Effects of wave loading conditions on the fragility of pile-supported wharves/piers

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Outline

1. Introduction
2. Problem description
3. Suggested approach
4. Case study
5. Results and conclusions
Wharves/Piers

Closed type
(earth fill extended to front wall)

Open type
(wood, steel, concrete piles)

(Cong et al. 2013)
Structural Vulnerability

- West pier collapse
- East pier uplift

Port of Gulfport (Mississippi) after Hurricane Katrina (2005) (Gutierrez et al. 2006)
Structural Vulnerability

Pier deck damage due to uplift wave forces at Cozumel Cruise terminal (photos provided by: Dr. Carlos Ospina, BergerABAM)
Fragility Analysis

1. Estimates failure probability conditioned on selected parameters (e.g., storm surge, wave)

2. Allows uncertainty propagation to input parameters affecting demand (e.g., wave period) and capacity (e.g., material properties)

3. Requires the definition of a limit state function

\[ g(C, D) = \begin{cases} 
\text{Capacity} \leq \text{Demand} \Rightarrow \text{Failure} \\
\text{Capacity} > \text{Demand} \Rightarrow \text{Safety} 
\end{cases} \]
Fragility Analysis

\[ g(C_i, D_i) = \begin{cases} \hspace{1cm} C_i - D_i \leq 0 \Rightarrow Failure \\ C_i - D_i > 0 \Rightarrow Safety \end{cases} \]

\( i = \) examined failure mode (e.g., uplift, shear, flexural, etc.)

\[ \rho_{f,uplift} = P\left[ g_{uplift} (C_{uplift}, D_{uplift}) \leq 0 \mid IMs \right] \]

\( IMs = \) intensity measures (e.g., surge elevation, wave height, wave period)

\( C_{uplift} = \) uplift capacity (connection strength, deck weight)

\( D_{uplift} = \) uplift demand (vertical wave forces)
Adopted Wave Model

McConnell et al. (2004)

\[ F_{v,\text{imp}} = F_{v,qs} \frac{a_{v,\text{imp}}}{(t_r/T_m)^{b_{v,\text{imp}}}} \]

\[ F_{v,qs} = \left( F_v^* \frac{a_{v,qs}}{\left[ \frac{\eta_{\text{max}} - Z_c}{H_s} \right]^{b_{v,qs}}} \right) \times \epsilon_1 \]

\( a, b = \) empirical coefficients from regression analysis of the test data (McConnell et al. 2004)

\( \epsilon_1 = \) model error to envelope data with a wide degree of scatter (Balomenos and Padgett 2018)
Empirical Coefficients (quasi-static)

<table>
<thead>
<tr>
<th>Configuration</th>
<th>$a_{v,qs}$</th>
<th>$b_{v,qs}$</th>
<th>$\varepsilon_1$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Distribution</td>
<td>Mean</td>
<td>Stdev</td>
</tr>
<tr>
<td>Seaward deck</td>
<td>0.82</td>
<td>0.61</td>
<td>Normal</td>
</tr>
<tr>
<td>Internal deck</td>
<td>0.71</td>
<td>0.71</td>
<td>Normal</td>
</tr>
</tbody>
</table>

Tested model (McConnell et al. 2004)

$$F_{v,qs} = \left( F_v^* \frac{a_{v,qs}}{\left[\left(\frac{\eta_{max} - Z_C}{H_s}\right)^{b_{v,qs}}\right]} \right) \times \varepsilon_1$$
Dowelled Deck-Pile Connection

Typical pile-supported port and connection details (Stringer and Harn 2013)
Examined Connections

2 Connections

Dowels above deck’s top mat reinforcement

Dowels below deck’s top mat reinforcement

Details of examined connections (Balomenos and Padgett 2018)

2 Scenarios/Connection

1. SM = Seaward deck
2. IM = Internal deck
Fragility Analysis Flowchart – Uplift

For each Scenario/Connection

Demand

For each IMs combination

Generate MCS samples

Calculate $F_{v,qs}, F_{v,imp}$

$D_{uplift}$

Capacity

Generate MCS samples

Calculate $F_{c,pull}$ and deck weight

$C_{uplift}$

Uplift fragility flowchart (Balomenos and Padgett 2018)
Fragility Analysis

\[ p_{f,\text{uplift}} = P[C_{\text{uplift}} \leq D_{\text{uplift}} | H_{\text{max}}, Z_C, T_m] \]

Wave forces on pile-supported deck (Balomenos and Padgett 2018)
Fragility Surface – Seaward (PM-IN)
Fragility Surfaces

$T_m = 6 \text{ s}$

Seaward

Internal

PM-IN

PM-OUT
Fragility Surfaces – Seaward

\[ T_m = 6 \text{ s} \]

Dowels **above** deck’s top mat reinforcement

Dowels **below** deck’s top mat reinforcement

\[ p_f \approx 16\% \]

\[ p_f \approx 46\% \]
Fragility curve

\[ Z_C = -1.15 \text{ m and } T_m = 6 \text{ s} \]

(SM connection)

Uplift probability

\[ Z_C = -1.15 \text{ m and } H_{max} = 2.11 \text{ m} \]

(SM=Seaward, IM=internal)
Fragility curve for $Z_C = -1.15 \text{ m}$ (Seaward Deck, PM-OUT connection)

Fragility curve for $Z_C = 1.15 \text{ m}$ (Seaward deck, PM-OUT connection)
Conclusions

1. This study
   - sheds light on the fragility of pile-supported port connections subjected to coastal hazards (fragility curves)
   - explores how different wave loading conditions affect their performance

2. Rapid increase of uplift probability with the increase of the storm surge

3. Sharper changes are expected to the uplift probability for a seaward deck

4. Sufficient anchorage of dowels can prevent deck uplift during coastal extreme events
Future Work

1. Comparative analysis for different wave models → examine the role of epistemic uncertainty in affecting the fragility models

2. Parameterized fragility models → apply these models across a region (regional risk assessment)

\[ p_f(\text{uplift}|X, IM) = \frac{\exp(g(X, IM))}{1 + \exp(g(X, IM))} \]

3. Fluid structure interaction (FSI) → capture full characteristics of the wave loading
Acknowledgements

THANK YOU