Session 46

Gary Consolazio

University of Florida

Barge Impact Testing at the St. George Island Bridge: Test Results & Design Implications

Topic Description

This presentation describes a research study undertaken to quantify and characterize impact loads imparted to bridge piers during barge-pier collision events. Because bridges that span over navigable waterways are at risk for such collisions, they must be designed to successfully resist potential barge impact loads. However, few experimental studies have ever been conducted to quantify the magnitude or dynamic nature of such loads. Barge-impact provisions included in the current AASHTO bridge design specifications are based on limited experimental data that were generated using reduced scale (~1:5) pendulum hammer impact tests. To address this issue, a series of fifteen full-scale experimental barge impact tests were conducted in April 2004 on the old—now demolished and replaced—St. George Island Causeway Bridge (Bryant Patton Bridge). During each impact test, instrumentation (sensor arrays) and high-speed data acquisition systems were used to directly measure dynamic impact loads and the resulting structure, soil, and barge responses. To compliment the physical testing, numerical finite element analysis (FEA) techniques were employed to aid in interpretation of experimental test data. Comparisons between measured experimental data and FEA results substantiated the validity of the experimental data, and provided additional insights into the nature of pier response to barge impact loading. Comparisons between experimentally measured data, analytically predicted data, and the AASHTO bridge design provisions are also presented and recommendations are given with regard to the development of improved barge impact design provisions.

Speaker Biography

Dr. Gary Consolazio is an Associate Professor of Civil & Coastal Engineering in the Structures group at the University of Florida. Gary earned his bachelors, masters, and doctoral degrees in Civil Engineering from the University of Florida and has served on the faculties of Rutgers University (1995-1998) and the University of Florida (1998-present). His areas of research specialization include the characterization of extreme-event loading of civil infrastructure systems, numerical analysis of nonlinear dynamic structural response, and numerical methods. In particular, his current research activities focus on dynamic loading and response of structures subjected to vessel collisions, vehicle impacts, and blast loading.

Barge Impact Testing at the St. George Island Bridge

Test Results & Design Implications

Gary R. Consolazio, Ph.D.

Associate Professor of Civil & Coastal Engineering
University of Florida, Gainesville, Florida

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Acknowledgements

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  - Ronald Cook, UF-CCE
  - Michael McVay, UF-CCE
- Graduate students
  - Alex Biggs
  - Long Bui
  - David Cowan
  - Michael Davidson
  - Jessica Hendrix
  - Benjamin Lehr
  - Scott Wasman

Contents

- Barge-bridge collision incidents
- AASHTO design specifications
- Experimental test program
- Experimental results
- Numerical analysis using FB-MultiPier
- Dynamic and static pier response
- Future design provisions
- Key findings and recommendations

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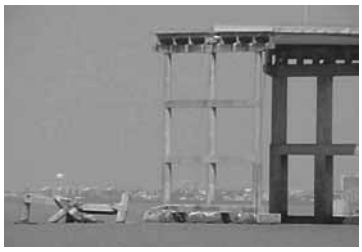
Collision incidents

- Big Bayou RR Bridge
- Mobile, Alabama (1993)
- Bridge displaced
- Destroyed by Amtrak Passenger Train
- 47 deaths

Collision incidents

- Queen Isabella Causeway Bridge
- South Padre Island, Texas (2001)
- 4 barge flotilla
- 240 ft. of bridge collapsed
- 8 deaths



Collision incidents

- I-40 bridge over the Arkansas River
- Webbers Falls, Oklahoma (2002)
- 580 ft. of bridge collapsed
- 14 deaths
- Detour of 20,000 vehicles/day for two months

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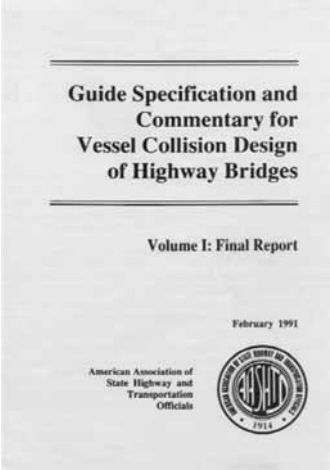
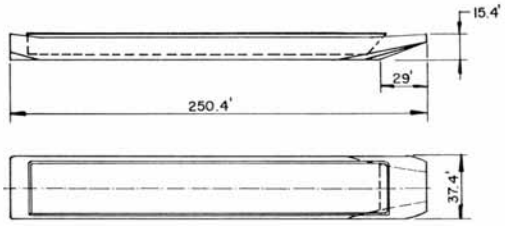
AASHTO vessel-collision guide specification

- Load calculation and risk analysis
- Provisions incorporated into AASHTO LRFD Bridge Design Specifications
- Covers ship and barge collisions



AASHTO barge impact provisions

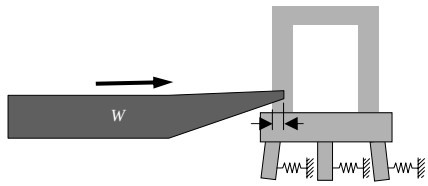
- Experimental studies (1980s) by Meir-Dornberg
  - Focus was on barge impacts with lock-entrance structures and bridge piers
  - Development of relationships between energy, deformation, and force
  - European Type IIa barges
  - ~1:5 scale pendulum hammer tests



AASHTO barge impact provisions

- Determination of equivalent-static barge impact loads

  - 1. Kinetic energy $$KE = \frac{C_H\, W\, V^2}{29.2}$$



  - 2. Crush depth $$a_B = \left(\sqrt{1+\frac{KE}{5672}}-1\right)\cdot\left(\frac{10.2}{R_B}\right)$$ where … $$R_B = \left(B_B/35\right)$$

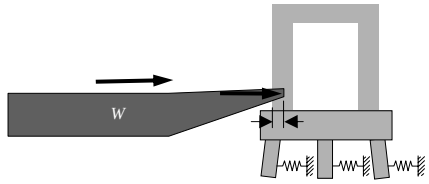
  - 3. Static load $$P_B = \begin{cases} 4112\, a_B\, R_B & a_B < 0.34 \text{ ft.} \\ \left(1349 + 110\, a_B\right) R_B & a_B \geq 0.34 \text{ ft.} \end{cases}$$

Barge bow crush deformation

Ohio River, Jan 2004: Barge impact on a lock-wall bull-nose
Barge flotilla: 18,000 tons, 15 barges
(Photo: U.S. Army Corps of Engineers)

AASHTO barge impact provisions

- Determination of equivalent-static barge impact loads



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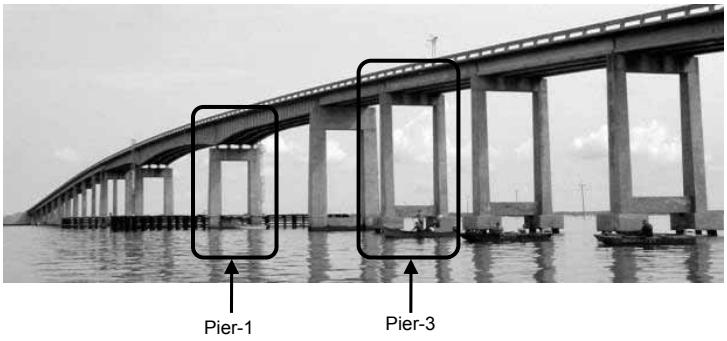
UF/FDOT experimental test program

- Supplement Meir-Dornberg reduced-scale data set by conducting full-scale barge-pier collision experiments
- St. George Island Causeway Bridge
  - Replacement and demolition of bridge provided testing opportunity
- Measurements
  - Impact forces
  - Pier response
  - Superstructure response
  - Soil response
  - Barge damage

Test site - St. George Island Causeway Bridge

Test site : St. George Island Causeway Bridge

- Constructed in the 1960s
- Pier-1 : Impact resistant pier (mud line footing)
- Pier-3 : Non-impact resistant pier (water line footing)



Structural configurations tested

Series P1

Series B3

Series P3

Experimental test program

- 15 experiments conducted
- Variations in pier configuration, barge speed, and mass

- High-speed data acquisition systems

Instrumentation & measurement summary

- Impact block / load cells
- Optical break beams
- Barge accelerometers
- Pier accelerometers
- Superstructure accelerometers
- Displacement transducers
- Barge deformation

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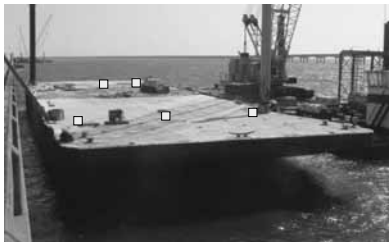

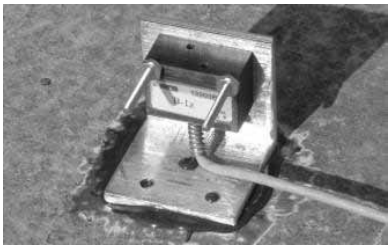

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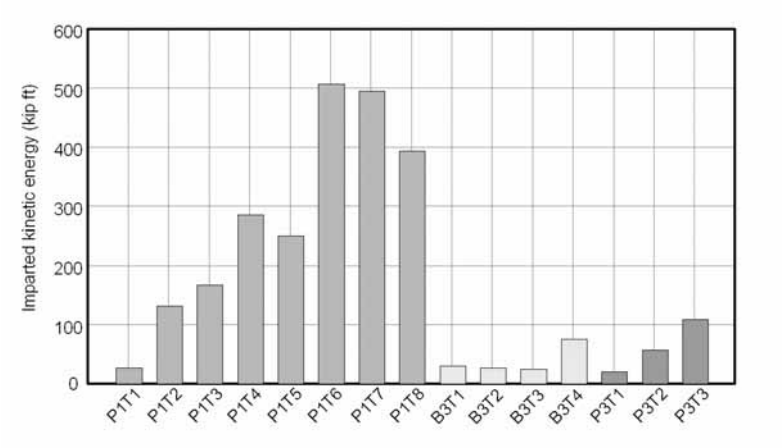
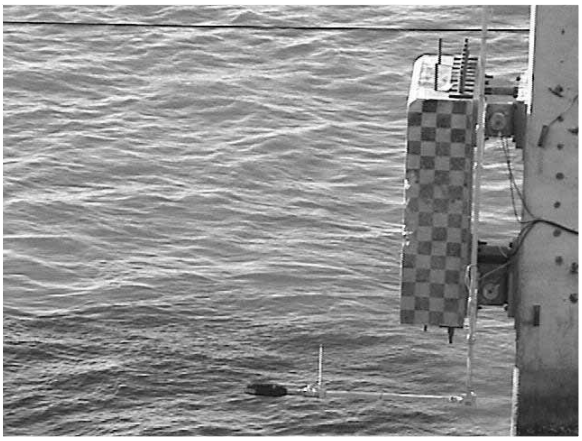
Test conditions

Test Series	Test Identifier	Impact speed (knots)	Barge weight (tons)
Series P1	P1T1	0.75	626
	P1T2	1.75	604
	P1T3	1.98	604
	P1T4	2.59	604
	P1T5	2.42	604
	P1T6	3.45	604
	P1T7	3.41	604
	P1T8	3.04	604
Series B3	B3T1	0.96	344
	B3T2	0.89	344
	B3T3	0.86	344
	B3T4	1.53	344
Series P3	P3T1	0.77	344
	P3T2	1.33	344
	P3T3	1.84	344

Test conditions



Test P1T6



Pier-1, 3.45 knots, 604 ton barge

Test P1T7

Pier-1, 3.41 knots, 604 ton barge

Test P1T8

Pier-1, 3.05 knots, 604 ton barge

Test P3T3

Pier-3 (superstructure removed), 1.84 knots, 344 ton barge

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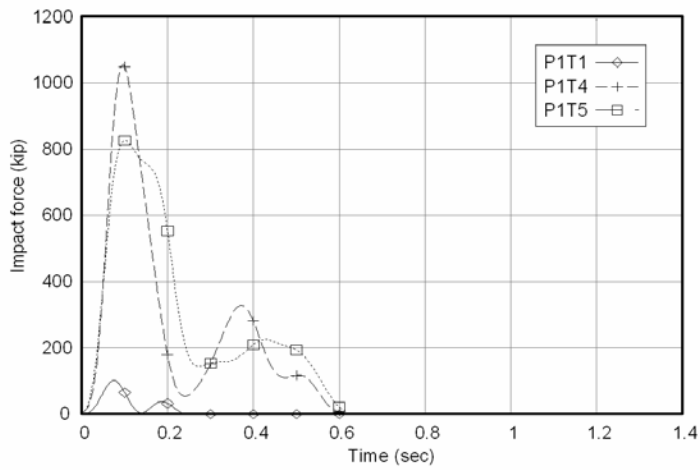
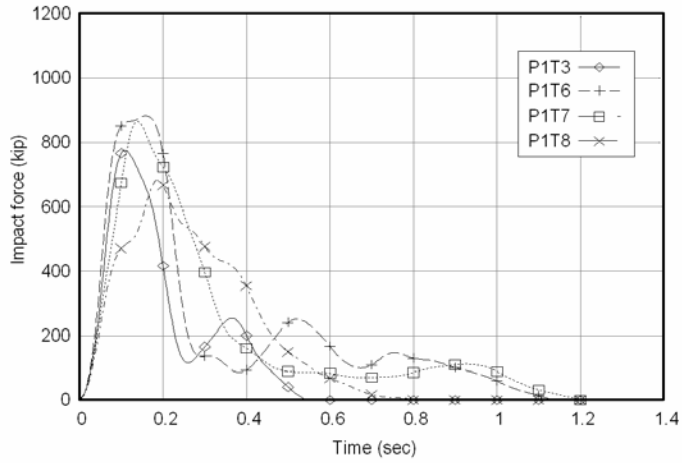
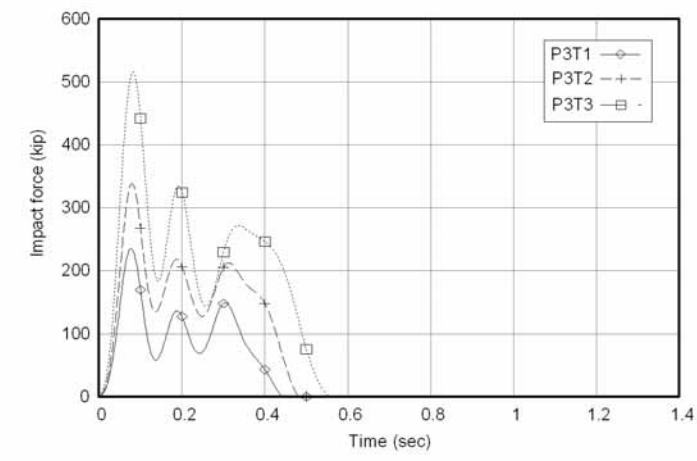
Results : P1, undamaged barge bow



Results : P1, damaged barge bow



Results : B3, impacts (superstructure present)



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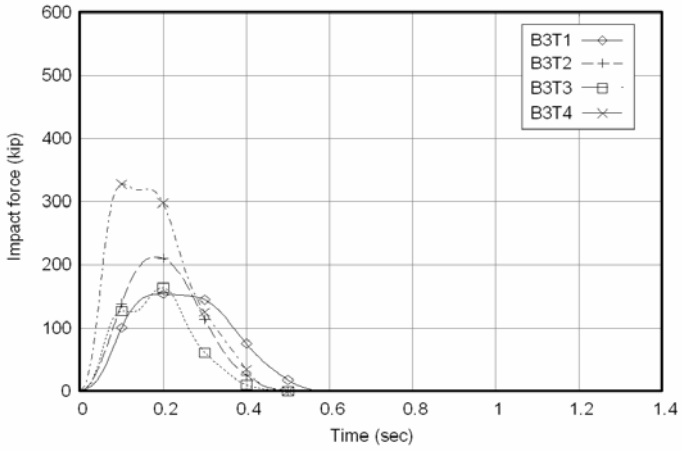
Results : P3, impacts (superstructure removed)



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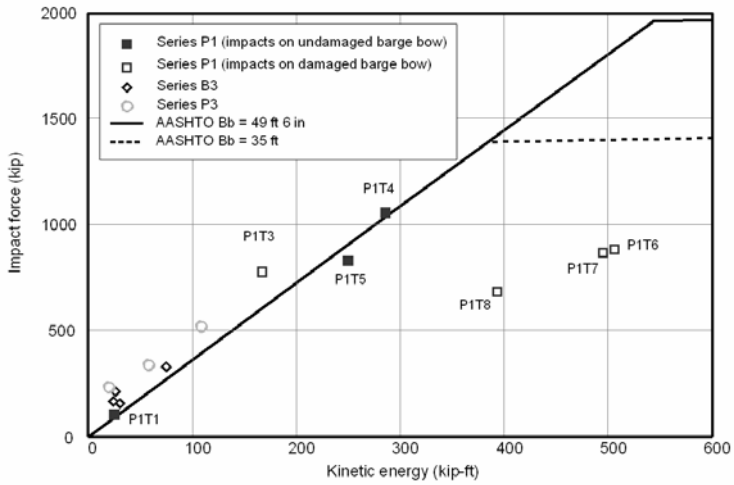
AASHTO vs. all experimental data



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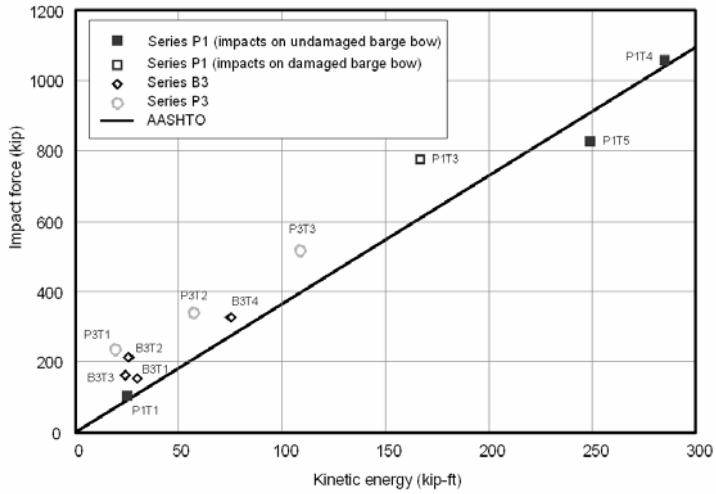
AASHTO vs. low-energy experimental data



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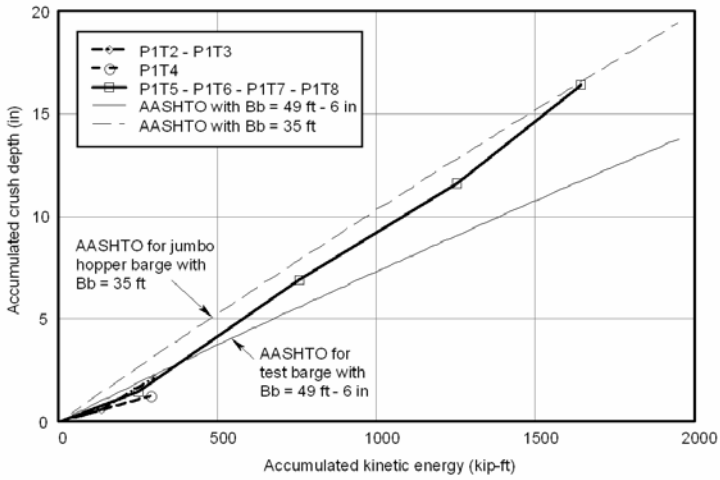
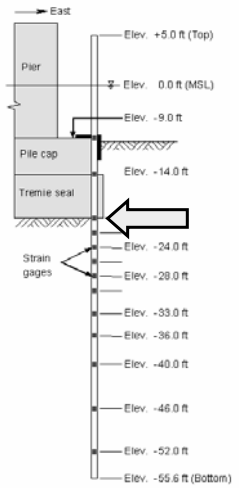
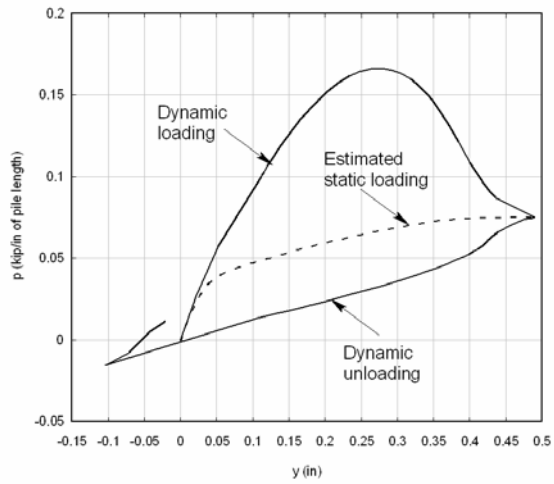
Barge crush deformation

AASHTO vs. experimental

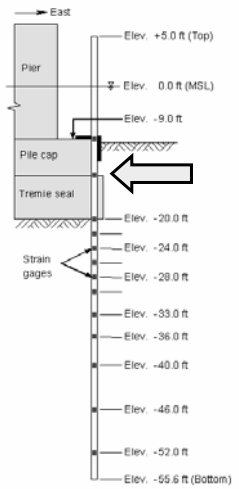


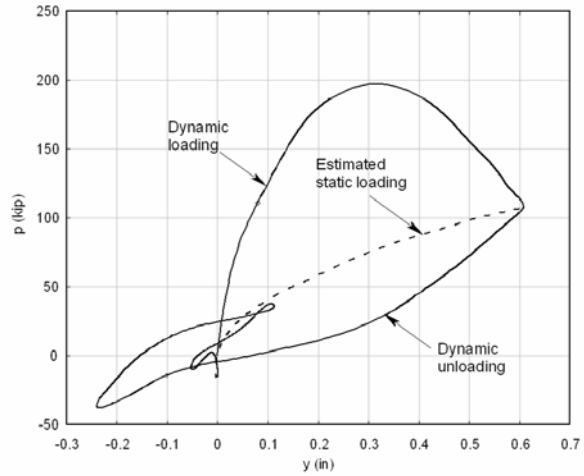
Soil resistance on piles





Soil resistance on cap+seal





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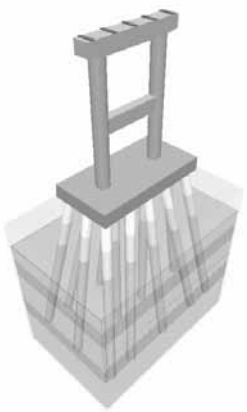
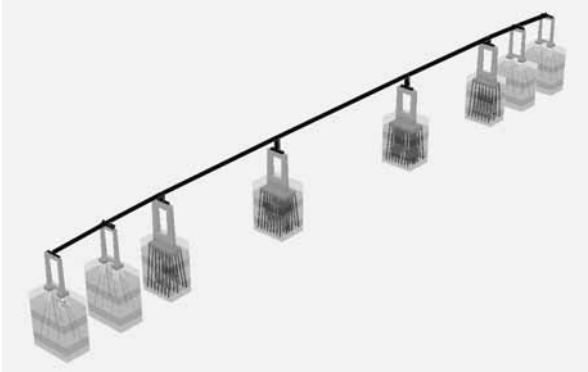
Numerical analysis using FB-MultiPier

- FB-MultiPier
  - Finite element structural analysis program
  - Bridge Software Institute (BSI)
- Calculation of structure and soil response to lateral loads
- Structural modeling
  - Linear or non-linear behavior
- Soil modeling
  - Linear or non-linear behavior
- Analysis capabilities
  - Static, dynamic



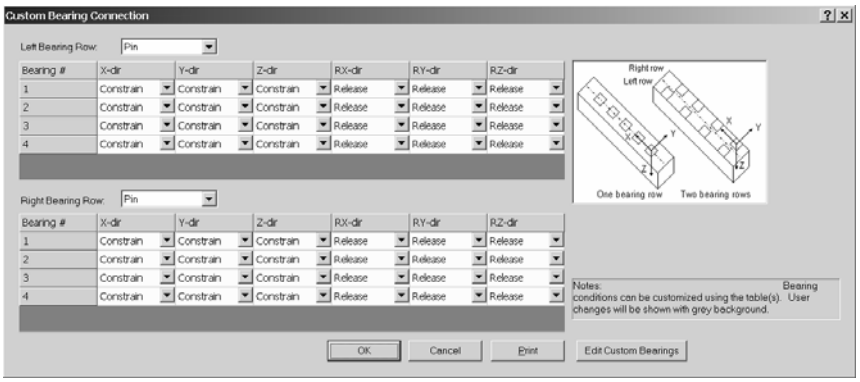
Numerical analysis using FB-MultiPier

- Multiple-pier, multiple-span structural analysis
  - Each pier may be unique : structural / geotechnical properties
  - Each span may be unique : span length, properties, horizontal alignment
  - Automatic inclusion of superstructure resistance



Numerical analysis using FB-MultiPier

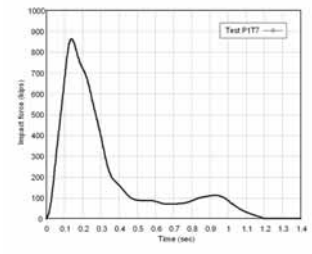
- Bearing modeling
  - 6-independent DOF at each bearing
  - Constraints, releases; linear or non-linear force-deformation curves



Numerical analysis using FB-MultiPier

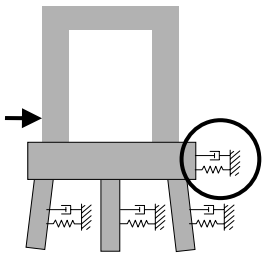
- Time-domain (time-history) dynamic analysis

Experimentally measured impact force



Measured dynamic force applied to numerical model

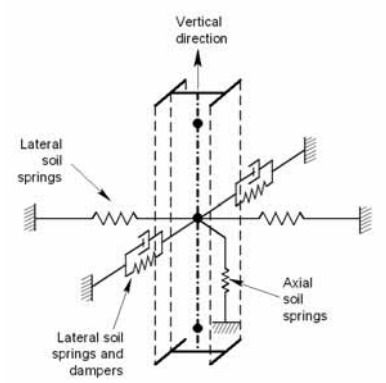
Dynamic FEA pier + soil model



- Displacement-dependent forces : stiffness
- Velocity-dependent forces : damping
- Mass and acceleration-dependent forces: inertia

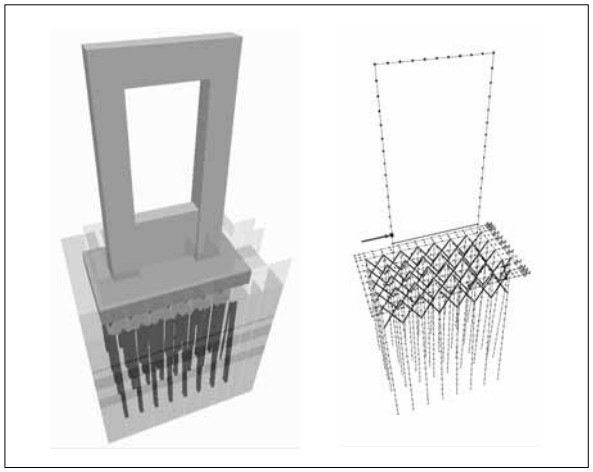
Numerical analysis using FB-MultiPier

- Soil modeling
  - Non-linear soil stiffness curves generated semi-automatically
  - Non-linear soil stiffness curves based on user-specified data
  - Row-multipliers (lead, trail, and interior rows)
  - Permanent soil deformation (“soil gapping”)
  - Cyclic degradation of soil stiffness
  - Dynamic stiffness increase
  - Energy dissipation



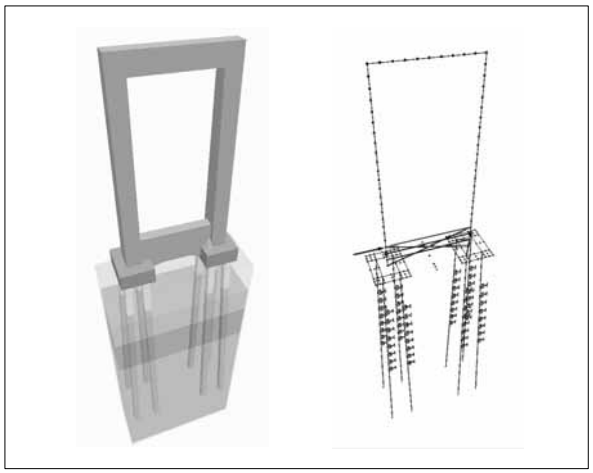
Numerical analysis using FB-MultiPier

- Model used to simulate test series P1



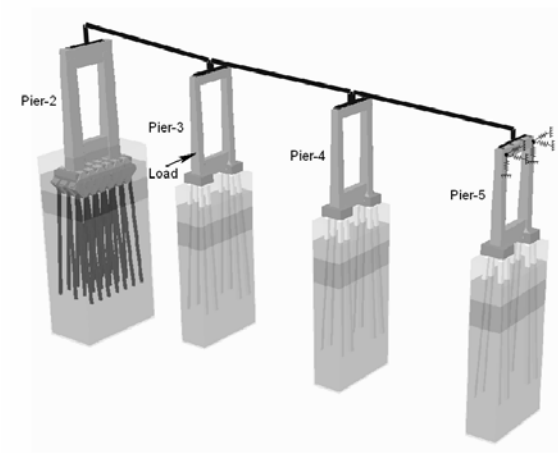
Numerical analysis using FB-MultiPier

- Model used to simulate test series P3



Numerical analysis using FB-MultiPier

- Model used to simulate test series B3



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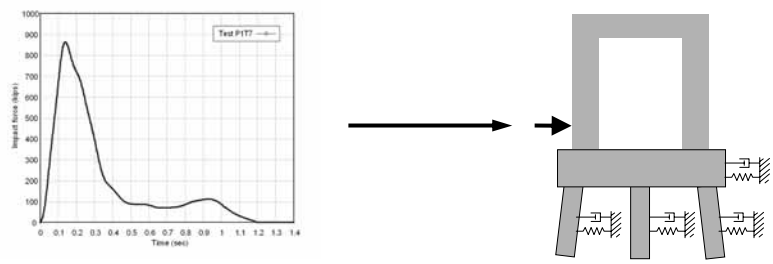
Objectives

- Establish confidence in measured experimental data
- Quantify forces that could not be measured experimentally
- Identify primary sources of impact resistance and load
- Permit comparison of dynamic and static structural behavior

Calibration of dynamic models

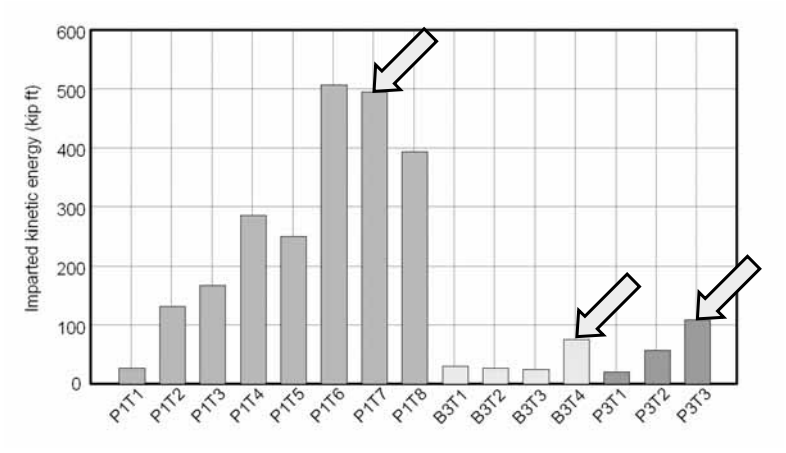
- Apply measured loads to dynamic pier + soil models



- Adjust material parameters to obtain agreement between analytical and experimental results :
  - Pier displacements, soil forces, pile shears, pile deflected shapes, superstructure accelerations, etc.

Calibration of dynamic models

- Detailed calibrations: P1T7, B3T4, P3T3



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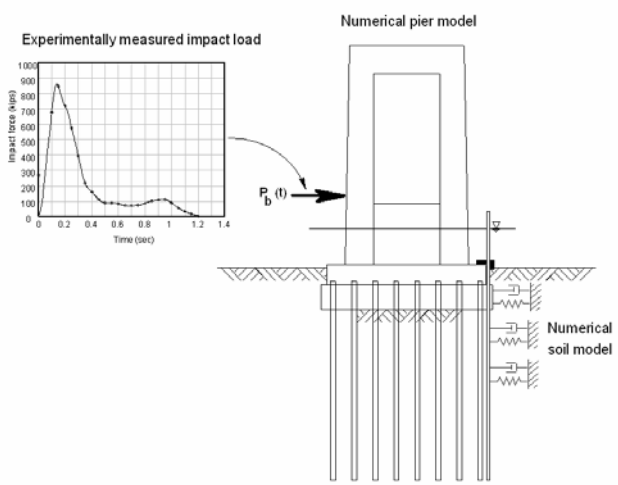
P1T7



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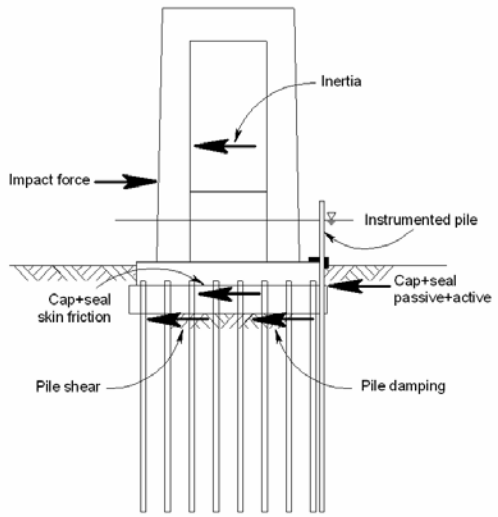
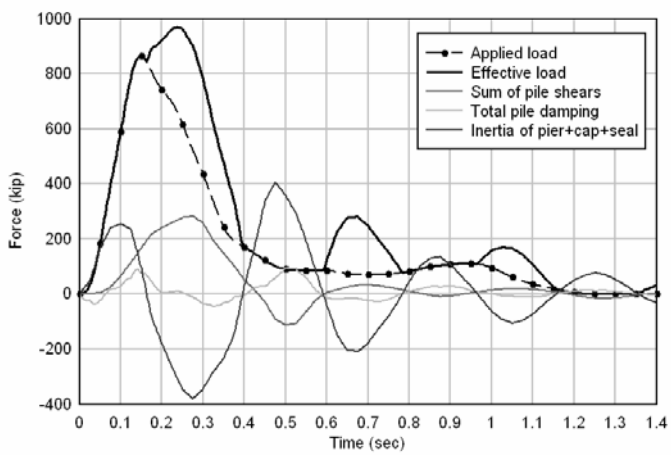
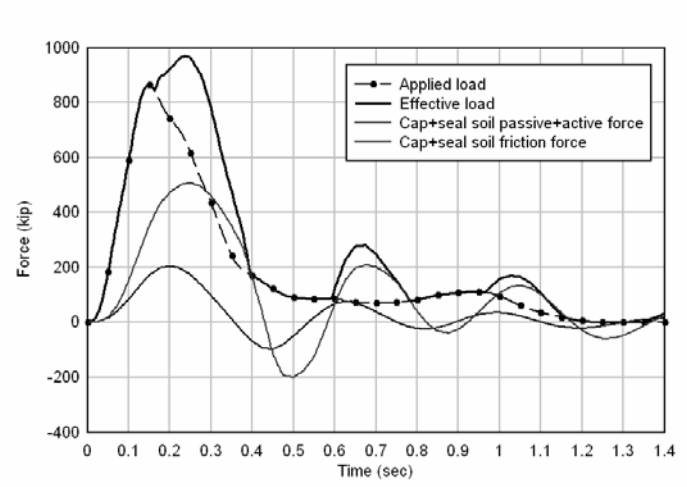
P1T7


Inertia
Impact force
Instrumented pile
Cap+seal
passive+active
Cap+seal
skin friction
Pile shear
Pile damping

P1T7


Applied load
Effective load
Sum of pile shears
Total pile damping
Inertia of pier+cap+seal
Force (kip)
Time (sec)
1000
800
600
400
200
0
-200
-400
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
1.2
1.3
1.4

P1T7



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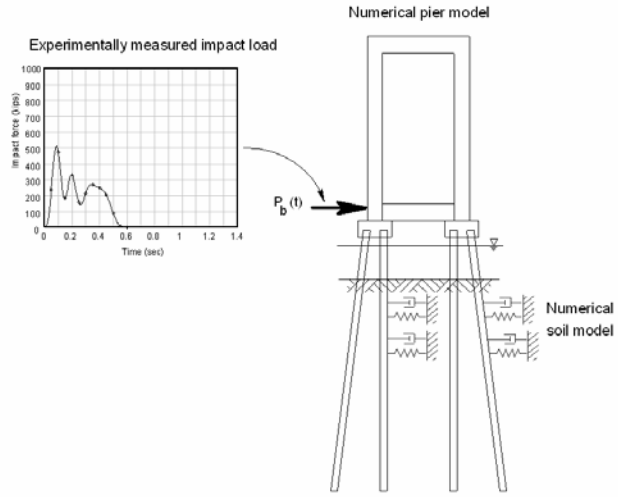
P3T3



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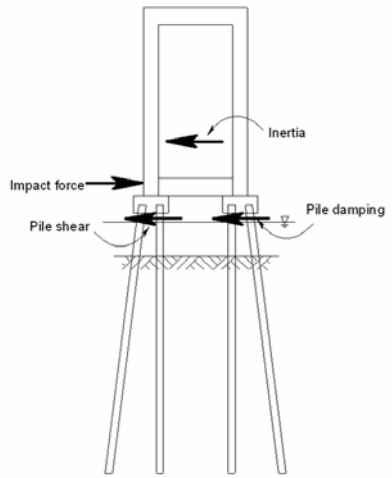
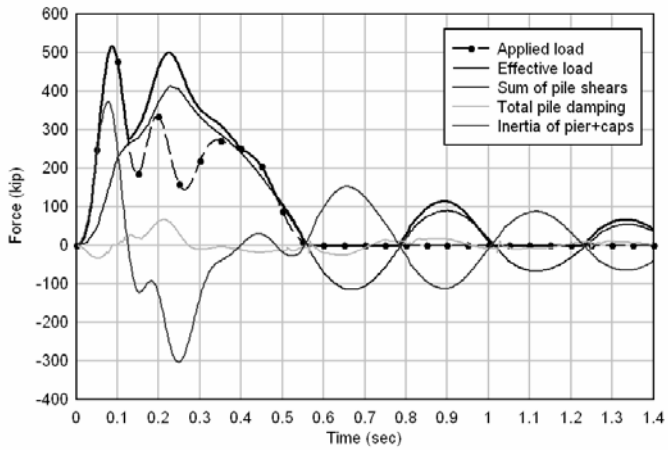
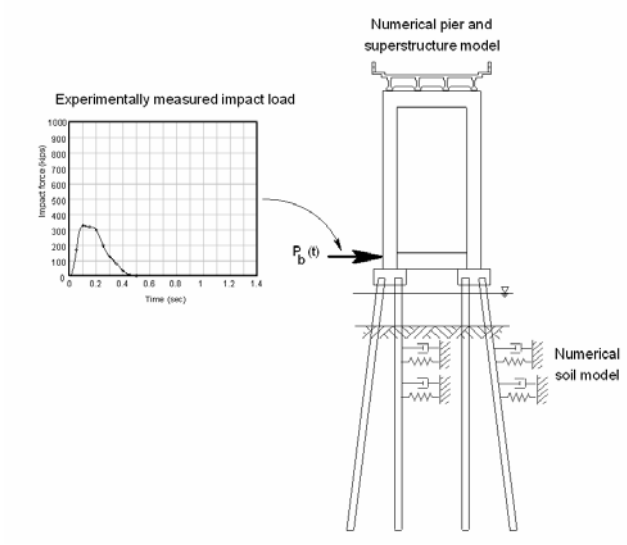
P3T3


Inertia
Impact force
Pile damping
Pile shear

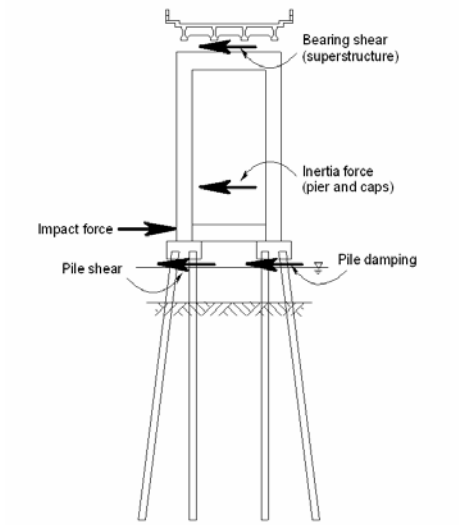
P3T3


Applied load
Effective load
Sum of pile shears
Total pile damping
Inertia of pier+caps
Force (kip)
Time (sec)
600
500
400
300
200
100
0
-100
-200
-300
-400
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
1.2
1.3
1.4

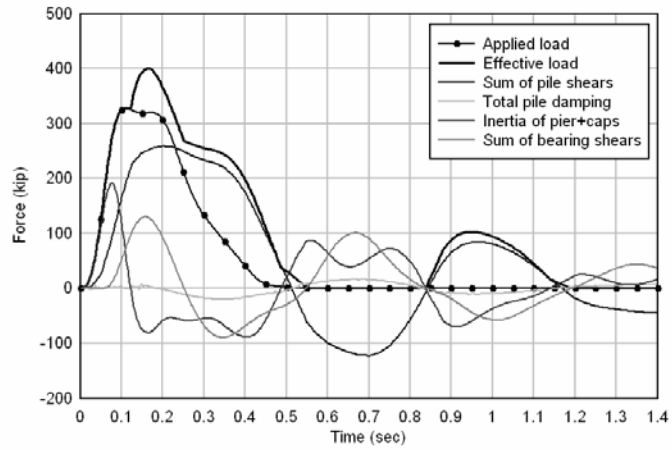
B3T4


Numerical pier and
superstructure model
Experimentally measured impact load
Impact force (kips)
Time (sec)
$P_b(t)$
Numerical
soil model

B3T4


Bearing shear
(superstructure)
Inertia force
(pier and caps)
Impact force
Pile shear
Pile damping

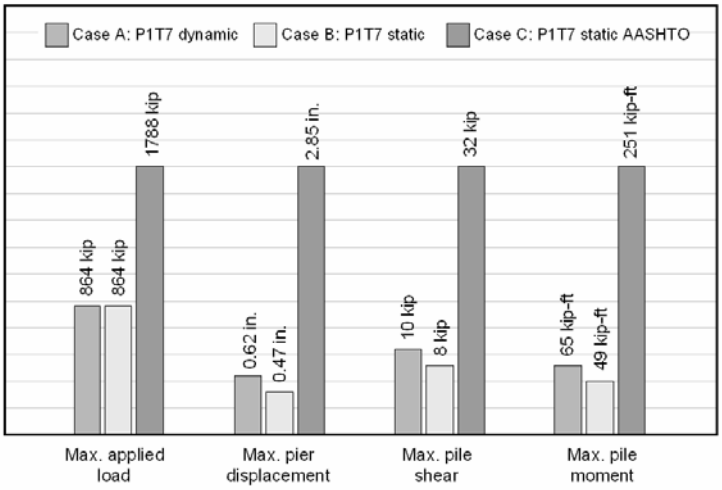
B3T4



Dynamic vs. static comparison

Case	Impact condition	Analysis type	Load description	Max. load (kip)
A	P1T7	Dynamic	Time-varying P1T7	864
B	P1T7	Static	Peak P1T7 load	864
C	P1T7	Static	AASHTO	1788
D	P3T3	Dynamic	Time-varying P3T3	516
E	P3T3	Static	Peak P3T3 load	516
F	P3T3	Static	AASHTO	398
G	B3T4	Dynamic	Time-varying B3T4	328
H	B3T4	Static	Peak B3T4 load	328
I	B3T4	Static	AASHTO	276

P1T7



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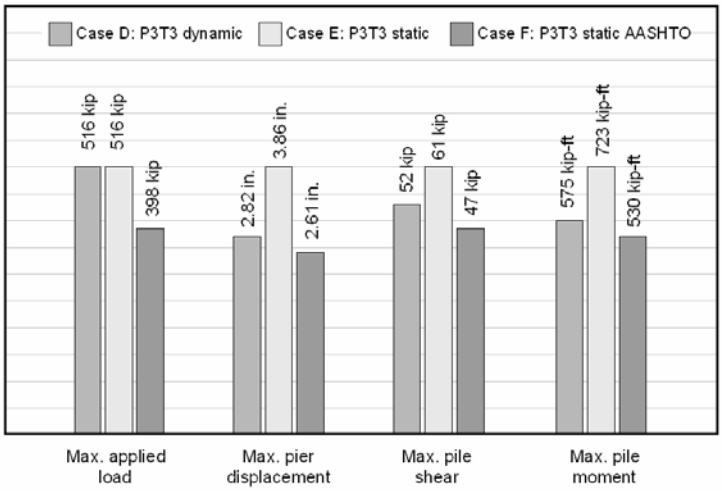
P3T3



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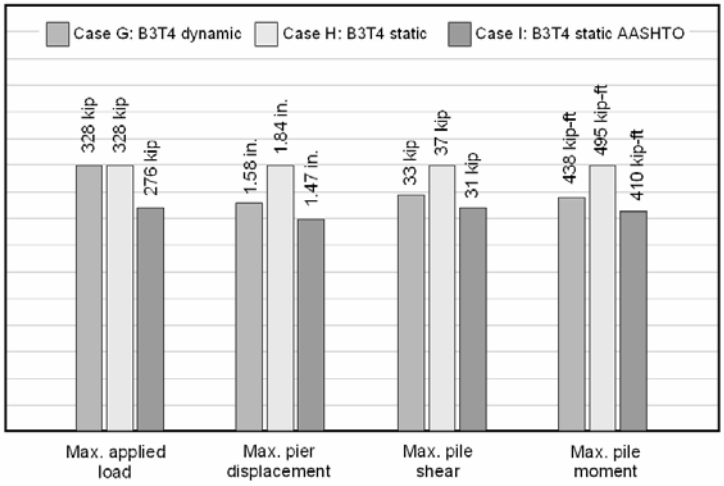
B3T4



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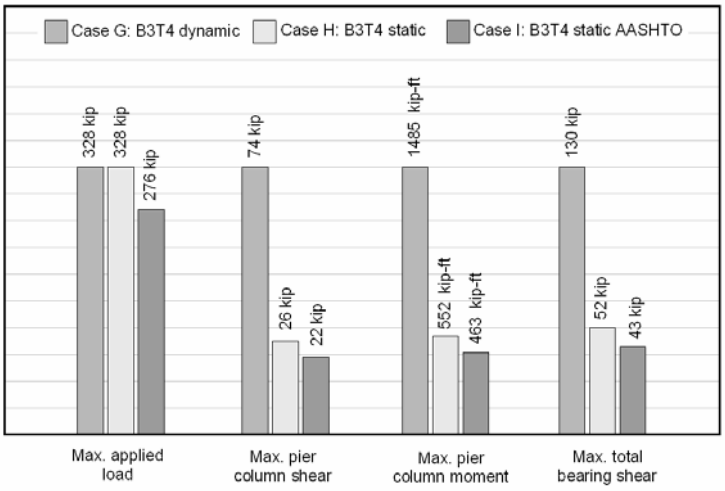
B3T4



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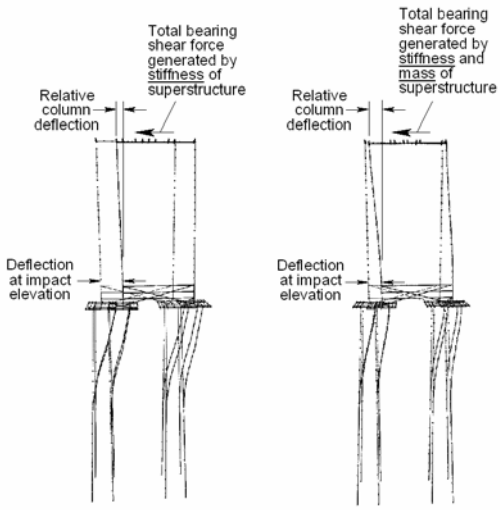
Dynamic amplification

- Superstructure inertia (mass) generates restraint at top of pier
- Column forces are amplified
- Extent of restraint dependent upon mass and stiffness of superstructure



Contents

- Barge-bridge collision incidents
- AASHTO design specifications
- Experimental test program
- Experimental results
- Numerical analysis using FB-MultiPier
- Dynamic and static pier response
- Future design provisions
- Key findings and recommendations

Future design provisions

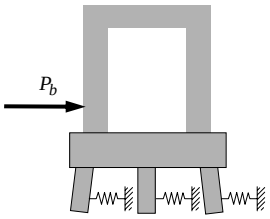
- Multi-level approach to load & response calculation

• Equivalent-static method	Simplified calculations
• Applied-dynamic method	↕
• Coupled-dynamic method	Refined calculations

Future design provisions

- Equivalent-static method
  - Update the current AASHTO static-load methodology
  - Incorporate new full-scale experimental data
  - Include approximate dynamic amplification effects
  - Eliminate intermediate calculation of barge crush depth

→ Vessel characteristics
→ Static load
→ Static analysis
→ Design forces

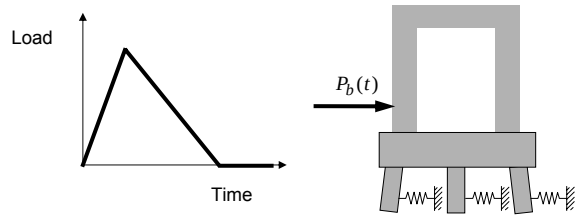


Pier + soil model

Future design provisions

- Applied-dynamic method
  - Dynamic time-domain analysis method
  - Dynamic amplification effects automatically included

→ Vessel characteristics
→ Simplified dynamic load
→ Dynamic time-domain analysis
→ Design forces

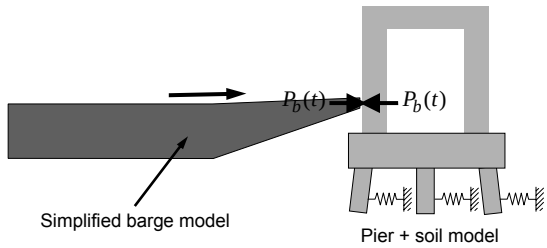


Simplified dynamic load Pier + soil model

Future design provisions

- Coupled-dynamic method
  - Dynamic time-domain analysis method
  - Dynamic amplification effects automatically included

→ Vessel characteristics
→ Coupled vessel-pier dynamic time-domain analysis
→ Impact load and design forces



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Key findings

- Foundation design with AASHTO loads
  - High energy impacts
    - AASHTO static loads appear to be conservative for foundation design
  - Low energy impacts (e.g. “drifting barge”)
    - AASHTO static loads produce foundation design forces in-line with dynamic forces
- Inertial forces
  - Constitute a form of resistance during early phase of impact
  - Become a form of load once pier mass has reached maximum velocity
- Pier column design and dynamic amplification
  - Inertial restraint from superstructure mass can produce column design forces that are more than 200% larger than those calculated from AASHTO static procedures
- Buried foundations
  - Soil resistance forces acting directly on buried foundation components (e.g. pile cap, tremie seal) can exceed total pile resistance
- Dynamic soil stiffness
  - Rapid impact loading can produce a 100% or more increase in soil stiffness

Key recommendations

- Need to develop revised design provisions
  - Improve the uniformity of economy and safety
- Multi-level approach
  - Will permit designer to select level of analysis sophistication based on needs and scope of project
    - Equivalent-static
    - Applied-dynamic
    - Coupled-dynamic
- Dynamic effects should be incorporated in design procedures, even if only through static approximation
  - Dynamic amplification of column forces
  - Dynamic changes in soil stiffness

Research reports

- FDOT research web-site:

  www.dot.state.fl.us/research-center/ProjectInfo.htm

- Under "Completed projects", click on "Structures"

- Search for "BC354-76" and "BD545-05"