Crane Loads & Wharf Structure Design: Putting the Two Together

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Arun Bhimani, S.E.
President
Liftech Consultants Inc.

Erik Soderberg, S.E.
Principal
Liftech Consultants Inc.
www.liftech.net
Crane Size Growth:
1st Container Crane & Jumbo Crane
Crane Service Wheel Loads

Waterside Operating Wheel Loads

Wheel Load

Year Manufactured

Crane Loads

Crane loads increasing
Codes becoming more complex
Consequences of misapplication more severe
Chance of engineering errors increasing
Presentation Outline

The Problem – Overview
Wharf Designer’s Perspective
Crane Designer’s Perspective
Putting the Two Together
Q&A and Feedback
The Problem – Overview

- Consultant
- Crane Purchaser
- Port
- Wharf Designer
- Crane Supplier
Crane Purchaser Difficulties

Purchaser specified

“Allowable wheel load: 200 kips/wheel”

Suppliers submit

Supplier A 180 k/wheel
Supplier B 200 k/wheel
Supplier C 220 k/wheel

Which suppliers are compliant?
Crane Supplier Difficulty

Purchaser specified

Allowable wheel load: 200 kips/wheel
In some cases, linear load (kips/ft)

Not defined

Operating or out-of-service?
Unfactored or factored?
Wind profile?
Increase for storm condition?
Wharf Designer Difficulty

Client provides limited crane load data

No loading pattern

No basis given – Unfactored or factored?

Same loads given for landside and waterside

No details of wind or seismic criteria
Wharf Designer Perspective
Wharf Designer Perspective

Codes and Design Principle
Crane Girder Design
Design for Tie-down Loads
Crane Stop Design
Seismic Design Considerations
Codes and Design Principle
Design Codes & Standards

Crane

FEM, DIN, BS, AISC …,
Liftech

Wharf Structures

ACI 318 Building Code and Commentary
ASCE 7-05 Minimum Design Loads for Buildings and Other Structures
AISC Steel Construction Manual
Design Principle - Wharf Structure Design

Load Resistance Factored Design (LRFD)

Required Strength \leq \text{Design Strength}

Required Strength = \sum \text{Service Loads} \times \text{Load Factors}

Design Strength = \text{Material Strength} \times \text{Strength Reduction Factor} \Phi
# Load Factors & $\Phi$ Factors

<table>
<thead>
<tr>
<th>ACI</th>
<th>Load Factors</th>
<th>Concrete $\Phi$ Factors</th>
</tr>
</thead>
<tbody>
<tr>
<td>318</td>
<td>D 1.4</td>
<td>Ten 0.90</td>
</tr>
<tr>
<td></td>
<td>L 1.7</td>
<td>Comp 0.75/.7</td>
</tr>
<tr>
<td></td>
<td>W 1.3</td>
<td>Shear 0.85</td>
</tr>
<tr>
<td>to 2002</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2002+</td>
<td>1.2</td>
<td>0.90</td>
</tr>
<tr>
<td></td>
<td>1.6</td>
<td>0.75/.6</td>
</tr>
<tr>
<td></td>
<td>1.6*</td>
<td>0.75</td>
</tr>
</tbody>
</table>

* 1.3 if directionality factor is not included
Design Principle – Soil Capacity

Allowable Stress Design

Generally use service loads

Factor of safety typically 2.0 for operating

1/3 increase for storm wind or overload
Crane Girder Design
Required Crane Geometry Data

- Sill Beam
- Tie-downs
- Bumper
- Stowage pin

\[(n-1) \, S\]

\[n = \text{number of wheels per corner}\]
\[S = \text{average wheel spacing}\]
Typical Wheel Loading Geometry

Typical Wheel Spacing

Recommended Wheel Design Load Geometry

40'  4'  40'
Dead Loads and Live Loads

Wharf Loads
D – Wharf structure self weight
L – Wharf live load, includes containers and yard equipment (does not control)

Crane Loads (ASCE 7-05)
D – Weight of crane excluding lifted load
L – Lifted load or rated capacity
### ACI Load Factors – Crane Loading

<table>
<thead>
<tr>
<th>ACI 318</th>
<th>Load Factors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Year</td>
<td>D</td>
</tr>
<tr>
<td>to 2002</td>
<td>1.4</td>
</tr>
<tr>
<td>2002+</td>
<td>1.2</td>
</tr>
</tbody>
</table>

Some designers treat crane dead load as live load and use the 1.6 factor. This results in 23% overdesign; $1.6 / 1.3 = 1.23$. 
# Example Combination Table: Service Wheel Loads

<table>
<thead>
<tr>
<th>Mode</th>
<th>Operating</th>
<th>Stowed</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>WOP1</td>
<td>WOP2</td>
</tr>
<tr>
<td>Dead Load</td>
<td>DL</td>
<td>1.0</td>
</tr>
<tr>
<td>Trolley Load</td>
<td>TL</td>
<td>1.0</td>
</tr>
<tr>
<td>Lift System</td>
<td>LS</td>
<td>1.0</td>
</tr>
<tr>
<td>Lifted Load</td>
<td>LL</td>
<td>1.0</td>
</tr>
<tr>
<td>Impact</td>
<td>IMP</td>
<td>0.5</td>
</tr>
<tr>
<td>Gantry Lateral</td>
<td>LATG</td>
<td>1.0</td>
</tr>
<tr>
<td>Op. Wind Load</td>
<td>WLO</td>
<td>1.0</td>
</tr>
<tr>
<td>Stall Torque Load</td>
<td>STL</td>
<td>1.0</td>
</tr>
<tr>
<td>Collision Load</td>
<td>COLL</td>
<td></td>
</tr>
<tr>
<td>Storm Wind Load</td>
<td>WLS</td>
<td></td>
</tr>
<tr>
<td>Earthquake Load</td>
<td>EQ</td>
<td></td>
</tr>
<tr>
<td>Allowable Wheel Loads</td>
<td>LS</td>
<td>50 x S</td>
</tr>
<tr>
<td>(tons/wheel)</td>
<td>WS</td>
<td>65 x S</td>
</tr>
</tbody>
</table>

$S =$ Average spacing, in meters, between the wheels at each corner.

**Example:**

$S = 1.5 \text{ m}, \text{ Allowable LS Operating} = 50 \text{ t/m} \times 1.5 \text{ m} = 75 \text{ t/wheel}$
## Example Combination Table: Factored Wheel Loads

<table>
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<tr>
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<td></td>
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</tr>
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<td>Lifted Load</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Impact</td>
<td></td>
<td></td>
</tr>
<tr>
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<td></td>
<td></td>
</tr>
<tr>
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<tr>
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</tr>
<tr>
<td>Earthquake Load</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Allowable Wheel Loads</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- **Example:**
  - **S** = 1.5 m, **Allowable WS Storm** = 100 t/m * 1.5 m = 150 t/wheel
Tie-down Design
Multiple Tie-downs at a Corner

Uneven tie-down forces
Causes of Uneven Distribution

Some reasons why forces are not evenly distributed:

- Crane deflection
- Construction tolerances
- Wharf pins not centered
- Links not perfectly straight due to friction
Tie-down Loads

Manufacturers typically provide the service corner uplift force

Needed data:

- Factored corner uplift force
- Distribution between tie-downs
- Direction of force (allow for slight angle)
Bumper Load Provided by Manufacturer

Rated Bumper Reaction

Bumpers sized for collision at maximum gantry speed

Does not address runaway crane
Recommended Crane Stop Design Load

Tipping Force

H = maximum load that can develop, i.e. the load at which the crane tips.

D = crane weight

H = approximately 0.25 x D per stop
Wharf Seismic Design – Crane Loading

The mass of typical jumbo A-frame cranes can be ignored

For certain wharves and cranes, a time-history analysis may be necessary

Large, short duration wheel loads can be ignored

Localized rail damage may occur

The crane may derail
Crane Designer Perspective
Crane Designer Perspective

Basic Loads
Storm Wind Load
Load Combinations and Factors
Tie-down Loads
Basic Loads
Dead and Live Loads

Dead Loads
DL: Crane structure weight
TL: Trolley structure weight
LS: Lift System Weight

Live Loads
LL: Rated container load
Inertial Loads

IMP: Vertical impact due to hoist acceleration

LATT: Lateral due to trolley acceleration

LATG: Lateral due to gantry acceleration
Overload

COLL: Collision

SNAG: Snagging headblock

STALL: Stalling hoist motors

*Normally do not control*
Environmental Loads

WLO:  Wind load operating (In-Service)

WLS*: Wind load storm (Out-of-Service)

EQ:  Earthquake load

*Often a major source of discrepancies
Wind Load, Out-of-Service
WLS: Out-of-Service Wind

Wind Force = \( \sum A \times C_f \times q_z \)

- **A** = Area of crane element
- **C_f** = Shape coefficient (including shielding)
- **q_z** = Dynamic pressure, function of:
  - Mean recurrence interval (MRI)
  - Gust duration
  - \( V_{ref}^2 \), where \( V_{ref} \) is a location-specific, code-specified reference wind speed
  - Exposure (surface roughness)

From wind tunnel testing

Need to clearly specify
Shape Coefficient, $C_f$

Empirical values: FEM, BSI, etc.

Wind tunnel tests are more accurate

- Boundary layer
- Angled wind effects
- Shielding effects
Angled Wind

Wind Tunnel Test

Liftech Equations

Fx

Fz

Reaction

Wind Direction, Degrees

0 45 90 135 180

Fz

Fx
WLS: Mean recurrence interval (MRI)

Wind Force = \( \sum A \times C_f \times q_z \)

\( A = \) Area of element
\( C_f = \) Shape coefficient (including shielding)
\( q_z = \) Dynamic pressure, function of:

- Mean recurrence interval (MRI)
- Gust duration
- \( V_{ref}^2 \), where \( V_{ref} \) is a location-specific, code-specified reference wind speed
- Exposure (surface roughness)

From wind tunnel testing

Need to clearly specify
## Mean Recurrence Interval

### Probability of Speed Being Exceeded

<table>
<thead>
<tr>
<th>MRI</th>
<th>Years in Operation</th>
<th>1</th>
<th>10</th>
<th>25</th>
<th>50</th>
<th>100</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 yrs</td>
<td></td>
<td>.10</td>
<td>.64</td>
<td>.93</td>
<td>.99</td>
<td>.99997</td>
</tr>
<tr>
<td>25 yrs</td>
<td></td>
<td>.04</td>
<td>.34</td>
<td>.64</td>
<td>.87</td>
<td>.98</td>
</tr>
<tr>
<td>50 yrs</td>
<td></td>
<td>.02</td>
<td>.18</td>
<td>.40</td>
<td>.64</td>
<td>.87</td>
</tr>
<tr>
<td>100 yrs</td>
<td></td>
<td>.01</td>
<td>.10</td>
<td>.22</td>
<td>.39</td>
<td>.64</td>
</tr>
</tbody>
</table>

**Example:**
Chance of 50-yr wind being exceeded in 25 years: 40%
WLS: Gust duration

\[ \text{Wind Force} = \sum A \times C_f \times q_z \]

\( A = \text{Area of crane element} \)
\( C_f = \text{Shape coefficient (including shielding)} \)
\( q_z = \text{Dynamic pressure, function of:} \)

- Mean recurrence interval (MRI)
- Gust duration
- \( V_{ref}^2 \), where \( V_{ref} \) is a location-specific, code-specified reference wind speed
- Exposure (surface roughness)

From wind tunnel testing

Need to clearly specify
Gust Duration

Wind Speed

Time
Wind Speed vs. Gust Duration

**Ratio of probable maximum speed averaged over “t” seconds to hourly mean speed.**

Reference, ASCE 7-05.

Example: converting 10-min speed to 3-sec speed

\[
V_3 = V_{10 \text{ min}} \left( \frac{V_{\text{hourly}}}{V_{10 \text{ min}}} \right) \left( \frac{V_3}{V_{\text{hourly}}} \right)
\]

\[
V_3 = V_{10 \text{ min}} \left( \frac{1}{1.04} \right)(1.52)
\]

\[
V_3 = V_{10 \text{ min}} (1.46)
\]
# Code Gust Durations

Code definitions of basic wind speed

<table>
<thead>
<tr>
<th>Code</th>
<th>Gust Duration</th>
<th>MRI</th>
</tr>
</thead>
<tbody>
<tr>
<td>EN 1991-1-4</td>
<td>10 min</td>
<td>50 yrs</td>
</tr>
<tr>
<td>FEM 1.004</td>
<td>10 min</td>
<td>50 yrs</td>
</tr>
<tr>
<td>ASCE 7-02</td>
<td>3 sec</td>
<td>50 yrs</td>
</tr>
<tr>
<td>HK 2004</td>
<td>3 sec</td>
<td>50 yrs</td>
</tr>
</tbody>
</table>
Typical Pressure Profiles

Shape of profile depends on surrounding surface roughness.
## Variation in WLS

<table>
<thead>
<tr>
<th>Variable</th>
<th>Variation</th>
<th>Effect on V</th>
<th>Effect on F *</th>
</tr>
</thead>
<tbody>
<tr>
<td>MRI</td>
<td>25 to 50 yrs</td>
<td>7.5%</td>
<td>15.6%</td>
</tr>
<tr>
<td>Gust</td>
<td>3 sec to 10 min</td>
<td>46%</td>
<td>113%</td>
</tr>
<tr>
<td>Profile</td>
<td>Open terrain to ocean exposure</td>
<td>5-10%</td>
<td>10-20%</td>
</tr>
</tbody>
</table>

*See later slides for effect on calculated tie-down load!
Recommendations for Specifying WLS

Return Period  Use 50-yr MRI
Basic wind speed
Gust duration  Use local civil code
Profile
Other factors
Shape coefficients Wind tunnel tests

Do not mix and match between codes for pressure and load factors!
Corner Reactions – Angled Wind

Do not use spreadsheet!

Use frame analysis program

Frame stiffness is significant to reactions
Load Combinations
Crane Design
Load Combinations

Load combinations
  Operating
  Overload
  Storm wind (out-of-service)

Design approaches
  Generally Allowable Stress Design (ASD)
Operating Condition Loads

DL: Crane weight*

LL: Rated container load

IMP & LAT: Inertial loads

WLO: Wind load, in service

*Excluding Rated Load
Out-of-Service & Overload

DL: Crane weight*
WLS: Wind load storm (out-of-service)

Overload Conditions (in and out-of-service)

*Including trolley and lift system
Recommendations

Requesting crane wheel load data
- Specify wind criteria
- Ask for basic loads
- Combine per ACI load factors

Requesting crane bids
- Provide factored load tables
- Ask to fill in tables
- Specify allowable factored loads
Tie-down Loads
Tie-Down Failures
Wind Load & Crane Reactions

\[ F_{\text{wind}} \]

\[ F_{\text{stow pin}} \]

\[ F_{\text{gantry}} \]

\[ F_{\text{tie-down}} \]
Error in Calculated Tie-down Force

Ratio of moments:

\[
\gamma = \frac{F_{\text{wind}} h}{D \frac{B}{2}} = \frac{\text{Overturning Moment}}{\text{Righting Moment}}
\]

Error in calculated tie-down force: if "e" = error in wind force,

\[
\frac{F_{\text{Tiedown,Actual}}}{F_{\text{Tiedown,Calculated}}} = \frac{1}{A} \left[ (1 + e) F_{\text{Wind}} h - D \frac{B}{2} \right] = \frac{(1 + e) \gamma - 1}{\gamma - 1}
\]
Error in Tie-down Force

![Graph showing the error in tiedown force ratio against Overturning Moment / Righting Moment (γ). The graph includes lines for 20%, 10%, 5%, and no error in V, with a horizontal line for the case with no error in V.](image-url)
Example:

Error in wind speed = 10%; $\gamma = 1.4$
Error in wind pressure = 21%

Error in calculated tie-down force = 74%
# Stability Load Factors

<table>
<thead>
<tr>
<th>Load</th>
<th>BSI</th>
<th>ACI</th>
<th>FEM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dead Load</td>
<td>1.0</td>
<td>0.9</td>
<td>1.0</td>
</tr>
<tr>
<td>TL + LS</td>
<td>1.0</td>
<td>0.9</td>
<td>1.0</td>
</tr>
<tr>
<td>Wind Load, 50-year</td>
<td>1.2</td>
<td>1.3*</td>
<td>1.2</td>
</tr>
<tr>
<td>MRI</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* 1.6 with ASCE 7-02 “directionality factor”
## Uplift: Factored vs. Service

<table>
<thead>
<tr>
<th>Load</th>
<th>Service</th>
<th>Factored</th>
<th>Load Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dead Load</td>
<td>-500</td>
<td>x 0.9 =</td>
<td>-450</td>
</tr>
<tr>
<td>Wind Load</td>
<td>+450</td>
<td>x 1.3 =</td>
<td>+585</td>
</tr>
<tr>
<td>Calculated Uplift</td>
<td>-50</td>
<td></td>
<td>+135</td>
</tr>
<tr>
<td>&quot;No Uplift&quot;</td>
<td></td>
<td></td>
<td>&quot;Uplift&quot;</td>
</tr>
</tbody>
</table>
Putting the Two Together
Problem Recap

Crane supplier and wharf designer work with incomplete and inconsistent data

Reasons:

Crane supplier generally uses Service Load approach

Wharf designer generally uses Factored Load approach

Neither knows what basis the other uses
Solution
Crane purchaser provide or facilitate detailed information
Obtain From Wharf Designer

Assumed wheel arrangement

Service or factored

Load factors

Load combinations for operating, overload, and out-of-service conditions

Complete wind criteria

Allowable wheel loads, kips/ft*

* Crane supplier tends to provide kips/wheel
## Example Combination Table: Service Wheel Loads

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<td>1.0</td>
</tr>
<tr>
<td>Lift System</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>Lifted Load</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>Impact</td>
<td>1.0</td>
<td></td>
</tr>
<tr>
<td>Gantry Lateral</td>
<td></td>
<td>1.0</td>
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<tr>
<td>Op. Wind Load</td>
<td></td>
<td>1.0</td>
</tr>
<tr>
<td>Stall Torque Load</td>
<td></td>
<td>1.0</td>
</tr>
<tr>
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<td></td>
<td></td>
</tr>
<tr>
<td>Storm Wind Load</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Earthquake Load</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Allowable Wheel Loads (tons/wheel)</td>
<td>LS</td>
<td>50 x S</td>
</tr>
<tr>
<td></td>
<td>WS</td>
<td>65 x S</td>
</tr>
</tbody>
</table>

**S** = Average spacing, in meters, between the wheels at each corner.

**Example:**

\[ S = 1.5 \text{ m}, \text{ Allowable LS Operating} = 50 \text{ t/m} \times 1.5 \text{ m} = 75 \text{ t/wheel} \]
## Example Combination Table: Factored Wheel Loads

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<td>WOP4</td>
<td>WS1</td>
</tr>
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<td>Dead Load</td>
<td>DL</td>
<td>1.2</td>
<td>1.2</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>Trolley Load</td>
<td>TL</td>
<td>1.2</td>
<td>1.2</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>Lift System</td>
<td>LS</td>
<td>1.2</td>
<td>1.2</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>Lifted Load</td>
<td>LL</td>
<td>1.6</td>
<td>1.6</td>
<td>1.0</td>
<td>1.2</td>
</tr>
<tr>
<td>Impact</td>
<td>IMP</td>
<td></td>
<td></td>
<td>0.8</td>
<td></td>
</tr>
<tr>
<td>Gantry Lateral</td>
<td>LATG</td>
<td>0.8</td>
<td></td>
<td></td>
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<td>EQ</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Allowable Wheel Loads</td>
<td>LS</td>
<td>60 x S</td>
<td></td>
<td></td>
<td>80 x S</td>
</tr>
<tr>
<td>(tons/wheel)</td>
<td>WS</td>
<td>75 x S</td>
<td></td>
<td></td>
<td>100 x S</td>
</tr>
</tbody>
</table>

S = Average spacing, in meters, between the wheels at each corner.

*Example:*

\[ S = 1.5 \text{ m}, \text{ Allowable WS Storm} = 100 \text{ t/m} \times 1.5 \text{ m} = 150 \text{ t/wheel} \]
Ask Crane Supplier For

Wheel arrangement

Wheel loads for individual loads

Combined wheel loads for operating, overload, and out-of-service conditions

Complete wind criteria used and basis for shape factors

Individual and corner factored loads for tie-downs including direction of loading
# Example Design Basic Load Table

Wharf Designer needs from Crane Supplier

<table>
<thead>
<tr>
<th></th>
<th>Wheel Load</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Seaside</td>
</tr>
<tr>
<td></td>
<td>LHS</td>
</tr>
<tr>
<td></td>
<td>RHS</td>
</tr>
<tr>
<td></td>
<td>Landside</td>
</tr>
<tr>
<td></td>
<td>LHS</td>
</tr>
<tr>
<td></td>
<td>RHS</td>
</tr>
<tr>
<td>Dead load</td>
<td>boom down</td>
</tr>
<tr>
<td></td>
<td>boom up</td>
</tr>
<tr>
<td>TL + LS</td>
<td>outreach</td>
</tr>
<tr>
<td></td>
<td>backreach</td>
</tr>
<tr>
<td></td>
<td>parked</td>
</tr>
<tr>
<td>LL</td>
<td>outreach</td>
</tr>
<tr>
<td></td>
<td>backreach</td>
</tr>
<tr>
<td>IMP</td>
<td>outreach</td>
</tr>
<tr>
<td></td>
<td>backreach</td>
</tr>
<tr>
<td>LATT</td>
<td>outreach</td>
</tr>
<tr>
<td>LATE</td>
<td>backreach</td>
</tr>
<tr>
<td>OWL&lt; (Angled Max)</td>
<td></td>
</tr>
<tr>
<td>Stall</td>
<td></td>
</tr>
<tr>
<td>COLL</td>
<td>boom down</td>
</tr>
<tr>
<td></td>
<td>boom up</td>
</tr>
<tr>
<td>EQx</td>
<td></td>
</tr>
<tr>
<td>EQz</td>
<td></td>
</tr>
<tr>
<td>SWL&lt; (Angled Max)</td>
<td></td>
</tr>
</tbody>
</table>

Liftech
Recap

- Obtain detailed crane and wharf design data
- Stick to one crane design code
- Stick to one wharf design code
- Use consistent design basis

Facilitate communication
Q & A
Crane Loads & Wharf Structure Design: Putting the Two Together

Thank you

This presentation will be available for download on Liftech’s website:

www.liftech.net

Arun Bhimani, S.E.
President
Liftech Consultants Inc.
www.liftech.net

Erik Soderberg, S.E.
Principal
Liftech Consultants Inc.