Integrated Bridge Load Rating Allowing Rational Assessment of Foundation Reuse

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GCI INC | AYRES ASSOCIATES
Mr. Bridges
Safe Weight Lifting Load

120 lbs.

Superstructure

Load Rating 200 lbs.

LOAD

Substructure

Load Rating 120 lbs.
Mr. Bridges
Leg (Substructure) Collapse

200 lbs.

Superstructure

Substructure Failure

Load Rating
200 lbs.

Load Rating
120 lbs.
Mr. Bridges
Safe Lifting via Weight Bench (Crutch Bent)
Background

- Sayed, Sunna, and Moore (2013) proposed the first known method to address the substructure load rating of bridges.

- Integrated Bridge Load Rating (IBLR): a combined load rating of the superstructure-substructure system whereby the smaller of the superstructure load rating and the substructure load rating is adopted as the IBLR.

- Foundation Reuse: Universal Definition
  - Any situation where the conditions dictating the performance of an existing foundation are different from those of the original design.

Load Rating Methodology
Superstructure
Rating Factor (RF) (AASHTO 2010)

\[ RF_{sup} = \frac{(C - A_1D)}{A_2L(1+I)} \]

Where:

- \( C \): Nominal capacity of the element being rated
- \( A_1 \) & \( A_2 \): Dead and live load factors, respectively
- \( D \): Dead load effect on the member
- \( L \): Live load effect on the member; and
- \( I \): Impact factor to be used
Rating Factor \((RF)\) (AASHTO 2010)

\[
RF_{sup} = \left[C - (\lambda_{DC})(DC) - (\lambda_{DW})(DW) \pm (\lambda_{p})P\right] / (\lambda_{L})(LL + IM)
\]

Where:

- **C**: Nominal capacity of the element being rated
- **\(\lambda_{DC}\)**: LFRD load factor for structural components and attachments
- **DC**: Dead load effect due to structural components and attachments
- **\(\lambda_{DW}\)**: LFRD load factor for wearing surface and utilities
- **DW**: Dead load effect due to wearing surface and utilities
- **\(\lambda_{p}\)**: LFRD load factor for permanent loads
- **P**: Permanent loads other than dead loads
- **\(\lambda_{L}\)**: Evaluation live-load factor
- **LL**: Live-load effect; and
- **IM**: Dynamic load allowance (LFRD method)
Superstructure Load Rating \( (RT_{sup}) \)

\[
RT_{sup} = (RF_{sup}) \ W
\]

Where:

\( W \)  Weight of the nominal truck
Load Rating Methodology

Substructure
\[ R = \eta_g \sum Q_o / FS \]

Where...

- \( R \): Allowable load per pile bent or pile group
- \( FS \): Factor of Safety
- \( \eta_g \): Pile group efficiency (Sayed and Bakeer 1992); and
- \( Q_o \): Nominal (ultimate or Davisson) pile capacity of single pile
\[ \gamma_n \sum \beta_i R_i = \eta_g \sum \varphi Q_o \]

Where...

- \( \gamma_n \): Group factor
- \( \beta_i \): Load factor for load component \( R_i \); and
- \( \varphi \): Performance (resistance) factor
\[ \sum \gamma_i R_i = \eta_g \sum \varphi Q_o \]

Where…

\( \gamma_i \)  Load factor for load component \( R_i \)
Substructure Load Rating \( (RT_{sub}) \)

\[
RT_{sub} = (RF_{sub}) W
\]

Where…

\( RF_{sub} \) is the substructure rating factor and equals \( \% LL \) for any predetermined settlement

(Note: \( \% LL \) = ratio of applied live load per pile to the live load per pile corresponding to the nominal truck)
History of Design Criteria for Bridges

- **ASD** Before 1973
- **LFD** 1973 – 2002
- **LRFD** After 1994
IBLR and Reuse

KF Bridges
Geo-Structural Data for Bridge No. 720366
Substructure LFR for Bridge No. 720366

Load Factor Design (LFD)
- Ultimate Pile Capacity (FB-Deep, FDOT 2002)
- Resistance Factor $\phi = 0.45$ (AASHTO)

- Not harmful (Bozozuk 1978)
- Harmful but tolerable (Bozozuk 1978; Grover 1988)
- Ride quality (Walkinshaw 1978)
- Structural distress (Walkinshaw 1978)
- Usually intolerable (Wahls 1990)
Continuous Multi-Girder Bridges

- PS Beams:
  - Service III \( \Delta = 0.0005L + 0.17 \) (in.)
  - Strength I \( \Delta = 0.13 \frac{L}{S} - 0.17 \) (in.)
- Steel Beams:
  - Service II and Strength I \( \Delta = 0.55\frac{L}{S} - 2.6 \) (in.)

Steel and PS Simple Span Bridges

- Rideability controls
- Angular Distortion \( \leq 1/250 \)
IBLR for Bridge No. 720366

<table>
<thead>
<tr>
<th>Truck No.</th>
<th>Weight (Tons)</th>
<th>Load Rating, Tons</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DESIGN TRUCK</td>
<td></td>
<td></td>
</tr>
<tr>
<td>HS-20</td>
<td>36</td>
<td></td>
</tr>
<tr>
<td>OTHER TRUCKS</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SU2</td>
<td>17</td>
<td></td>
</tr>
<tr>
<td>SU3</td>
<td>33</td>
<td></td>
</tr>
<tr>
<td>SU4</td>
<td>35</td>
<td></td>
</tr>
<tr>
<td>C3</td>
<td>28</td>
<td></td>
</tr>
<tr>
<td>C4</td>
<td>37*</td>
<td></td>
</tr>
<tr>
<td>C5</td>
<td>40</td>
<td></td>
</tr>
<tr>
<td>ST5</td>
<td>40</td>
<td></td>
</tr>
</tbody>
</table>

Legend:
- Red: Inventory - Superstructure
- Orange: Inventory - Substructure
- Green: Operating - Substructure
- Blue: Operating - Superstructure

Integrated Bridge Load Rating (IBLR)

1 ton = 8.9 kN
1 ft = 0.3048 m

* Actual weight, 36.65 tons

Diagram notes:
- Pile Top: EL +3.1
- 18 in □ PSC Pile
- Critical Scour Mudline: EL -44.0
- Pile Tip: EL -55.1

NOTE: Data shown for the existing mudline
Rating Factors for Bridge No. 720366
IBLR and Reuse

UF Bridges
Bridge No. 124042
Bridge 124042

Existing bridge pile bent

Driving piles for new bridge
Issues Impacting UF Bridges

- Embedment
- Geotechnical Design Criteria
- Structural Design Criteria
Embedment of Deep Foundations

For selected pile size:

- Deterministic
- Pile Group
- At any Mudline
- Realistic for any Soil Conditions
- Unique Solution

-L = Embedment
-P = Load < Ultimate Pile Capacity (Satisfying Stability)
-Δ = Deformation < Specified Requirements (Satisfying Functionality)

S/B-C

FHWA/FDOT RE

NDT

- Guesstimate
- Single Pile
- At Construction Mudline for RE
- Unrealistic/Risky if Softer Layers Exist Below “Calculated” Tip
- Lack Uniqueness
S/B-C Schematic Representation

Legend
- Non-convergence
- Convergence with excessive deformation
- Convergence with acceptable deformation
- $\Delta=1''$ Maximum axial displacement, $\Delta$, (in.)
- Allowable axial load

$L = f(P, \Delta)$

Pile Embedment, $L$

Pile Axial Load, $P$
Effect of Embedment
Bridge No. 124042
Embedment Determination via S/B-C
Bridge No. 124042
Embedment at Existing Mudline

- NDT (PIT)
- S/B-C with SF=1.5
- S/B-C with SF=2.0

Diagram showing embedment details with various measurements and materials.
Bridge No. 124042
Embedment at 100 Year Scoured Mudline

NDT (PIT)
(Bridge is gone)

S/B-C with SF=1.5

S/B-C with SF=2.0

100-Year Scoured Mudline (EL -26.9')

97.5 tons

130 tons

Sand and Shell

Sand

34.5'

0.6'

35.1'

9.4'

35.1'

15.4'

-36.3'

-42.3'
Bridge No. 124042
Allowable Stress Rating (ASR)

Allowable Stress Design (ASD)
- Allowable Pile Capacity (FB-Deep, FDOT 2002)
- Factor of Safety = 2.5

Percent Live Load
Ratio of applied live load per pile to the live load per pile corresponding to truck HS-20

Maximum Pile Head Displacement, in.

IR OR

Existing mudline
100-year scoured mudline
S/B-C embedment based on ASD with SF = 1.5
S/B-C embedment based on ASD with SF = 2.0
Corresponding to truck HS-20

A Not harmful (Bozozuk 1978)
B Ride quality (Walkinshaw 1978)
C Structural distress (Walkinshaw 1978)
D Harmful but tolerable (Bozozuk 1978; Grover 1988)
E Usually intolerable (Wahls 1990)
Bridge No. 124042
Load Factor Rating (LFR)

Load Factor Design
- Davisson Pile Capacity (FB-Deep, FDOT 2002)
- Resistance Factor $\varphi = 0.65$

**Legend**
- Existing mudline
- S/B-C embedment based on ASD with SF = 1.5
- S/B-C embedment based on ASD with SF = 2.0
  - Corresponding to truck HS-20

**Percent Live Load**
Ratio of applied live load per pile to the live load per pile corresponding to truck HS-20
Bridge No. 124042
Load Factor Rating (LFR)

Percent Live Load

Load Factor Design
- Ultimate Pile Capacity (FB-Deep, FDOT 2002)
- Resistance Factor $\phi = 0.65$

- Existing mudline
- 100-year scoured mudline
- S/B-C embedment based on ASD with SF = 1.5
- S/B-C embedment based on ASD with SF = 2.0
- Corresponding to truck HS-20

Not harmful (Bozozuk 1978)
Ride quality (Walkinshaw 1978)
Structural distress (Walkinshaw 1978)
Harmful but tolerable (Bozozuk 1978; Grover 1988)
Usually intolerable (Wahls 1990)

Percent Live Load
Ratio of applied live load per pile to the live load per pile corresponding to truck HS-20
Effect of Geotechnical Design Criteria
Bridge No. 124042
Load Factor Rating (LFR)

Load Factor Design

Resistance Factor $\varphi = 0.65$

Legend:
- Existing mudline
- S/B-C embedment based on ASD with SF=1.5
- S/B-C embedment based on ASD with SF=2.0
- Corresponding to truck HS-20

Percent Live Load
Ratio of applied live load per pile to the live load per pile corresponding to truck HS-20

IR
OR
Effect of Structural Design Criteria
Bridge No. 124042
Substructure ASR vs. LFR

**Percent Live Load**

**Maximum Pile Head Displacement, in.**

**Allowable Stress Design**
- Ultimate Pile Capacity (FB-Deep, FDOT 2002)
- Factor of Safety = 2.5

**Load Factor Design**
- Ultimate Pile Capacity (FB-Deep, FDOT 2002)
- Resistance Factor $\varphi = 0.65$

- Existing mudline
- Load Factor Rating
- Allowable Stress Rating
- S/B-C embedment based on ASD with SF=1.5
- S/B-C embedment based on ASD with SF=2.0
- Corresponding to truck HS-20

**Percent Live Load**
- Not harmful (Bozozuk 1978)
- Ride quality (Walkinshaw 1978)
- Structural distress (Walkinshaw 1978)
- Harmful but tolerable (Bozozuk 1978; Grover 1988)
- Usually intolerable (Wahls 1990)

**Legend:**
- A
- B
- C
- D
- E
# IBLR and Reuse – UF Bridges

<table>
<thead>
<tr>
<th>Rating Type&lt;sup&gt;a&lt;/sup&gt;</th>
<th>Superstructure Load Rating (tons)</th>
<th>Superstructure Load Rating&lt;br&gt;Tip Elevation (ft)</th>
<th>Embedment (ft)</th>
<th>LFR w/ Ultimate Capacity (tons)</th>
<th>LFR w/ Davisson Capacity (tons)</th>
<th>ASR w/ Ultimate Capacity (tons)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inventory</td>
<td>34&lt;sup&gt;b&lt;/sup&gt; 58&lt;sup&gt;c&lt;/sup&gt;</td>
<td>-36.3</td>
<td>16.5</td>
<td>29</td>
<td>NA</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>-42.3</td>
<td>22.5</td>
<td>50</td>
<td>14</td>
<td>20</td>
</tr>
<tr>
<td>Operating</td>
<td>46&lt;sup&gt;b&lt;/sup&gt; 97&lt;sup&gt;c&lt;/sup&gt;</td>
<td>-36.3</td>
<td>16.5</td>
<td>40</td>
<td>1</td>
<td>13</td>
</tr>
<tr>
<td></td>
<td></td>
<td>-42.3</td>
<td>22.5</td>
<td>70</td>
<td>22</td>
<td>35</td>
</tr>
</tbody>
</table>

<sup>a</sup> HS-20 (36 tons)  
<sup>b</sup> Based on FDOT database (FDOT 2006) for opensteel grating span no. 38  
<sup>c</sup> Based on CONSPAN (2009) for prestressed girder spans  
<sup>d</sup> Based on S/B-C @ existing mudline  

ASR: Allowable Stress Rating  
LFR: Load Factor Rating  
N/A: Not available due to excessive displacement or non-convergence (i.e., instability)
## Relevance of IBLR to LTBP

<table>
<thead>
<tr>
<th>Bridge Crossing</th>
<th>Condition Requiring IBLR</th>
</tr>
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<tbody>
<tr>
<td>Waterway</td>
<td>Scour-prone bridges</td>
</tr>
<tr>
<td>Land</td>
<td>Groundwater fluctuations</td>
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<tr>
<td>Waterway/Land</td>
<td>Reuse of existing foundations</td>
</tr>
<tr>
<td></td>
<td>Bridge widening and rehabilitation</td>
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<tr>
<td></td>
<td>Increase in loads (i.e., dead load due to resurfacing or live load due to heavier truck loadings)</td>
</tr>
<tr>
<td></td>
<td>Load rating methodology not matching original design</td>
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<td>Physical deterioration (e.g., corrosion, decay, settlement)</td>
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<tr>
<td></td>
<td>Changes in specifications or policies</td>
</tr>
<tr>
<td></td>
<td>Truck Platooning</td>
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</tbody>
</table>
## Benefits of IBLR

<table>
<thead>
<tr>
<th>Area</th>
<th>Benefits</th>
</tr>
</thead>
<tbody>
<tr>
<td>Performance</td>
<td>Better evaluation; prevention of functional and catastrophic failures</td>
</tr>
<tr>
<td>Maintenance</td>
<td>Proactive and preventive maintenance; more robust bridge posting if implemented</td>
</tr>
<tr>
<td>Capital Expenditures</td>
<td>Reduction in expenditures over the useful life of the bridge; optimized planning of need for bridge replacement</td>
</tr>
</tbody>
</table>
CONCLUSIONS
Conclusions

- Current practice usually assigns load ratings based on evaluation of the superstructure
- Load carrying capacity of the substructure rarely considered
- A bridge load rating based on the superstructure alone could cause either catastrophic or functional failure
- A methodology for assigning substructure and integrated bridge load rating (IBLR) is developed
- Inventory substructure load rating should be based on tolerable displacement (1” to 1.25”)
- Operating substructure load rating should be based on settlement that would not cause structural damage or soil-foundation failure (2” to 2.25”)

Conclusions continued

- The basic settlement criteria can be adjusted as necessary to accommodate special soil-foundation systems, foundation reuse, widening, construction sequence, etc.

- Original (Geo and Structural) design methodology must be considered in performing IBLR analysis

- Reliable determination of the embedment of pile foundation is a must for IBLR of UF bridges

- For UF bridges, due diligence is needed to locate or establish basic data regarding the design and construction at the time the bridge was originally built