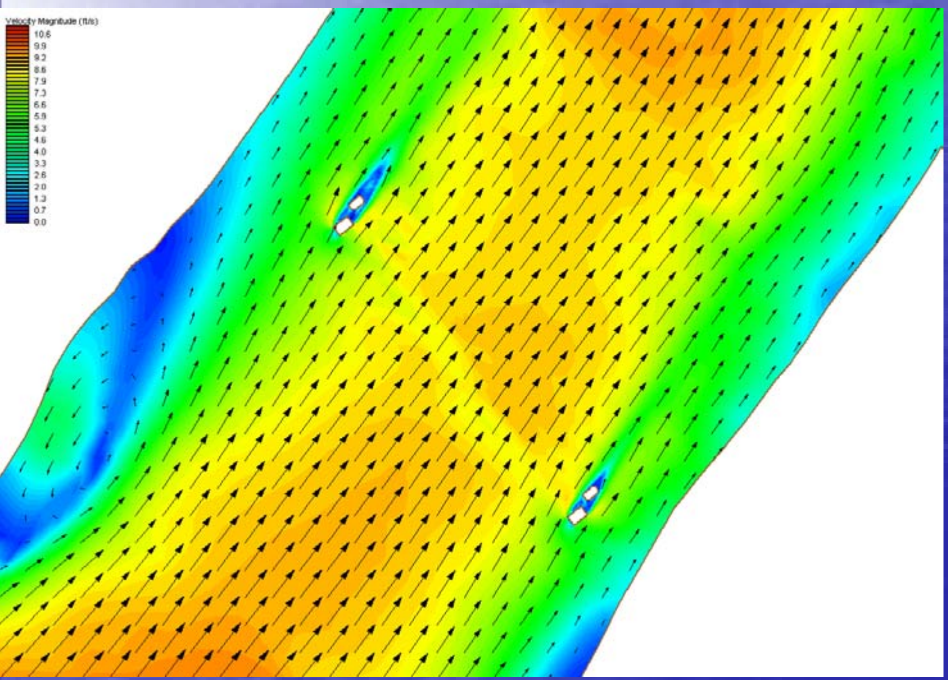
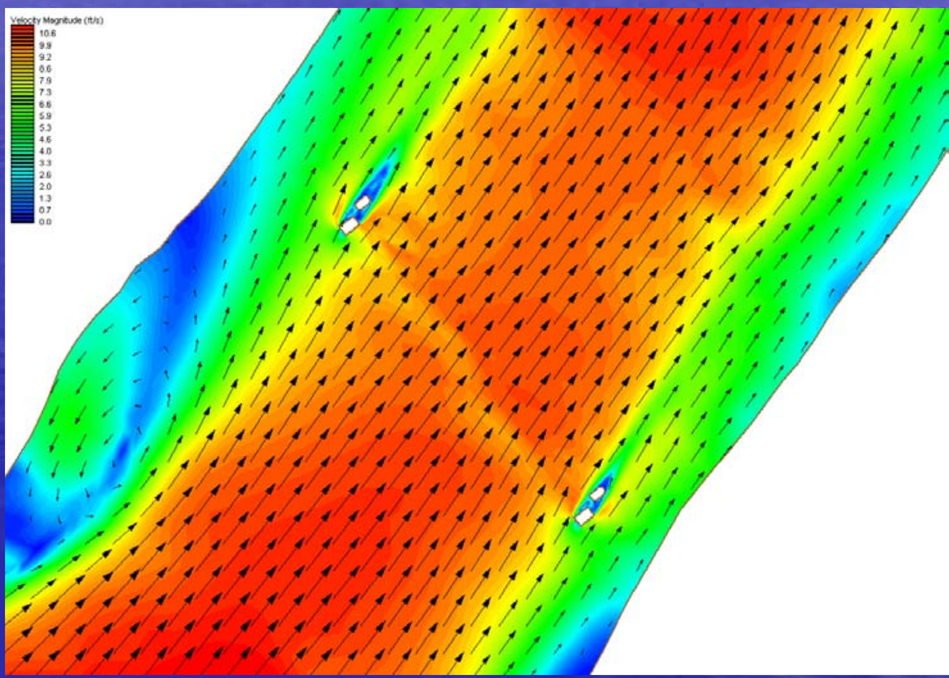
Model Results

- 500 year Storm Surge - Ebb

V(west) = 9.2 ft/s

V(west) = 10.0 ft/s





V(east) =8.7 ft/s

V(east) =9.9 ft/s

No Runoff

Runoff

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Design Flow Conditions

- 100 year return interval flows
  - East Piers
    - Flood flow with runoff
      - Velocity = 9.1 ft/s
      - Skew Angle = 20.1 deg
  - West Piers
    - Flood flow with runoff
      - Velocity = 11.3 ft/s
      - Skew Angle = 19.3 deg

Check Flow Conditions

- 100 year velocities Plus 10%
  - East Piers
    - Flood flow with runoff
      - Velocity = 10.0 ft/s
      - Skew Angle = 20.1 deg
  - West Piers
    - Flood flow with runoff
      - Velocity = 12.4 ft/s
      - Skew Angle = 19.3 deg

Sediment Transport - Bridge Scour

- Bed sediment
  - Fine sand D_{50} ~ 0.15 mm
  - Armor layer D_{50} ~ 50 mm
  - Even though high velocity flows bed is stable
  - Little sediment movement
  - Clearwater local scour conditions

Bridge Scour

- Aggradation – Degradation
  - Minimal
- Contraction Scour
  - Blockage due to existing and proposed piers minimal
- Local Scour
  - Existing Piers
  - Existing and New Piers

Local Scour

- Existing Piers
  - In place for ~ 63 years
  - East Pier
    - Rip rap placed in scour hole soon after construction
    - Higher velocity flows
  - West Pier
    - Natural armoring

Local Scour

- New Bridge Piers
  - To be located inland of existing piers
  - Larger in size than existing piers
  - In close proximity to existing piers
  - Centers of new and existing piers ~ inline with mean flow

Local Scour

- Design local scour analysis methodology
  - Use approach discussed in earlier presentation
  - Conduct physical model tests
  - Analyze test results
  - Use test results along with prototype flow and sediment conditions to determine prototype scour depths

Local Scour

- Local scour at existing piers
  - Records indicate equilibrium depths reached
  - Since clearwater scour conditions exist equilibrium depths due to peak velocities
  - East pier - scour depth effected by rip rap
  - West pier – natural armoring only

Local Scour

- Predicted/Measured scour depths at existing piers

PIER	PREDICTED SPRING TIDE SCOUR DEPTH HEC-18 (ft)	PREDICTED SPRING TIDE SCOUR DEPTH UF (ft)	MEASURED SCOUR DEPTH (ft)
EAST	86	57	24
WEST	82	57	36

Physical Model Scour Tests

- Tests conducted in Hydraulics Laboratory at Colorado State University (CSU)
- Model test philosophy:
  - Conduct tests to determine effective diameters for different pier/flow configurations
  - Account for scour modification agents in tests

Physical Model Scour Tests

- Factors that influence equilibrium scour depth
  - Flume sediment size distribution (armoring)

Bed Armoring in Model Tests

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Physical Model Scour Tests

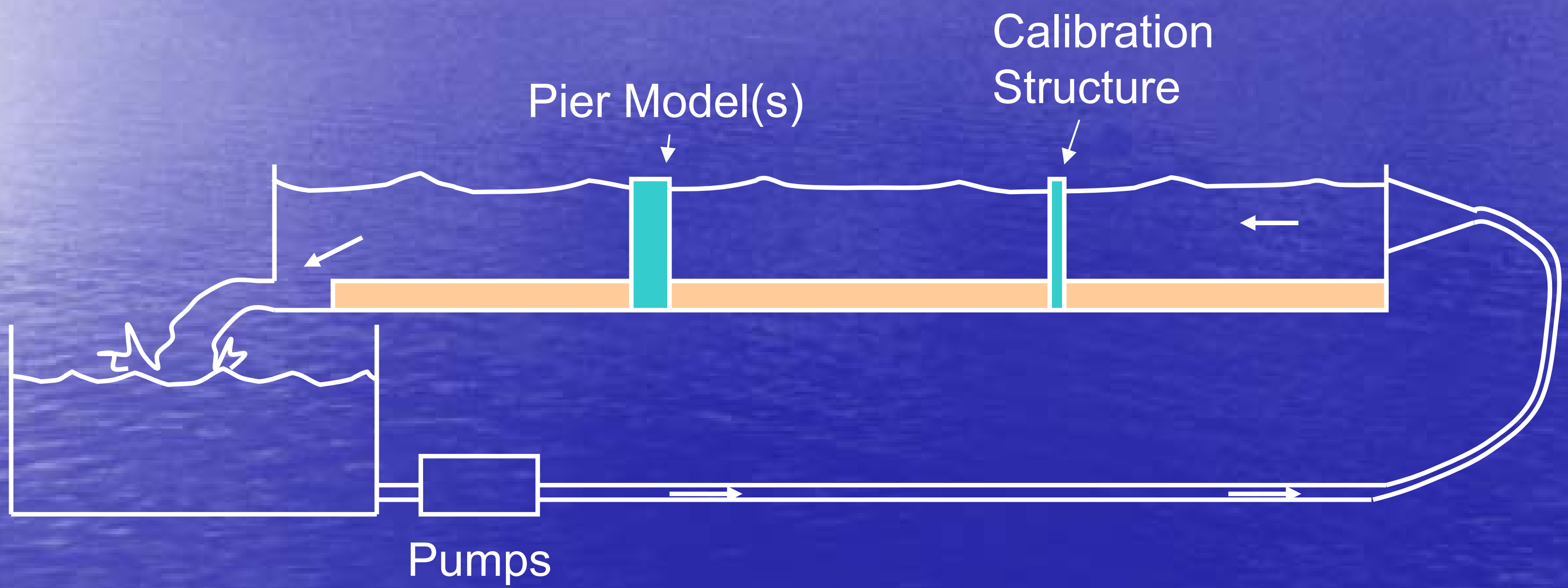
- Factors that influence equilibrium scour depth
  - Flume sediment size distribution (armoring)
  - Suspended fine sediment in water column
  - Fine sediments in bed materials (cohesive forces)
  - Duration of the test
  - Sediment supply (for live bed scour tests)

Physical Model Scour Tests

- How can you account for these factors and obtain an accurate equilibrium scour depth at the model?
  - If time/resources and flume permit, use a calibration structure

Physical Model Scour Tests

- Calibration structure



Schematic Drawing of the CSU Flume

Data Correction Procedure

- Compute the equilibrium scour depth for the calibration structure
- Divide computed by measured value
- Use this ratio to scale the measured value at the model pier to equilibrium

CSU Flume

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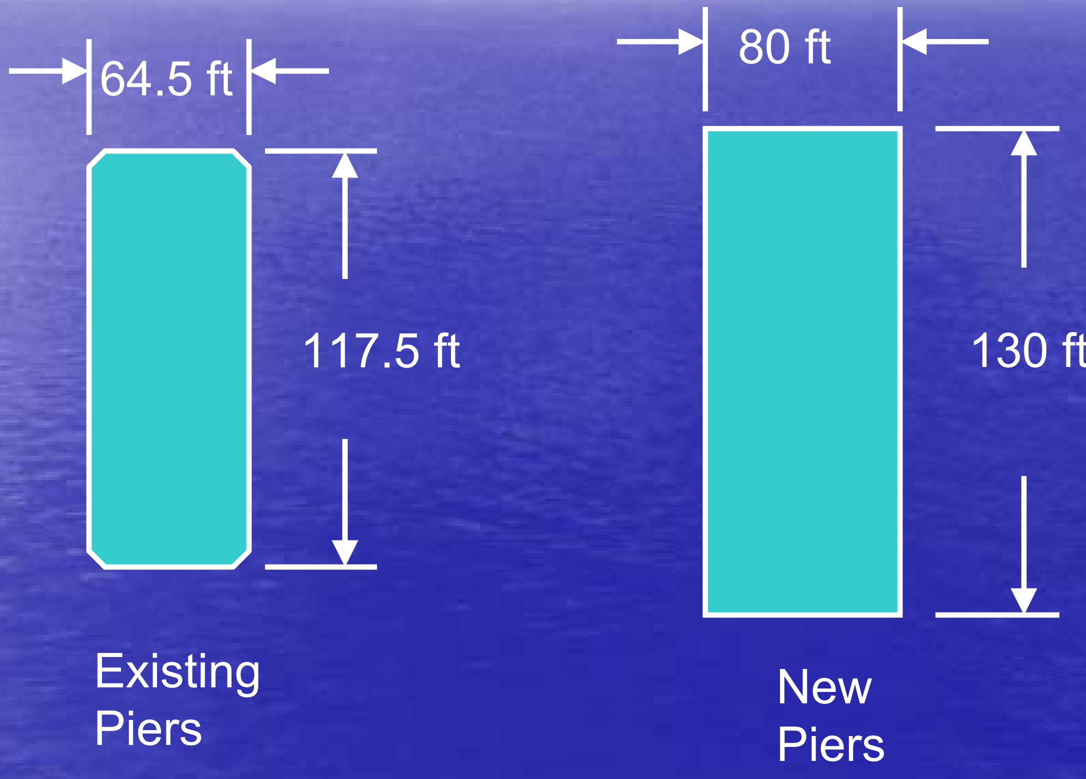
CSU Flume

Existing and New Prototype Pier Dimensions



Existing Pier Models

Scale
1:120

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New Pier Models

Scale
1:120

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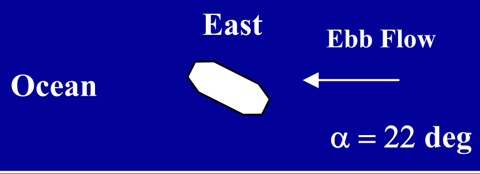
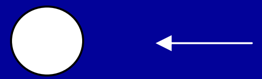
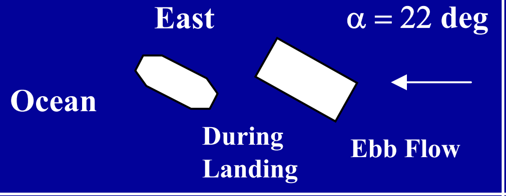
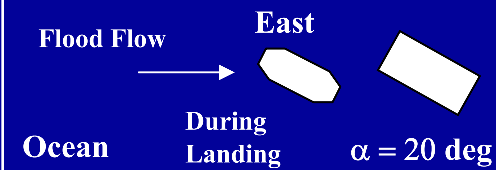
Physical Model tests

Test	Structure(s)	Depth (ft)	Velocity (ft/s)	Scour (ft)
1P		1.28	0.95	-
1S		1.26	0.92	0.27
2P		1.34	0.95	0.16
2S		1.34	0.95	0.15

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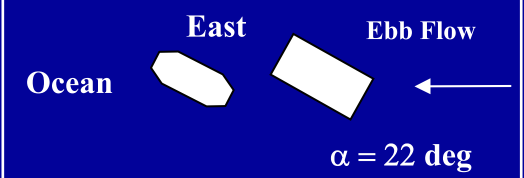
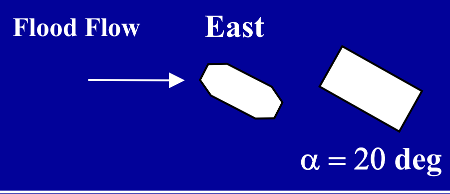
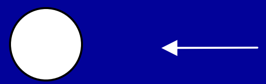
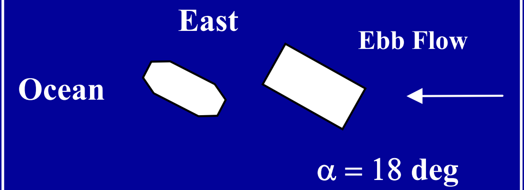
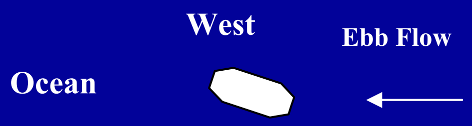
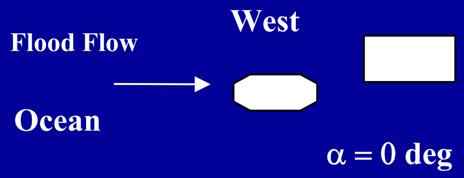
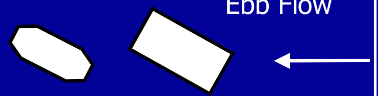
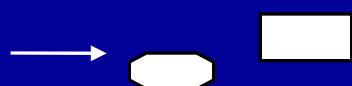
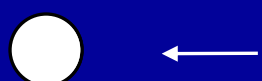
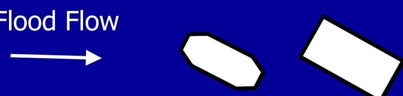
Physical Model tests (cont.)

Test	Structure(s)	Depth (ft)	Velocity (ft/s)	Scour (ft)
3P		1.19	1.03	0.56
3S		1.30	0.99	0.58
4P		1.11	0.92	0.36
4S		1.18	0.87	0.28

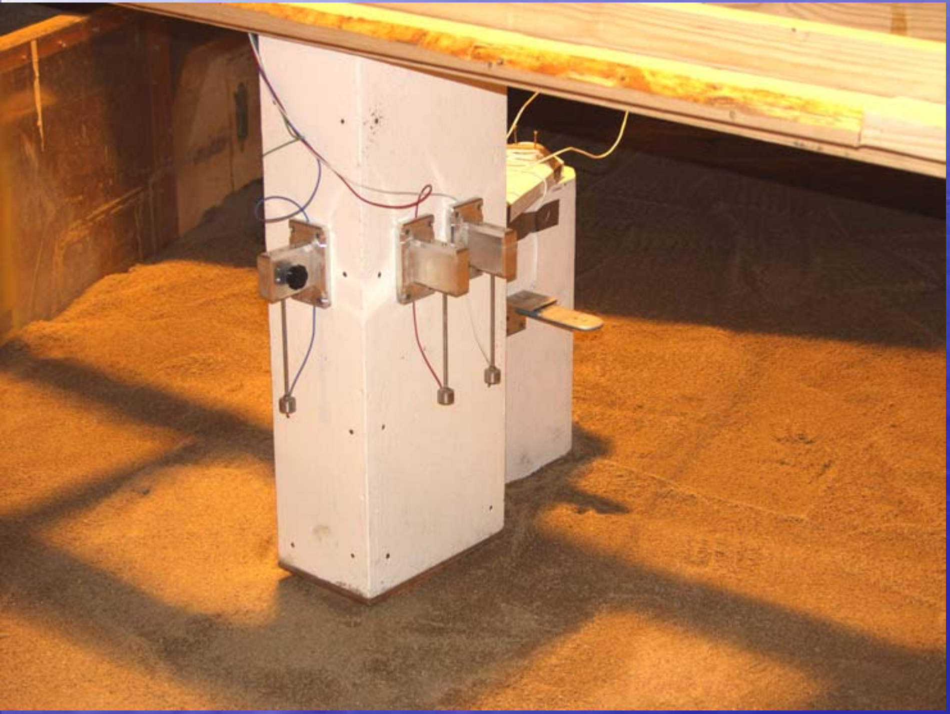
Physical Model tests (cont.)

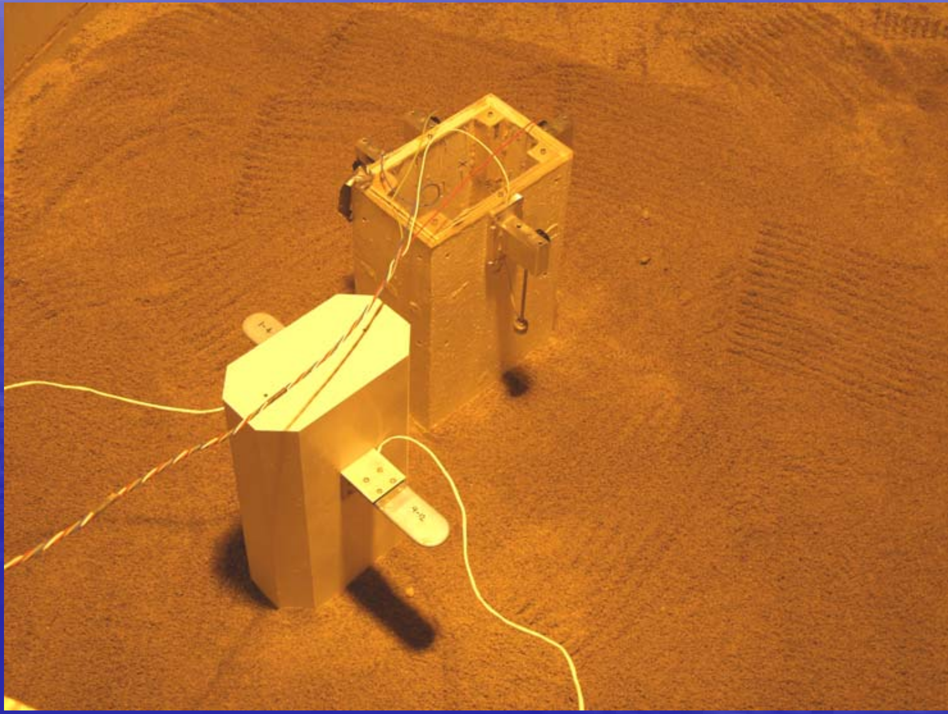
Test	Structure(s)	Depth (ft)	Velocity (ft/s)	Scour (ft)
5P		1.0	1.02	0.32
5S		1.14	0.94	0.32

Physical Model tests (cont.)

Test	Structure(s)	Depth (ft)	Velocity (ft/s)	Scour (ft)
6P	 Ebb Flow Ocean Rip-rap $\alpha = 22$ deg	1.32	1.04	0.32 0.06
6S	 Flood Flow Ocean Rip-rap $\alpha = 0$ deg	1.32	1.07	0.00 0.22
7P		1.22	1.00	0.36
7S	 Flood Flow Ocean $\alpha = 24$ deg	1.37	0.97	0.41

Scour Instrumentation





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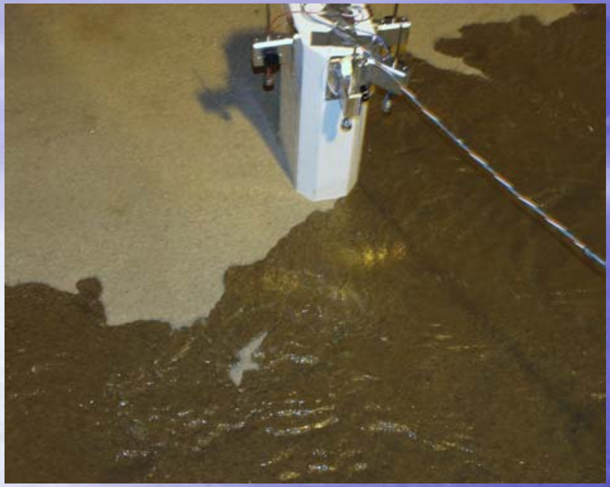

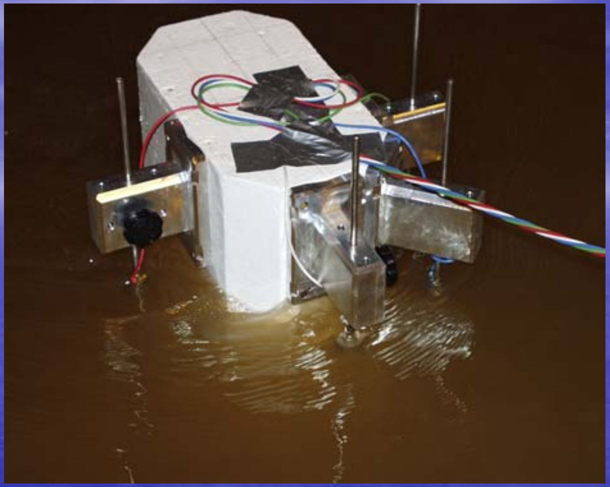


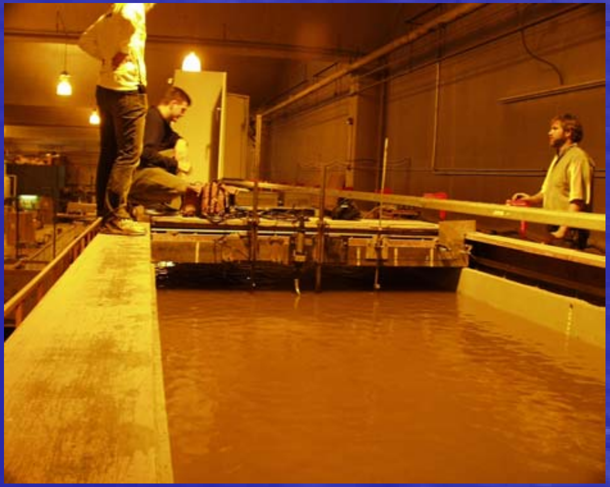

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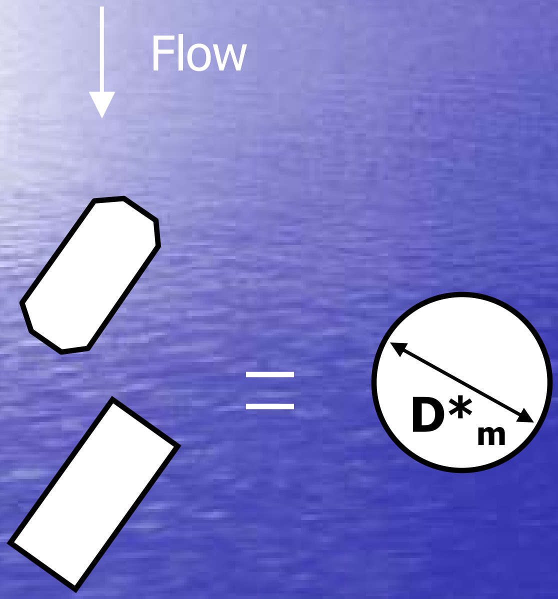
Procedure to Obtain Prototype Scour Depths from Physical Model Results



1. Adjust measured scour depth for:
   - flume sediment sigma
   - suspended fine sediment
   - duration of test
2. Compute D^*_m for Model
3. Compute D^*_p for Prototype ($120 \times D^*_m$)
4. Compute Design Scour Depth for Prototype

- Determine effective diameter of models, D_m^*

$$\frac{y_s}{D_m^*} = K_s \, 2.5 \, f_1\left(\frac{y_0}{D_m^*}\right) f_2\left(\frac{V}{V_c}\right) f_3\left(\frac{D_m^*}{D_{50}}\right)$$

where

$y_s \equiv$ maximum measured scour depth

Compute Effective Diameter of Prototype,

$$D_p^* = 120\ D_m^*$$

Compute Prototype Scour Depth

- Clearwater scour

$$y_s = D_p^* K_s \; 2.5 \; f_1\left(\frac{y_0}{D_p^*}\right) f_2\left(\frac{V}{V_c}\right) f_3\left(\frac{D_p^*}{D_{50}}\right)$$

- Live Bed scour

$$y_s = D_p^* f\left(\frac{y_0}{D_p^*}, \frac{V}{V_c}, \frac{D_p^*}{D_{50}}, \frac{V_{lp}}{V_c}\right)$$

Scour Calculations

- Inputs
  - 2D Flow Model Results
  - D^*_p computed from model test results
  - Pre-1939 Mudline
    - East Caisson Bed Elevation = -117 (NAVD 88)
    - East Caisson Bed Elevation = -97 (NAVD 88)
- Calculate Scour for 100, 500-year and Check Event with and without Runoff

Design Scour Calculations Input

Piers	V (ft/s)	y_0 (ft)	D_{50} (mm)	D^* (ft)
East	9.1	123	0.15	105
West	11.3	113	0.15	98

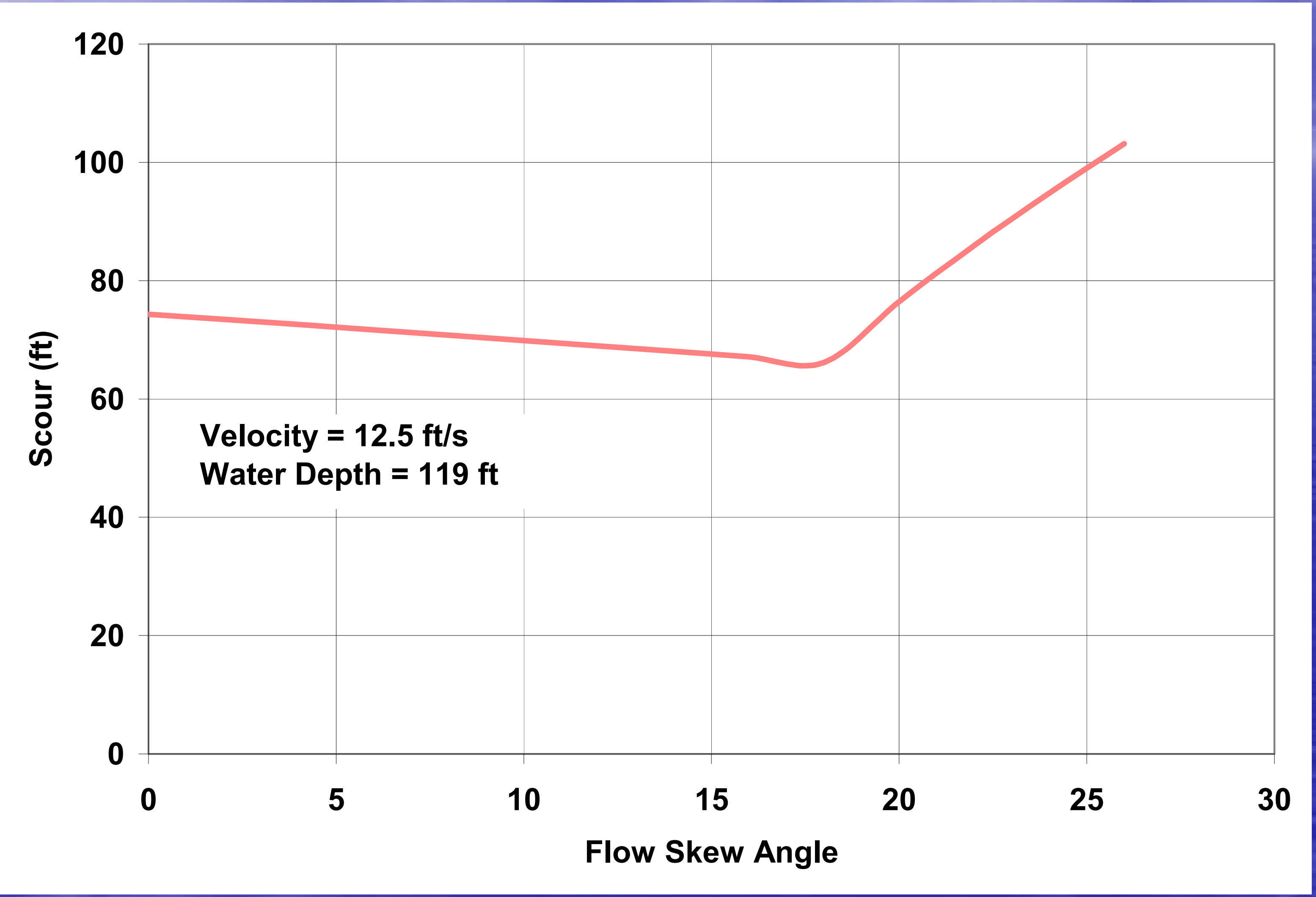
Scour Depth Summary Table New and Existing East Piers

Event	Flow	Scour Depth (ft)	Design Scour Depths (ft)
100 Year	Flood	67	68
	Ebb	68	
500 Year	Flood	65	68
	Ebb	68	
Check	Flood	70	70
	Ebb	70	

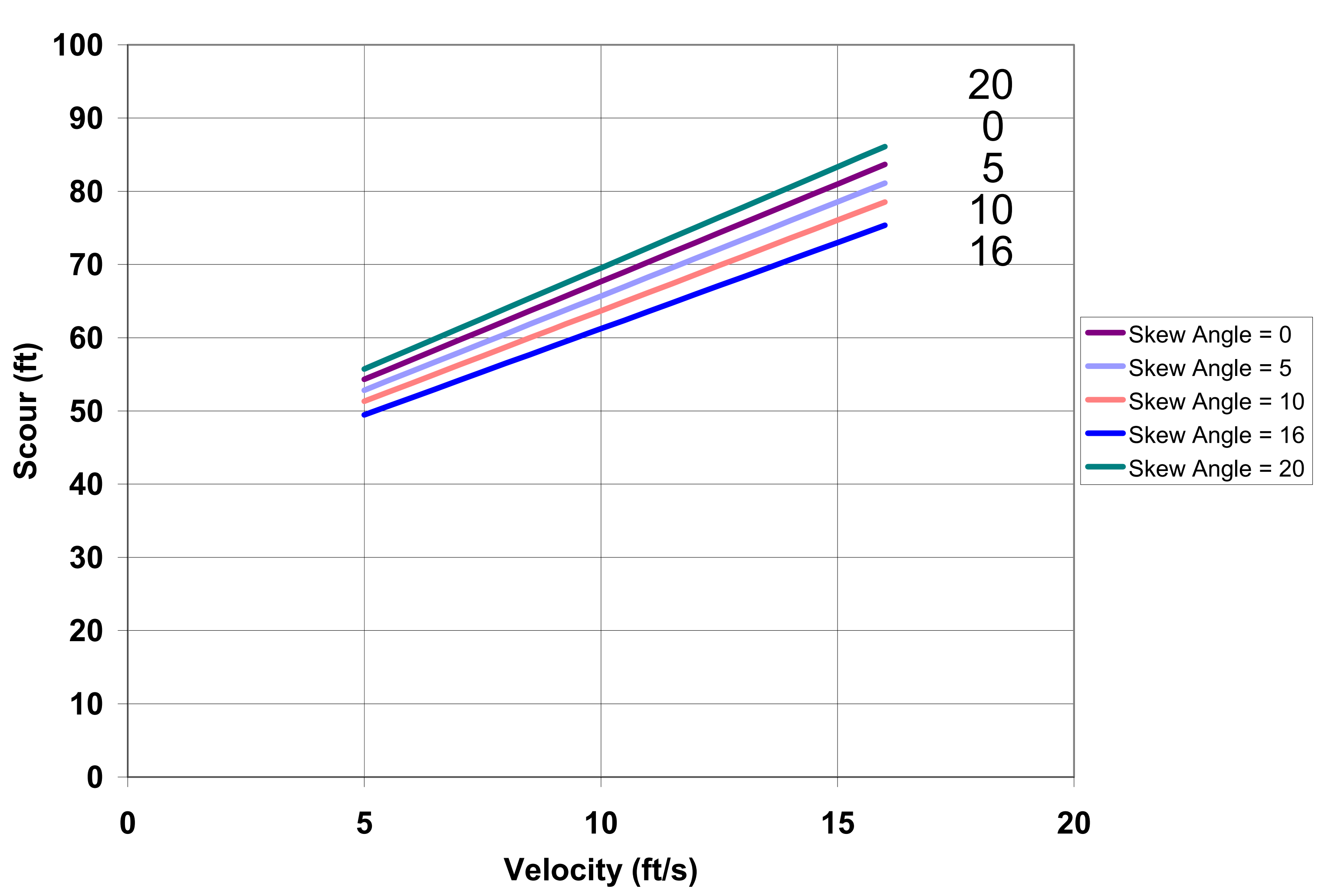
Scour Depth Summary Table New and Existing West Piers

Event	Flow	Scour Depth (ft)	Design Scour Depths (ft)
100 Year	Flood	70	70
	Ebb	60	
500 Year	Flood	68	68
	Ebb	61	
Check	Flood	73	73
	Ebb	62	

Scour Sensitivity to Flow Skew Angle



Scour Sensitivity to Flow Velocity



Questions?
Comments