LESSONS ON GEOTECHNICAL ASPECTS
FROM RECENT MAJOR LONG-SPAN BRIDGE
DESIGN AND RETROFIT PROJECTS

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Presentation Outline

Review of Past Retrofit Projects
for Foundation Types & Soil Conditions

Examples in Foundation Modeling

Foundation Retrofit Designs
Long Span Bridge Retrofit Contracts
Bridges on Large Cellular Caissons
Bay Bridge West Span Suspension Bridge
Existing Bay Bridge East Span Steel Truss
Carquinez Steel Truss Bridge
New York City Verrazano Bridge
Brooklyn Bridge
Manhattan Bridge
Coleman Bridge near D.C.

Bridges on Piles
Existing Bay Bridge East Span Steel Truss- Steel and Timber Piles
Richmond-San Rafael Steel Truss- 14HP89 Steel Piles
Carquinez Steel Truss Bridge- 24” Concrete and 14” Steel Pile Footings
Benicia-Martinez Bridge- Large Diameter Rock Socket Piles
Vincent-Thomas Bridge- Large Pile Groups, Small Concrete and Steel Piles
Coronado Bay Bridge- 54-Inch Hollow Concrete Piles

Caissons & Smaller Pile Footings for Older Vintage Bridges

Recent New Design Long-Span Bridge Contracts
Bay Bridge East Span Replacement- 98-in Diameter Steel Pipe Piles
New Carquinez Suspension Bridge- 10-ft Diameter Cast-In Place Piles
Benicia-Martinez Bridge- 10-ft Diameter Cast-In Place Piles
Charleston Cooper River Bridge- 10-ft Diameter Cast-In Place Piles

Tacoma Narrows 2nd Crossing- Large Cellular Caissons

Large-Diameter Piles (Drilled or Driven) Favored for New Bridges
BASIC GEOTECHNICAL ISSUES IN BRIDGE RETROFIT PROJECTS

Assist in developing foundation & input motions to the global bridge model

Provide geotechnical capacity parameters in integrity check

Characterize other site hazard and stability issues

Assist in foundation retrofit design

Because of relative costs and difficulties in retrofit construction, Emphasis must be placed on avoiding undue conservatism, Especially in characterizing the seismic loading demand!
2000 MCEER Report on Foundation Modeling Approaches

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2004 MCEER Report on Foundation Modeling Approaches

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The Most Important Issue for Geotechnical Engineers in Retrofit Projects

Implement the appropriate Seismic Loading Criteria for the Project:

(1) Choice of Reference Rock Motion Spectrum.
(2) Conduct Site Response Analysis.
(3) Formulate the Appropriate Input Motion to the Global Bridge Model.
(4) Clarification to Relevant Parties on the Equivalent Response Spectrum.

Due to the very high cost for retrofit projects, hidden built-in conservatism should be avoided.
WHAT IS SEISMIC DEMAND ??

Foundation Compliance & Damping Tends to Reduce Forces, but Increase Displ.

Soft Soils at Water Crossing Sites can amplify Ground Shaking

Site Response Solutions from Bay Bridge Skyway Project
Site Geology

YBI Structures: on rock and shallow sand
Suspension Bridge: 2 supports on rock, 1 support in soft soil
Skyway Viaduct: all in soil sediment (approx. 100 m thick)

Soil Layer Information

Typical Sequence
- Young Bay Mud
- Merritt Sand
- Old Bay Mud
- Upper Alameda
- Lower Alameda
- Franciscan Rock
Site Response Solutions

Comparison among depth varying ground motions from site response
Forces are transmitted to the structure due to ground displacements whose amplitudes vary with depth.

The transmitted forces would be the product of ground displacement and soil stiffness.

The displacement amplitude tends to increase toward ground surface while the soil stiffness decreases.

For soft soil sites, soil stiffness at the mudline can be so small that its implied force would be small and mudline ground motions might not be relevant for design.
PREFERRED SOIL-STRUCTURE INTERACTION MODELS:
DETAILED TOTAL FOUNDATION MODELING APPROACH

A Total Foundation Modeling Approach, such as those illustrated in The Preceeding Slide was adopted in Most Recent Projects, including:

**New Bridge Design Contracts**
- Bay Bridge Replacement
- South Carolina Cooper River Bridge
- Tacoma Narrows Bridge
- New Benicia-Martinez Bridge
- New Carquinez Strait Bridge

**Retrofit Design Contracts**
- Verrazano Narrows Bridge
- Brooklyn Bridge
- Coronado Bay Bridge
- Existing Bay Bridge West Span
- Old Carquinez Strait Bridge

Above Included both Pile and Caisson Foundations

Foundation Modeling Approach for Caisson Foundations

A Total Foundation Modeling Approach is Also the Preferred Approach for Caisson Foundations from Recent Project Experiences, including:

**New Bridge Design Contracts**
- Tacoma Narrows Bridge

**Retrofit Design Contracts**
- Verrazano Narrows Bridge
- Brooklyn Bridge
- Existing Bay Bridge West Span
- Old Carquinez Strait Bridge

Above are Exclusively Caisson Foundations
Modeling Approach for Caissons

Figure 4. Caisson Model Employed at Tacoma Narrows Bridge

Figure 5. Concept of Nonfield Level 51 Winkler Spring Model adapted for Tacoma Narrows Bridge Causational Model System
Push Analysis to Extract SSI Springs

Force - Displacement (Pushover) Diagram
West Caisson - Embedment = 25 ft - Best Estimate Soil Springs

Global Spine Wrinkler Spring - Superstructure Included
Continuum Stand-Alone Model

Checking SSI Wrinkler Springs Against F.E. Continuum Solutions by Pseudo-Static Pushover

Force - Displacement (Pushover) Diagram
West Caisson - Embedment = 25 ft - Best Estimate Soil Springs
For shallowly embedment caissons, modeling the cyclic caisson rocking behavior would be very important. Which requires modeling the gapping behavior at the caisson/soil interface, especially at the caisson base.

Nonlinear-Gapping SSI Soil Springs at Caisson/Soil Boundary, especially at the base where much of the force interaction force transfer take place. Depth-varying input Motion along each SSI spring to take advantage of the lower shaking from deeper motions (e.g. at caisson base)

Key Lessons for Caisson Foundations

Pushover Solution to develop SSI Springs and also used for Back Substitution
Nonlinear SSI Soil Springs at Caisson Base
Lower Shaking from Motions Deconvoluted to Caisson Base

Representative Dynamic Response Solutions

Fig. 13: Displacement Time-History at Top of West Caisson
Lessons from Large Pile Group Foundations

- Large number of smaller piles found at many older vintage water crossing bridges.
- In California, (probably other states), the 14HP89 Steel Piles have been encountered.
- In some occasions, timber piles were encountered.
- Group configuration can be rather complex, often involving battered piles.
- Some of the pile groups involve hundreds of closely spaced piles.
- The Truss Bridge for the Existing Bay Bridge East Span involves over 600 timber piles.
- The Vincent Thomas Bridge Tower Involves Over 300 Steel Piles.
- Large Pile Groups with Piles Battered at a Large Angle are Often found at suspension bridge anchorages.
Foundation Modeling of Large Pile Groups of Small Diameter Piles

Vincent Thomas Bridge Foundations

Richmond-San Rafael Bridge Foundation

New Carquinez Bridge Anchorage Foundation

Earth Mechanics, Inc.

Federal Highway Administration
Modeling of Large Pile Groups

A full representation of all piles for these foundations would be impractical!! The No. of DOF in the foundation can easily exceed the bridge.

Also, there is a need for back substitution for foundation stresses.

Foundation substructuring techniques would be needed to reduce the foundation model so that the size of the global model could be managed.

Representation of the foundation stiffness using a 6X6 stiffness matrix, or some form of rotational and translational foundation springs have been well practiced and documented in other FHWA reports (Lam et al., 1986 FHWA reports, and also in 1998 MCEER reports) for regular highway bridge foundations.

The following discussions highlight some of the unique issues pertaining to large pile groups for major long span bridges at water crossings.

UNIQUENESS OF TYPICAL PILE FOUNDATIONS FOR MAJOR WATER CROSSING BRIDGES

Much More Complex Pile Layout. Therefore One Needs to Be Careful About the Form of the Stiffness Matrix

\[ K_{pile} = \begin{bmatrix}
K_x & 0 & 0 & 0 & 0 & 0 \\
0 & K_y & 0 & 0 & K_{y/90} & 0 \\
0 & 0 & -K_{x/90} & 0 & 0 & 0 \\
(symmetric) & & & & & \\
0 & 0 & 0 & K_{x/90} & 0 & 0 \\
& & & & & K_{y/90}
\end{bmatrix} \]

where \( K_x \) is the axial stiffness, \( K_y \) and \( K_{x/90} \) are the lateral stiffnesses, \( K_{x/90} \) and \( K_{y/90} \) are corresponding coupled stiffnesses between shear and overturning moment.
### Example of a Stiffness Matrix from the Richmond-San Rafael Foundation

![Diagrams showing stiffness matrices](image)

**Table 3.2 Pile Group Stiffness Matrix of at Richmond – San Rafael Bridge**

<table>
<thead>
<tr>
<th>Translation</th>
<th>Rotation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.97E+06</td>
<td>-1.89E+00</td>
</tr>
<tr>
<td>-1.89E+00</td>
<td>1.99E+06</td>
</tr>
<tr>
<td>-3.82E+00</td>
<td>-7.61E-01</td>
</tr>
<tr>
<td>2.30E+03</td>
<td>-1.87E+08</td>
</tr>
<tr>
<td>1.29E+08</td>
<td>7.09E+01</td>
</tr>
<tr>
<td>-2.83E+04</td>
<td>-2.75E+03</td>
</tr>
</tbody>
</table>

Note: the coordinate system used in this table is shown in Figure 3-16 where x- and y-axes are horizontal directions and z-axis is the vertical direction. Units: lb, in, rad
Lessons Learnt From Large Pile Groups

Substructuring to obtain the pile group stiffness matrix
Needs to be rigorous mathematically
Because of cross-coupling of moment vs. shear
In many cases non positive definite stiffness matrices
were introduced to the model which led to many problems.

The form of the stiffness matrix can be much more complex
than typically assumed.

Some basic principles of foundation substructuring
will be discussed below, not only for foundation stiffness,
but also on the issue regarding earthquake input motions,
and some issues on substructuring the
foundation masses and dampings.

Review of Total Foundation Model (e.g. the Bay Bridge Model)
Foundation Substructuring and Concept of Kinematic Motion

Concept of Kinematic Motion
Verification of Kinematic Motions Presented by Ingham et al.
Kinematic Motion, Vertical vs. Battered Pile

- The method (documented in the 2000 MCEER Report) has been verified in past major bridge projects.
- Proven to be practical in past projects.
- The procedure avoids undue conservatism (say using overly intensive mudline ground motion shaking criteria).
- The kinematic motion spectrum facilitate a clear cut appreciation of the basis of the design ground motion which can be compared with widely understood ARS (a design response spectrum).
- Often, an ARS criteria so developed was used for other part of the bridge (say at the approach structures) which are designed by less complicated response spectrum methods.
- The kinematic spectrum approach facilitate parametric studies to optimize the most efficient foundation system (layout, etc.)
Various Alternatives for Substructuring a Pile Group Foundation

MODEL A
- Detailed single pier total-system model to verify various aspects of SSI

MODEL B
- Single pile (substructuring at residual pile at mudline) model to evaluate SSI methods

MODEL C
- Pile group (substructuring at pile cap)

Further Example of Alternative Way for Substructuring the Pile Foundation
Research Programs for Evaluating the Structural Capacity of the HP 14x89 Steel Piles

Many of the California Water Crossing Bridges encountered the same HP 14x89 Steel Piles. Hence Caltrans embarked on a research program to provide experimental data on the structural capacity of such steel piles.

Richmond-San Rafael- Circular Bell Shaped Piles with some battered
Carquinez Strait- Vertical Pile Group
Vincent-Thomas Bridge- Vertical & Battered Pile Group
Research on Structural Capacity of Steel Piles

Analyses for Displacement Capacity of Richmond-San Rafael Battered Piles
Analyses for Displacement Capacity of Richmond-San Rafael Battered Piles

Analyses for Displacement Capacity of Carquinez Bridge Vertical Piles
The Pile Capacity Research Program Led to Significant Reduction in Foundation Retrofit for Caltrans

The need for foundation retrofit was eliminated for the Carquinez Strait Bridge

The capacity data confirmed the no foundation retrofit conclusions at the Vincent Thomas Bridge

Large diameter short piles were recommended for Richmond-San Rafael to add lateral foundation stiffness

Research on Structural Capacity of Steel Piles

In ground pile moment induced by kinematic ground displacements (freefield ground curvatures) In addition to pile moment from inertial structural loading.

Kinematic soil-pile interaction can be a major issue for some situation, especially in liquefiable spreading ground

Unrealistically high pile moment from overly simplified analyses led to wrong conclusions to adopt the use of bigger piles (especially for large diameter hollow concrete piles)

Permanent displacement often projected at deep bay mud or at embankments sites

Conventional geotechnical approach tend to be overly conservative

P-Y at soil layer interface of large soil stiffness contrast need research

Need to account for how the presence of the pile would affect the amplitude of ground displacement and the ground curvature

Sometimes, more sophisticated SSI analyses would be beneficial to answer some of the above questions, especially prior to embarking on a costly foundation retrofit design.

Other Design Issues Related to Pile Moment at Depth
Other Design Issues Related to Pile Moment at Depth

There are often questions on how pile moment induced by structural inertial loading be combined with pile moment induced by kinematic ground displacement (ground curvature).

From our experience, it is justified to uncouple the two load cases. For simplicity, and to avoid over conservatism, one can assumed that the two load cases are uncoupled.

Most often, large pile moments from the inertial structural loading induces localized pile moment only at shallow depth (say the upper 10 pile diameters), while kinematic ground displacement induced pile moments are introducing large pile moment at depth. Therefore, significant pile moment zones between the two load cases are naturally uncoupled in space.

Also, for the seismic tectonic conditions at CEUS (i.e. little near fault Issues, time of peak moment due to liquefaction tends to occur toward the end of the earthquake as oppose to the inertial load case which occur during the earthquake, and hence are naturally uncoupled in time.

LESSIONS ON SSI

Interaction with structural analysts on the appropriate SSI model. Needs to be modified for different situations. Be able to utilize analytical as well as experimental data.

Tremendous merit to conduct analysis using a common numerical platform used by both structural and geotechnical engineers, so that transfer of the geotechnical model along with its input parameters can be transferred directly be used by structural engineers, rather than by a geotechnical report and overly large and complicated databases.
### Bridges on Liquefiable Soils: Retrofit Measures

#### Table 11-1. Summary of ground improvement methods for liquefaction remediation at existing bridges

<table>
<thead>
<tr>
<th>Method</th>
<th>Principle</th>
<th>Suitable Soil Types</th>
<th>Treated Soil Properties</th>
<th>Relative Costs</th>
<th>Abatement Applicability**</th>
<th>Plan Applicability*</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compressible Soil</td>
<td>High-precision grout with high-pressure grout pumping; soil pressure grouting is practiced.</td>
<td>Compressible soils with some fines.</td>
<td>Improved D, S.E.G, C.E. &gt; 80 to 150</td>
<td>Low</td>
<td>Moderate to high</td>
<td>Moderate to high</td>
<td>Must control base pressure and maintain high-quality concretes.</td>
</tr>
<tr>
<td>Particulate Grouting</td>
<td>Resin-based grouting; fill and sandstone.</td>
<td>Sands and gravels.</td>
<td>Centrifuge grouting: high strength.</td>
<td>Low</td>
<td>Moderate to high</td>
<td>Moderate to high</td>
<td>Must control base pressure and maintain high-quality concretes.</td>
</tr>
<tr>
<td>Chemical Grouting</td>
<td>Solutions of lime or lime-soda mixtures to form a retarding agent.</td>
<td>Sands and gravels.</td>
<td>Low to high strength.</td>
<td>High</td>
<td>Moderate to high</td>
<td>Moderate to high</td>
<td>Must control base pressure and maintain high-quality concretes.</td>
</tr>
<tr>
<td>Jet Grouting</td>
<td>High-pressure jetting of fines with high-quality stabilizer with jet to form column or slurry.</td>
<td>Sands and gravels.</td>
<td>Low to high strength.</td>
<td>High</td>
<td>Moderate to high</td>
<td>Moderate to high</td>
<td>Must control base pressure and maintain high-quality concretes.</td>
</tr>
<tr>
<td>Viscous Fill</td>
<td>Dense or medium compressible columns.</td>
<td>Sands and gravels.</td>
<td>Low to high strength.</td>
<td>High</td>
<td>Moderate to high</td>
<td>Moderate to high</td>
<td>Must control base pressure and maintain high-quality concretes.</td>
</tr>
<tr>
<td>Viscous Compression</td>
<td>Dense or medium compressible columns.</td>
<td>Sands and gravels.</td>
<td>Low to high strength.</td>
<td>High</td>
<td>Moderate to high</td>
<td>Moderate to high</td>
<td>Must control base pressure and maintain high-quality concretes.</td>
</tr>
</tbody>
</table>

#### Table 11-1. (continued) Summary of ground improvement methods for liquefaction remediation at existing bridges

<table>
<thead>
<tr>
<th>Method</th>
<th>Principle</th>
<th>Suitable Soil Types</th>
<th>Treated Soil Properties</th>
<th>Relative Costs</th>
<th>Abatement Applicability**</th>
<th>Plan Applicability*</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vibro-Consolidation</td>
<td>Dense or medium compressible columns.</td>
<td>Sands and gravels.</td>
<td>Low to high strength.</td>
<td>High</td>
<td>Moderate to high</td>
<td>Moderate to high</td>
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</tr>
</tbody>
</table>

**Note:** Item No. 1 indicates applicability of improvement method for foundations over or in liquefiable soils. Item No. 2 indicates applicability for pile or drilled shaft foundations extending through liquefiable soils.
Thank You