Honolulu Rail Transit Project: Drilled Shaft Design Considerations and Challenges

Presented By:

Ahilan Selladurai, P.E., S.E
Ahmad Abdel-Karim, Ph.D., P.E
PROJECT INTRODUCTION

1. West Oahu/Farrington Design-Build
2. Kamehameha Design-Build
3. Airport Design-Bid-Build
4. City Center Design-Bid-Build

20-Mile Guideway
Session-5C: Honolulu Rail Transit Project: Drilled Shaft Design Considerations and Challenges

PROJECT DESCRIPTION

- Over 10 miles of Segmental Viaduct
- Approx. 400 bents
- 12 Aerial Stations
GENERAL SPAN / PIER LAYOUT

Typical Bent

C-Bent

Straddle Bent

Typical Span Layout

Session-5C: Honolulu Rail Transit Project: Drilled Shaft Design Considerations and Challenges
### Pier Summary

<table>
<thead>
<tr>
<th>Pier Type</th>
<th>Airport</th>
<th>City Center</th>
</tr>
</thead>
<tbody>
<tr>
<td>Typical Pier</td>
<td>(Pier 423-Pier 636)</td>
<td>(Pier 637-Pier 808)</td>
</tr>
<tr>
<td>C-Pier</td>
<td>163</td>
<td>107</td>
</tr>
<tr>
<td>Hammerhead Stations</td>
<td>11</td>
<td>20</td>
</tr>
<tr>
<td>Hammerhead Transition Piers</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>Straddle Station Piers</td>
<td>7</td>
<td>8</td>
</tr>
<tr>
<td>Straddle Piers</td>
<td>18</td>
<td>13</td>
</tr>
<tr>
<td>C - Straddles</td>
<td>0</td>
<td>3</td>
</tr>
<tr>
<td>Total Piers</td>
<td>214</td>
<td>172</td>
</tr>
<tr>
<td>Total Shafts</td>
<td>239</td>
<td>196</td>
</tr>
</tbody>
</table>
### Geotechnical Summary

<table>
<thead>
<tr>
<th>Type</th>
<th>Date</th>
<th>No. of Piers</th>
<th>Borings</th>
</tr>
</thead>
<tbody>
<tr>
<td>G-1</td>
<td>30-Sep-13</td>
<td>20</td>
<td>439</td>
</tr>
<tr>
<td>G-2</td>
<td>17-Oct-13</td>
<td>20</td>
<td>471</td>
</tr>
<tr>
<td>G-3</td>
<td>25-Oct-13</td>
<td>20</td>
<td>508</td>
</tr>
<tr>
<td>G-4</td>
<td>29-Oct-13</td>
<td>10</td>
<td>525</td>
</tr>
<tr>
<td>G-5</td>
<td>24-Nov-13</td>
<td>21</td>
<td>584</td>
</tr>
<tr>
<td>G-6</td>
<td>27-Jan-14</td>
<td>20</td>
<td>423</td>
</tr>
<tr>
<td>G-7</td>
<td>18-Apr-14</td>
<td>20</td>
<td>485</td>
</tr>
<tr>
<td>G-8</td>
<td>30-May-14</td>
<td>20</td>
<td>517</td>
</tr>
<tr>
<td>G-9</td>
<td>13-Jun-14</td>
<td>18</td>
<td>514</td>
</tr>
<tr>
<td>G-9A</td>
<td>14-Jul-13</td>
<td>3</td>
<td>541</td>
</tr>
<tr>
<td>G-10</td>
<td>17-Oct-14</td>
<td>20</td>
<td>638</td>
</tr>
<tr>
<td>G-11</td>
<td>24-Oct-14</td>
<td>30</td>
<td>658</td>
</tr>
<tr>
<td>G-12</td>
<td>31-Oct-14</td>
<td>20</td>
<td>463</td>
</tr>
<tr>
<td>G-13</td>
<td>4-Nov-14</td>
<td>30</td>
<td>688</td>
</tr>
<tr>
<td>G-14</td>
<td>7-Nov-14</td>
<td>30</td>
<td>738</td>
</tr>
<tr>
<td>G-15</td>
<td>7-Nov-14</td>
<td>20</td>
<td>427</td>
</tr>
<tr>
<td>G-16</td>
<td>14-Nov-14</td>
<td>25</td>
<td>614</td>
</tr>
<tr>
<td>G-17</td>
<td>5-Dec-14</td>
<td>30</td>
<td>760L</td>
</tr>
<tr>
<td>G-18</td>
<td>8-Dec-14</td>
<td>30</td>
<td>787</td>
</tr>
<tr>
<td>G-19</td>
<td>25-Dec-14</td>
<td>1</td>
<td>637</td>
</tr>
<tr>
<td>G-20</td>
<td>10-Feb-15</td>
<td>3</td>
<td>465</td>
</tr>
<tr>
<td>G-21</td>
<td>10-Feb-15</td>
<td>23</td>
<td>697L</td>
</tr>
<tr>
<td>G-22</td>
<td>10-Feb-15</td>
<td>2</td>
<td>716</td>
</tr>
</tbody>
</table>

**Total:** 435 Borings
OUTLINE

- Project Introduction
- Shaft Configurations / Details
- Design Criteria / Process
- Construction
- Post-Grouting (Sac RT Project)
- Conclusions
DRILLED SHAFT CONFIGURATIONS

- Two Basic Shaft Configurations:
  - Prismatic
  - Stepped

- Stepped Shaft used to reduce the total shaft length based on the stability considerations ($L_2 < L_1$).
Session-5C: Honolulu Rail Transit Project: Drilled Shaft Design Considerations and Challenges
OUTLINE

- Project Introduction
- Shaft Configurations / Details
- Design Criteria / Process
- Construction
- Post-Grouting (Sac RT Project)
- Conclusions
## DESIGN CRITERIA

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Limit State</th>
</tr>
</thead>
<tbody>
<tr>
<td>Axial-Flexural-Shear Capacity</td>
<td>Strength and Extreme Limit States</td>
</tr>
<tr>
<td>Lateral Stability</td>
<td>Strength and Extreme Limit States</td>
</tr>
<tr>
<td>Buckling Capacity</td>
<td>Strength and Extreme Limit States</td>
</tr>
<tr>
<td>Lateral Deflections</td>
<td>• Service Limit State-1” (excluding wind effects)</td>
</tr>
<tr>
<td></td>
<td>• Extreme (Seismic) Limit State-18” at Top of Rail (Seismic)</td>
</tr>
</tbody>
</table>
SEISMIC PARAMETERS

Project Subsurface Profile

Elevation (ft)

-240
-180
-120
-60
0
60

Begin of Project
STA 1000+00.00

End of Project
STA. 1272+27.80

Coral
Tuff
Basalt
Older Alluvium
Recent Alluvium
SEISMIC PARAMETERS

Site-Specific Response Spectrum

Site Class
- C
- D
- E
- F1
- F2
- F3

Acceleration (g)

Period (sec)

0.0 0.5 1.0 1.5 2.0 2.5
FLEXIBLE DESIGN PROCESS TO ACCOMMODATE CHANGES:

- Layout
- Profile
- Utilities
- Roadways
- Geotechnical
- Parametric Studies
Seismic Analysis

• Setting Up Automation Procedure
  • Large Scale Project
    • Near 400 Piers with Varying Configurations/Design Data
  • Time Consuming
    • Response Spectrum Analysis (RSA)
    • 12-Span Finite Element Modeling (FEM)
• Possible Re-work Due To Changes In
  • Pier Geometry
  • Soil Data
SEISMIC ANALYSIS 3-STEP AUTOMATION

RSA Model

HRTP Alignment from AutoCAD

RSA Models Match Project Alignment and Profile
SEISMIC ANALYSIS 3-STEP AUTOMATION

Pier Models (Templates)

Typical Pier

C-bent

Straddle bent

Hammerhead

Station Concourse Bent
Straddle Bent - Template
Straddle Bent - Modified

Modifications Include:

- Horizontal Curve
- Vertical Profile
- Pier Offsets / Properties
Assembling Pier Models
Assembling Pier Models
SEISMIC ANALYSIS 3-STEP AUTOMATION

Assembling Pier Models
Assembled RSA Model
SEISMIC ANALYSIS 3-STEP AUTOMATION

Assembled RSA Model
### Model for Each Pier #

<table>
<thead>
<tr>
<th>Model #</th>
<th>Model Name</th>
<th>Begin Pier</th>
<th>End Pier</th>
<th># of Spans</th>
<th>Run</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>M422</td>
<td>416</td>
<td>428</td>
<td>12</td>
<td>X</td>
</tr>
<tr>
<td>2</td>
<td>M423</td>
<td>417</td>
<td>429</td>
<td>12</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>M424</td>
<td>418</td>
<td>430</td>
<td>12</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>M425</td>
<td>419</td>
<td>431</td>
<td>12</td>
<td>X</td>
</tr>
<tr>
<td>5</td>
<td>M426</td>
<td>420</td>
<td>432</td>
<td>12</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>M427</td>
<td>421</td>
<td>433</td>
<td>12</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>M428</td>
<td>422</td>
<td>434</td>
<td>12</td>
<td>X</td>
</tr>
<tr>
<td>8</td>
<td>M429</td>
<td>423</td>
<td>435</td>
<td>12</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>M430</td>
<td>424</td>
<td>436</td>
<td>12</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>M431</td>
<td>425</td>
<td>437</td>
<td>12</td>
<td>X</td>
</tr>
<tr>
<td>11</td>
<td>M432</td>
<td>426</td>
<td>438</td>
<td>12</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>M433</td>
<td>427</td>
<td>439</td>
<td>12</td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>M434</td>
<td>428</td>
<td>440</td>
<td>12</td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>M435</td>
<td>429</td>
<td>441</td>
<td>12</td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>M436</td>
<td>430</td>
<td>442</td>
<td>12</td>
<td></td>
</tr>
<tr>
<td>16</td>
<td>M437</td>
<td>431</td>
<td>443</td>
<td>12</td>
<td></td>
</tr>
<tr>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
</tbody>
</table>

### Pick Which Pier to Analyze

- Model Name:
- Begin Pier:
- End Pier:
- # of Spans:
- Run:
Step 1: Generate Pier Models
- Creates Pier Templates.
- Modify Templates to Match Actual Alignment & Profile and Pier Properties.

Step 2: Assemble Model
- “Splice” Pier Models

Step 3: Run All Assembled Models
- Runs Assembled Models From Step 2
- Read and Summarize Results

<table>
<thead>
<tr>
<th>Model #</th>
<th>Model Name</th>
<th>Begin Pier</th>
<th>End Pier</th>
<th># of Spans</th>
<th>Run</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>M422</td>
<td>416</td>
<td>428</td>
<td>12 X</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>M423</td>
<td>417</td>
<td>429</td>
<td>12 0</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>M424</td>
<td>418</td>
<td>430</td>
<td>12 0</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>M425</td>
<td>419</td>
<td>431</td>
<td>12 X 1</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>M426</td>
<td>420</td>
<td>432</td>
<td>12 0</td>
<td>0</td>
</tr>
<tr>
<td>6</td>
<td>M427</td>
<td>421</td>
<td>433</td>
<td>12 0</td>
<td>0</td>
</tr>
<tr>
<td>7</td>
<td>M428</td>
<td>422</td>
<td>434</td>
<td>12 X 1</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>M429</td>
<td>423</td>
<td>435</td>
<td>12 0</td>
<td>0</td>
</tr>
<tr>
<td>9</td>
<td>M430</td>
<td>424</td>
<td>436</td>
<td>12 0</td>
<td>0</td>
</tr>
<tr>
<td>10</td>
<td>M431</td>
<td>425</td>
<td>437</td>
<td>12 X 1</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>M432</td>
<td>426</td>
<td>438</td>
<td>12 0</td>
<td>0</td>
</tr>
<tr>
<td>12</td>
<td>M433</td>
<td>427</td>
<td>439</td>
<td>12 0</td>
<td>0</td>
</tr>
<tr>
<td>13</td>
<td>M434</td>
<td>428</td>
<td>440</td>
<td>12 0</td>
<td>0</td>
</tr>
<tr>
<td>14</td>
<td>M435</td>
<td>429</td>
<td>441</td>
<td>12 0</td>
<td>0</td>
</tr>
<tr>
<td>15</td>
<td>M436</td>
<td>430</td>
<td>442</td>
<td>12 0</td>
<td>0</td>
</tr>
<tr>
<td>16</td>
<td>M437</td>
<td>431</td>
<td>443</td>
<td>12 0</td>
<td>0</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
</tbody>
</table>
SEISMIC ANALYSIS 3-STEP AUTOMATION

Step 1: Generate Pier Models
• Creates Pier Templates.
• Modify Templates to Match Actual Alignment & Profile and Pier Properties.

Step 2: Assemble Model
• “Splice” Pier Models

Step 3: Run All Assembled Models
• Runs Assembled Models From Step 2
• Read and Summarize Results

<table>
<thead>
<tr>
<th>Pier #</th>
<th>Pier type</th>
<th>Col Height</th>
<th>Col Diameter</th>
<th>Top of Rail Max Disp.</th>
<th>Top of Column Max Disp.</th>
<th>Bottom of Column Max Disp.</th>
<th>Top of Column Max Shear</th>
<th>Top of Column Max Moment</th>
<th>Bottom of Column Max Shear</th>
<th>Bottom of Column Max Moment</th>
<th>Bottom Col. Axial</th>
</tr>
</thead>
<tbody>
<tr>
<td>422</td>
<td>Transition Pier</td>
<td>29.05</td>
<td>6</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>423</td>
<td>Typical</td>
<td>30.66</td>
<td>6.5</td>
<td>11.51</td>
<td>11.06</td>
<td>3.65</td>
<td>495.64</td>
<td>3189.90</td>
<td>524.33</td>
<td>15900.25</td>
<td>-1400.547</td>
</tr>
<tr>
<td>424_L</td>
<td>Straddle Bent</td>
<td>29.08</td>
<td>6</td>
<td>11.51</td>
<td>9.41</td>
<td>3.09</td>
<td>337.50</td>
<td>4179.25</td>
<td>351.35</td>
<td>10586.23</td>
<td>-1659.889</td>
</tr>
<tr>
<td>424_R</td>
<td>Typical</td>
<td>9.05</td>
<td>2.95</td>
<td>9.05</td>
<td>2.95</td>
<td>314.21</td>
<td>4355.38</td>
<td>327.48</td>
<td>10243.27</td>
<td>-1535.425</td>
<td></td>
</tr>
<tr>
<td>425</td>
<td>C-Pier</td>
<td>31.17</td>
<td>6.5</td>
<td>21.21</td>
<td>16.40</td>
<td>9.36</td>
<td>655.47</td>
<td>16987.05</td>
<td>700.76</td>
<td>26728.65</td>
<td>-1739.524</td>
</tr>
<tr>
<td>426</td>
<td>Typical</td>
<td>36.61</td>
<td>6.5</td>
<td>17.87</td>
<td>14.57</td>
<td>4.44</td>
<td>545.11</td>
<td>4799.96</td>
<td>583.71</td>
<td>16930.53</td>
<td>-1363.617</td>
</tr>
<tr>
<td>427</td>
<td>Typical</td>
<td>35.06</td>
<td>6.5</td>
<td>17.23</td>
<td>13.86</td>
<td>4.14</td>
<td>525.12</td>
<td>4045.77</td>
<td>563.66</td>
<td>17433.87</td>
<td>-1267.738</td>
</tr>
<tr>
<td>428</td>
<td>Typical</td>
<td>33.17</td>
<td>6.5</td>
<td>16.04</td>
<td>12.67</td>
<td>3.82</td>
<td>497.14</td>
<td>2561.16</td>
<td>529.84</td>
<td>17248.10</td>
<td>-1255.023</td>
</tr>
</tbody>
</table>
SEISMIC ANALYSIS 3-STEP AUTOMATION

Step 1: Generate Pier Models
• Creates Pier Templates.
• Modify Templates to Match Actual Alignment & Profile and Pier Properties.

Step 2: Assemble Model
• “Splice” Pier Models

Step 3: Run All Assembled Models
• Runs Assembled Models From Step 2
• Read and Summarize Results

<table>
<thead>
<tr>
<th>Pier #</th>
<th>Pier type</th>
<th>Col Height</th>
<th>Col Diameter</th>
<th>Top of Rail Max Disp.</th>
<th>Top of Column Max Disp.</th>
<th>Bottom of Column Max Disp.</th>
<th>Top of Column Max Shear</th>
<th>Top of Column Max Moment</th>
<th>Bottom of Column Max Shear</th>
<th>Bottom of Column Max Moment</th>
<th>Bottom Col. Axial</th>
</tr>
</thead>
<tbody>
<tr>
<td>422</td>
<td>Transition Pier</td>
<td>29.05</td>
<td>6</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>-1400.547</td>
</tr>
<tr>
<td>423</td>
<td>Typical</td>
<td>30.66</td>
<td>6.5</td>
<td>11.51</td>
<td>11.06</td>
<td>3.65</td>
<td>495.64</td>
<td>3189.90</td>
<td>524.33</td>
<td>15900.25</td>
<td></td>
</tr>
<tr>
<td>424_L</td>
<td>Straddle Bent</td>
<td>29.08</td>
<td>6</td>
<td>11.51</td>
<td>9.41</td>
<td>3.09</td>
<td>337.50</td>
<td>4179.25</td>
<td>351.35</td>
<td>10586.23</td>
<td>-1659.885</td>
</tr>
<tr>
<td>424_R</td>
<td>Typical</td>
<td>9.05</td>
<td>2.95</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1659.885</td>
</tr>
<tr>
<td>425</td>
<td>C-Pier</td>
<td>31.17</td>
<td>6.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>-1739.524</td>
</tr>
<tr>
<td>426</td>
<td>Typical</td>
<td>36.61</td>
<td>6.5</td>
<td>17.87</td>
<td>14.57</td>
<td>4.44</td>
<td>545.11</td>
<td>4799.96</td>
<td>583.71</td>
<td>16930.53</td>
<td>-1363.617</td>
</tr>
<tr>
<td>427</td>
<td>Typical</td>
<td>35.06</td>
<td>6.5</td>
<td>17.23</td>
<td>13.86</td>
<td>4.14</td>
<td>525.12</td>
<td>4045.77</td>
<td>563.66</td>
<td>17433.87</td>
<td>-1267.738</td>
</tr>
<tr>
<td>428</td>
<td>Typical</td>
<td>33.17</td>
<td>6.5</td>
<td>16.04</td>
<td>12.67</td>
<td>3.82</td>
<td>497.14</td>
<td>2561.16</td>
<td>529.84</td>
<td>17248.10</td>
<td>-1255.023</td>
</tr>
</tbody>
</table>

OTHER DESIGN PROCEDURES WERE ALSO AUTOMATED IN A SIMILAR FASHION.
OUTLINE

- Project Introduction
- Shaft Configurations / Details
- Design Criteria / Process
- Construction
- Post-Grouting (Sac RT Project)
- Conclusions
Typical Shaft Construction
Step 1

Excavate Top 20’ of Hole

20’-0’’
Typical Shaft Construction

Step 2

Install Corrugated Metal Pipe Shoring

20’-0”

3’-0”

20’-0”
Typical Shaft Construction
Step 3

Place CLSM Backfill

20'-0"
Typical Shaft Construction
Step 4

Excavate Lower Portion of Shaft
Extend Construction Joint 3 to 5 ft into CMP Casing.
Typical Shaft Construction

Step 6

Construction Joint 2

Construction Joint 1
Typical Shaft Construction

Step 7

Column

Construction Joint 2

Construction Joint 1
CONSTRUCTION PHOTOS

Session-5C: Honolulu Rail Transit Project: Drilled Shaft Design Considerations and Challenges
SHAFT CAPACITY

Side Resistance

Tip Resistance
Tip Resistance

- Hard to Estimate
- Conservative

Side Resistance

Tip Resistance Typically Ignored:
**Tip Resistance**

Zero Tip Resistance:
- Could be Very Conservative
- Actual SF Unknown
- Is SF 5 or 6 or > 6 OK?
- A Good Design is *Economical*
Tip Resistance

Significant Potential Savings w/:
- In-Situ Testing
- Post-Grouting
- Better Construction Practices

Side Resistance

Tip Resistance
PILE CAPACITY SCENARIOS - NOT ENOUGH CAPACITY

Top Soil

Sand/Rock

Soft Layer

Competent Soil/Rock
PILE CAPACITY SCENARIOS -
ZERO TIP EXTEND SHAFT TO COMPETENT SOIL

Top Soil
Sand/Rock
Soft Layer
Competent Soil/Rock
POST-GROUTING SCENARIOS - PILE IS SIGNIFICANTLY LONGER

- Top Soil
- Sand/Rock
- Soft Layer
- Competent Soil/Rock
Session-5C: Honolulu Rail Transit Project: Drilled Shaft Design Considerations and Challenges
PILE CAPACITY SCENARIOS - SHORTER PILE

- Top Soil
- Sand/Rock
- Soft Layer
- Competent Soil/Rock
IN-SITU TESTING: PRESSURE METER
IN-SITU TESTING: PRESSURE METER
POST-GROUTING
POST-GROUTING
POST-GROUTING BENEFITS: SAC RT PROJECT

Construction Cost: $22 Million

Post-Grout Savings: $2 Million!
CONCLUSION

- HRTP Project Shafts were each designed with pier-specific geotechnical boring data.

- VBA Excel Macros proved very effective for
  - Designing a Large Number of Shafts
  - Accommodating Many Changes Quickly
  - Enhancing Quality Control

- SacRT: In-Situ Testing / Post-Grouting Saved $$
QUESTIONS & ANSWERS