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# Seismic Response of Large Pile Moored Floating Structures

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Liftech Consultants Inc. is a consulting engineering firm, founded in 1964, with special expertise in the design and procurement of dockside container handling cranes and other complex structures. Our experience includes structural design for wharves and wharf structures, heavy lift structures, buildings, container yard structures, and container handling equipment.

Erik Soderberg is Liftech's president and a California structural engineer with experience in the design, review, and modification of a variety of structural systems including hundreds of container cranes, over a dozen bulk loader structures, and over two dozen wharves and piers. Other structures include crane lift and transfer systems and concrete and steel floats.

## Background

Many recent float projects in SF Bay Area

Storm loading readily estimated and significant

Is earthquake loading significant?

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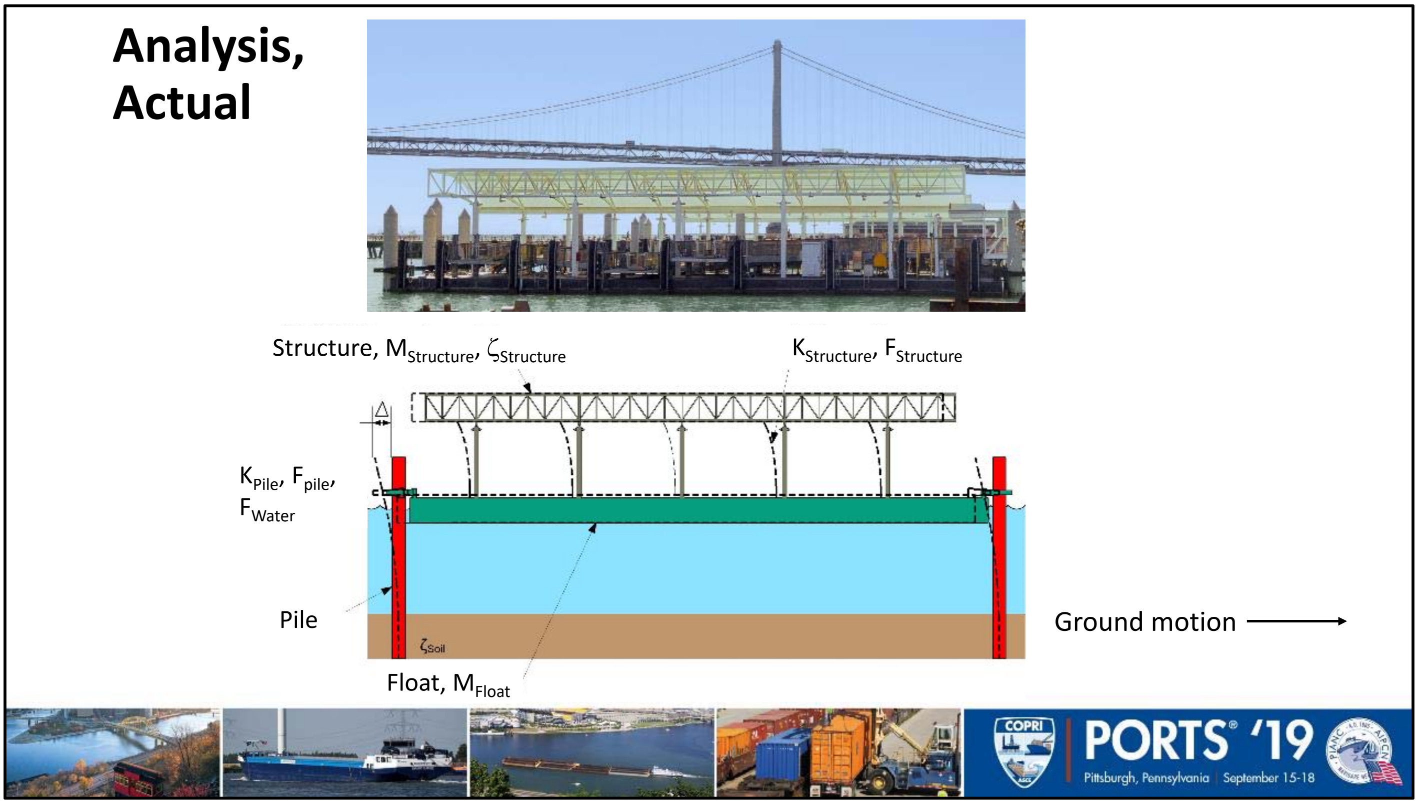
Erik has worked on the structural design of 18 pile moored floats in the San Francisco Bay.

| | |
|---|---|
| WETA SSF Ferry Terminal Float and Gangway | 1 |
| WETA SF Pier 9 Layover Berths | 2 |
| WETA Oakland Clay Street Float | 1 |
| WETA Alameda Refurbishment | 1 |
| WETA Central Bay O&M Facility | 8 |
| WETA Downtown SF Ferry Terminal Expansion | 3 |
| Alameda Seaplane Lagoon | 1 |
| Treasure Island | 1 |

For these projects, the design storm loading is readily estimated using sophisticated ship design programs. Loads are typically severe controlling the float structure and piling design, with pile factored lateral loads up to 250 kip (115 tonne).

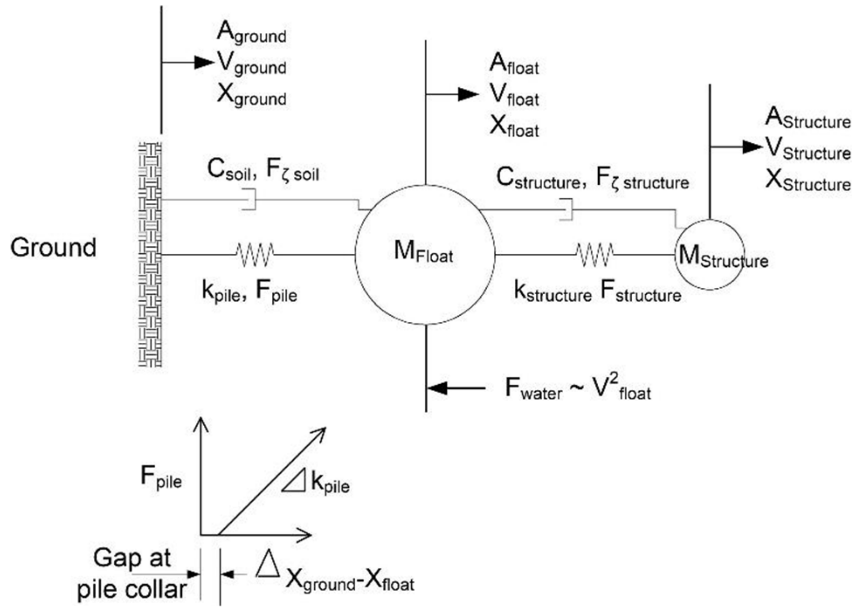
The earthquake design load has often not been analyzed, based on the expectation that the float is adequately isolated by the long piles and significant water resistance. Is this a reasonable expectation?




In an earthquake, the ground moves relative to the float, resulting in loads on the piling, between the piling and the float, and between the float and structures on the float. Masses; stiffnesses of deflecting elements, such as the piling and the structure on the float; and damping in the soil and in the structure on the float are significant factors.

No vessel and no ramp effects are included in the analyses.

## Analysis – Simplified





For our studies, the elements described on the previous slide were simplified to a system of masses, springs, and dampers, as shown. Gaps between the pile and float were considered as well.

Key simplifications include: no roll or pitch or rotational inertia, no effect of gangway connected to the float.

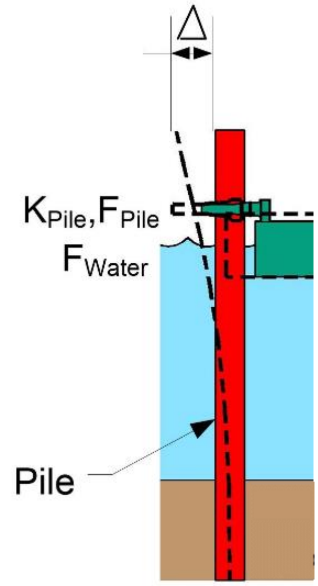
## Float Mass

Water displacement, minus calculated mass of structure on the float


The float mass was estimated as the water displacement, minus the calculated mass of the structure on the float.

## Piling Stiffness

- Varies significantly with water level
- Design low-water stiffness about 3x the high-water stiffness
- Analyzed design low-water and high-water conditions
- Low water = maximum piling forces
- High water = maximum float displacements



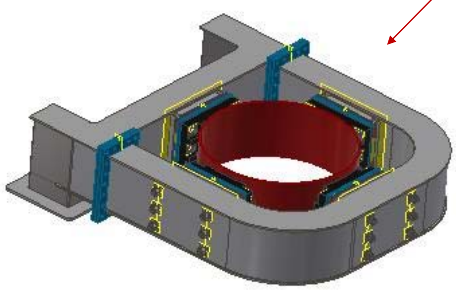


The stiffness of the piling varies depending on water level.  Design low-water stiffness is three times the stiffness at high water.

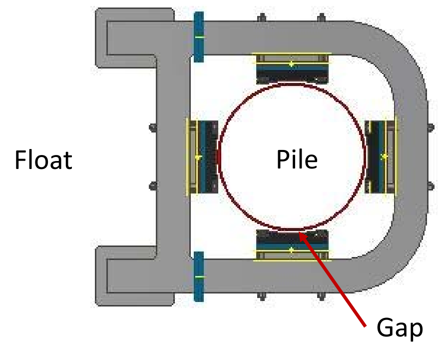
Analyses were made for both conditions (design low water and high water).

Low-water results in the maximum piling forces and high-water results in the maximum float displacements.

## Pile-Float Gap

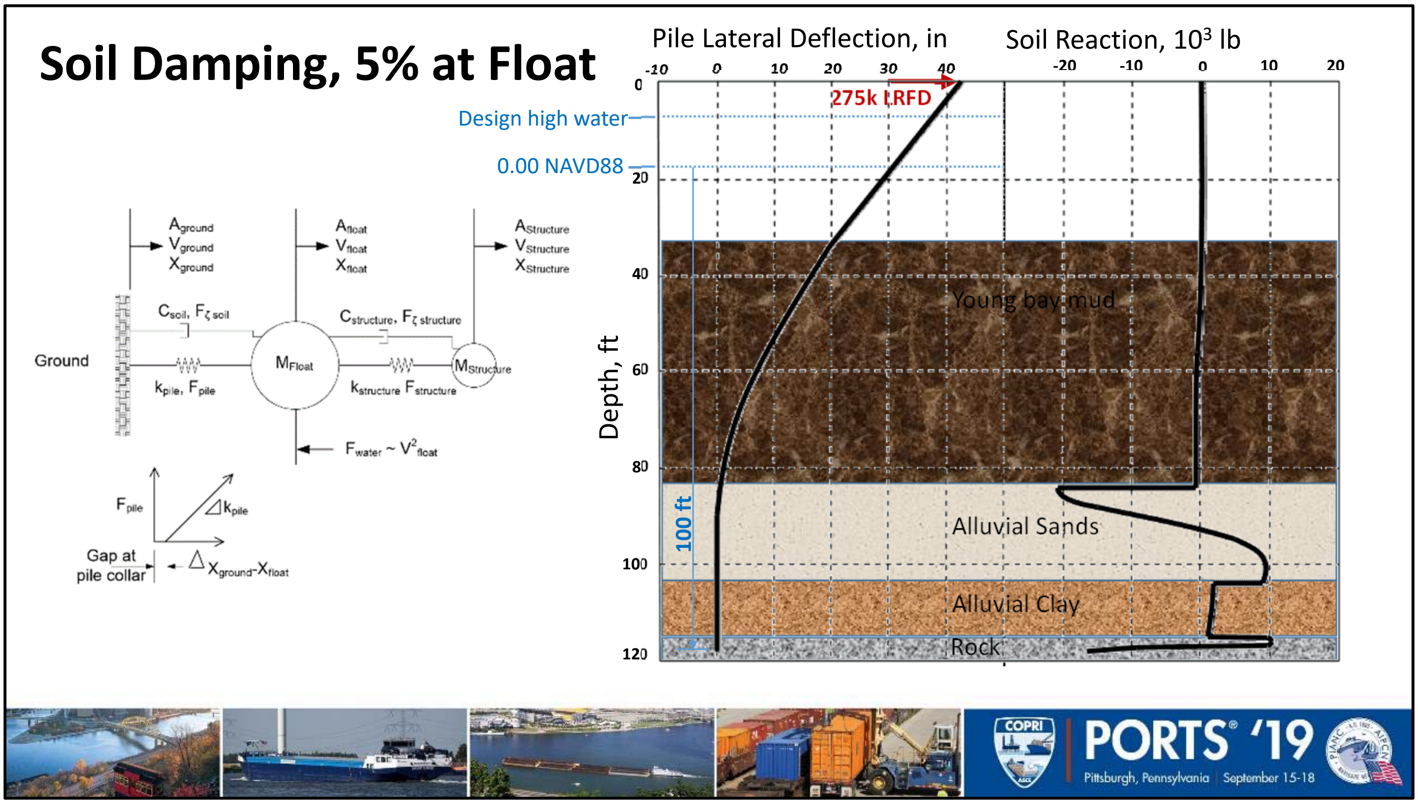


Isometric




Section


The pile-float gap used is typically 1 in (25 mm) in each direction, 2 in (50 mm) total gap, and is sometimes as little as ½ in each direction.

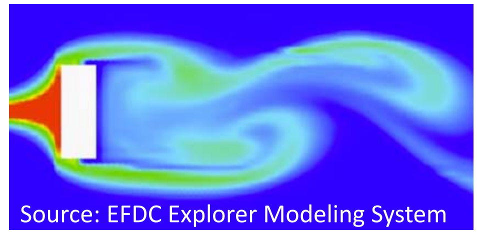



Soil damping was estimated by comparing the soil energy (integrated product of ½ soil reaction on pile x pile displacement in the LPILE analysis) with the energy absorbed by the soil spring in time-history analysis for the maximum displacement, conservatively assuming an elastic soil response.

The estimated damping is reasonable for small float movements with elastic soil deformations but is expected to be small for the larger movements with plastic soil deformations.

(Refer to pile analysis results from Liftech's Project 2212 calculations set, §6.3.6.4.)

## Estimated Water Resistance


Source: EFDC Explorer Modeling System

Limited guidance to estimate water resistance of an object moving back and forth in water over short distances

Used guidance for barges being moved by a ship

Float water force based on

- ½ $\rho v^2$ x 0.6 (drag coefficient) x 1.5 (amplification due to back and forth movement and additional resistance on piles)


The drag coefficient we used was based on barges being moved by a ship (Nowacki et al 1968). This was increased by 1.5 to account for the rapid back and forth motion (water mass effect) and additional resistance on piling. The accuracy and sensitivity of this estimate was studied and is presented later.

## Float Systems Studied

<u>System 1</u>
Concrete ferry float
Large float mass, large draft

<u>System 2</u>
Steel ferry float
Small float mass

<u>System 3</u>
Steel float with building on deck
Large building mass and damping

*Source: Shah Kawasaki Architects*


We have studied three different floats:

Two ferry floats: System 1 is made from concrete and is relatively massive; System 2 is made of steel and is much lighter.

System 3 is a large steel float with a relatively massive building on its deck.

## Structures on Float

**System 1**

Canopy = 4% of float mass
ξ = 0.5%
Lateral stiffness = 2 times stiffer than piling at design low water

**System 2**

Canopy = 12% of float mass
ξ = 0.5%
Lateral stiffness = 2 times stiffer than piling at design low water

**System 3**

Building = 90% of float mass
ξ = 5%
Lateral stiffness = 6 times stiffer than piling at design low water

*Source: Shah Kawasaki Architects*



Systems 1 and 2 had canopy structures and 0.5% damping was assumed based on Liftech's measurements of crane structures and not overestimating the damping.

System 3 had a relatively massive building and 5% damping was assumed based on what is typically used for building design.

## Earthquake Ground Motions

### Systems 1 and 2

Port of Los Angeles Design Earthquake

Not site specific

Applied for convenience

### System 3

Site specific Design Earthquake

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Port of Los Angeles Design Earthquake ground motions were used for Systems 1 and 2 (Abrahamson et al 2006).

These ground motions were not site specific but were applied for convenience.

Design Earthquake ground motions for System 3 were developed based on site specific analysis of the geology (Rudolph, Serna et al 2018), probable earthquakes, and estimated location of pile fixity.

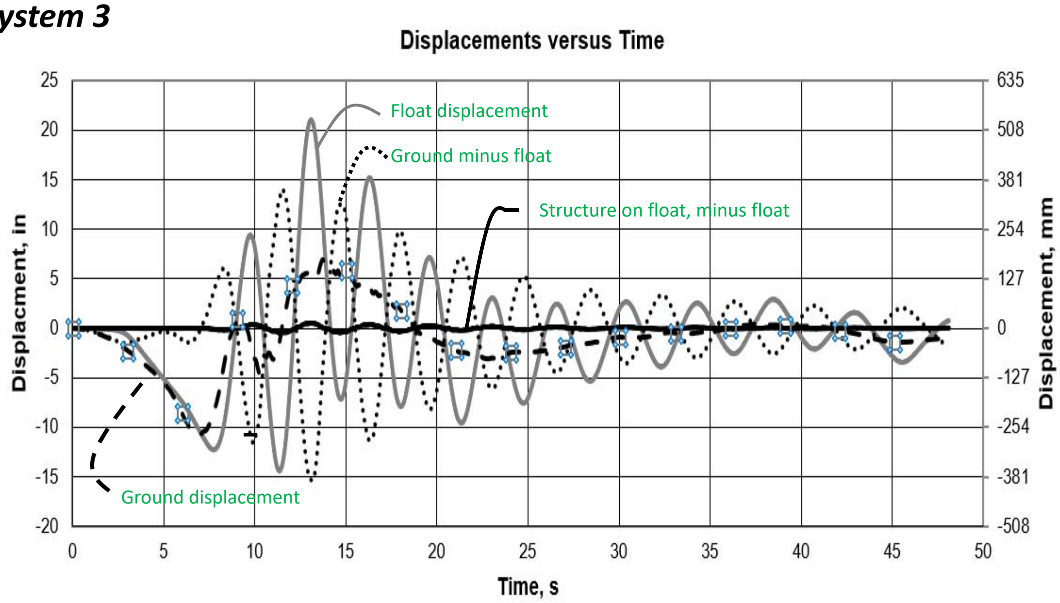
## Key Analysis Parameters

| System | Float | | | | | Piling | | | | Soil | Structure on Float | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Width ft | Length ft | Depth ft | Draft ft | Weight kip | # | OD in | t wall in | Lateral Stiffness kip/ft | ξ % | Weight kip | Lateral Stiffness 0° kip/in | Lateral Stiffness 90° kip/in | ξ % |
| 1 | 45 | 115 | 10.5 | 7.5 | 2,450 | 4 | 42 | 1.00 | 600 | 5 | 96 | 77 | 170 | 0.5 |
| 2 | 42 | 135 | 5.3 | 2.5 | 805 | 6 | 36 | 1.25 | 576 | 5 | 96 | 77 | 170 | 0.5 |
| 3 | 95 | 173 | 9.0 | 4.0 | 1,965 | 4 | 60 | 1.18 | 480 | 5 | 1,770 | 725 | 550 | 5.0 |


The table lists various parameters for the three systems.

# Analysis Results – Displacement vs Time

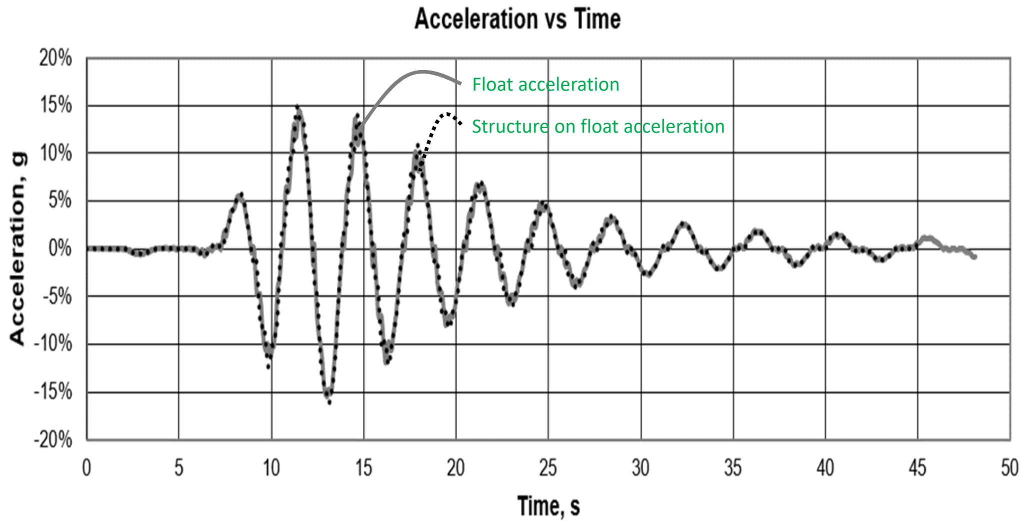
***System 3***




EQ:  Landers 1992, Dir 345

# Analysis Results – Acceleration vs Time

***System 3***

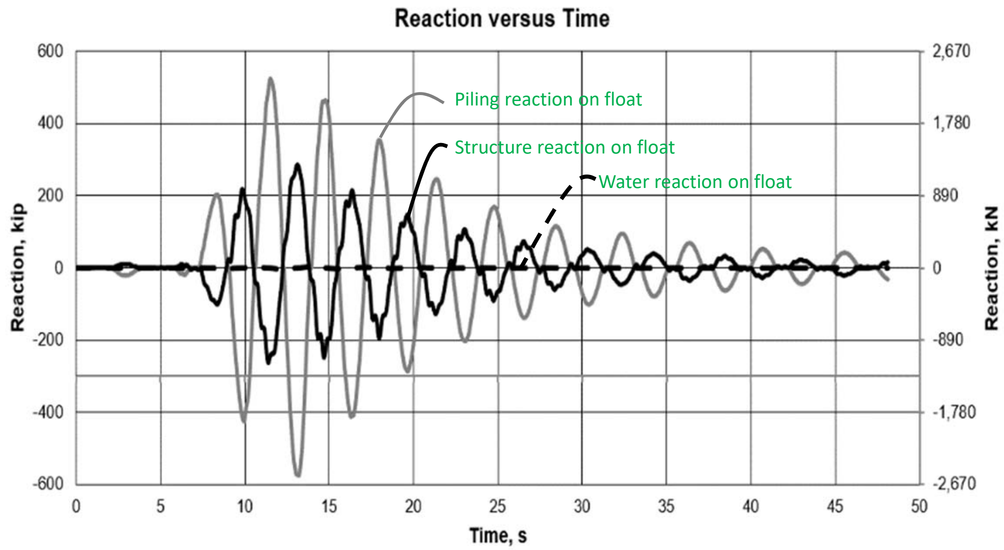




EQ: Landers 1992, Dir 345

# Analysis Results – Reaction vs Time

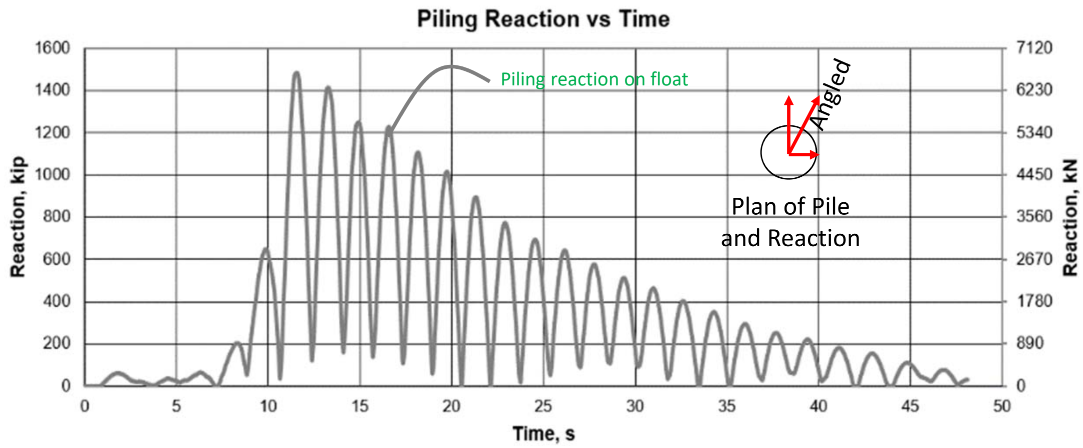
***System 3***




EQ: Landers 1992, Dir 345

# Analysis Results – Angled Piling Reaction vs Time

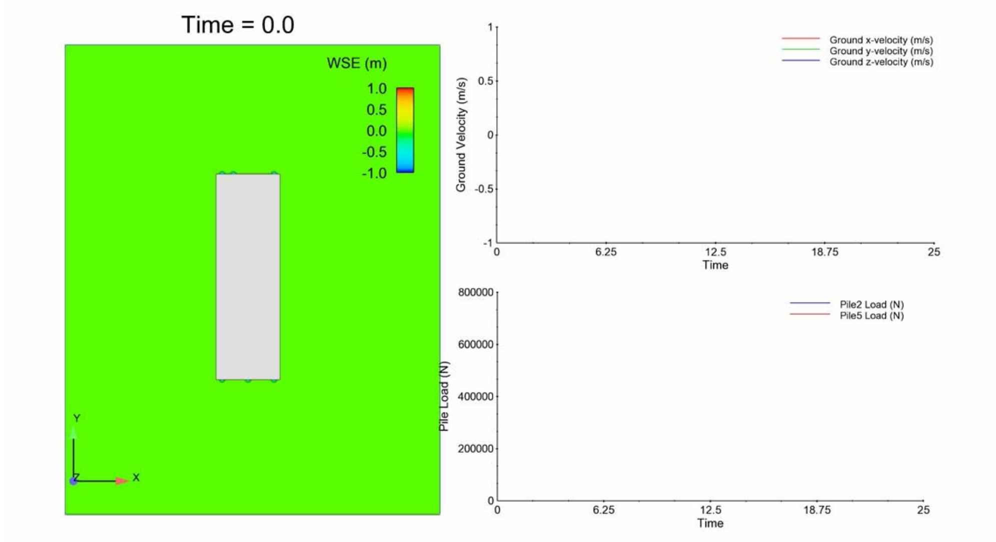
***System 3***





EQ: Landers 1992, Dir 345

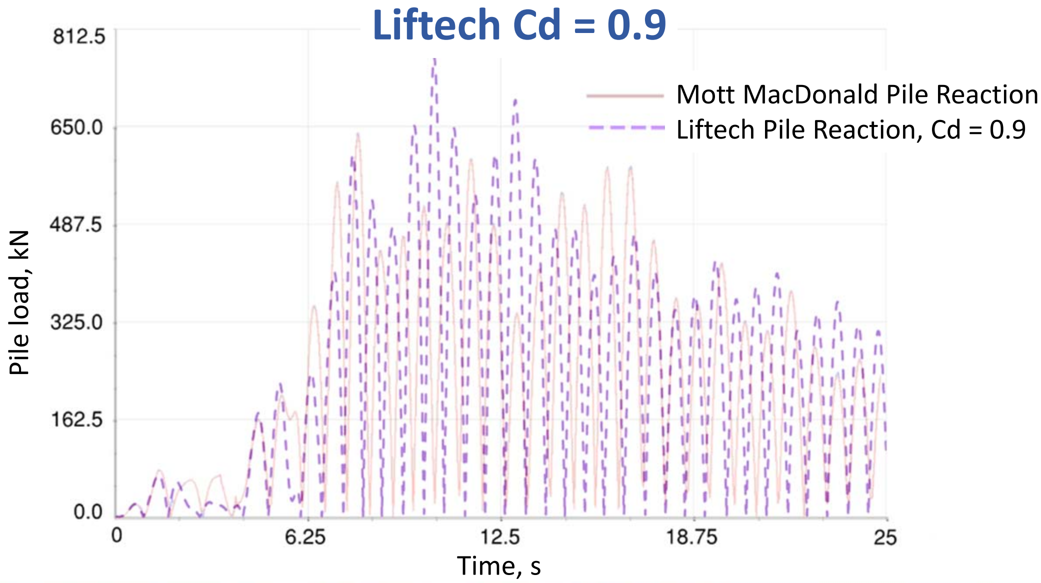
# Analysis Comparison – Fluid Dynamic Model
## *by Mott MacDonald*





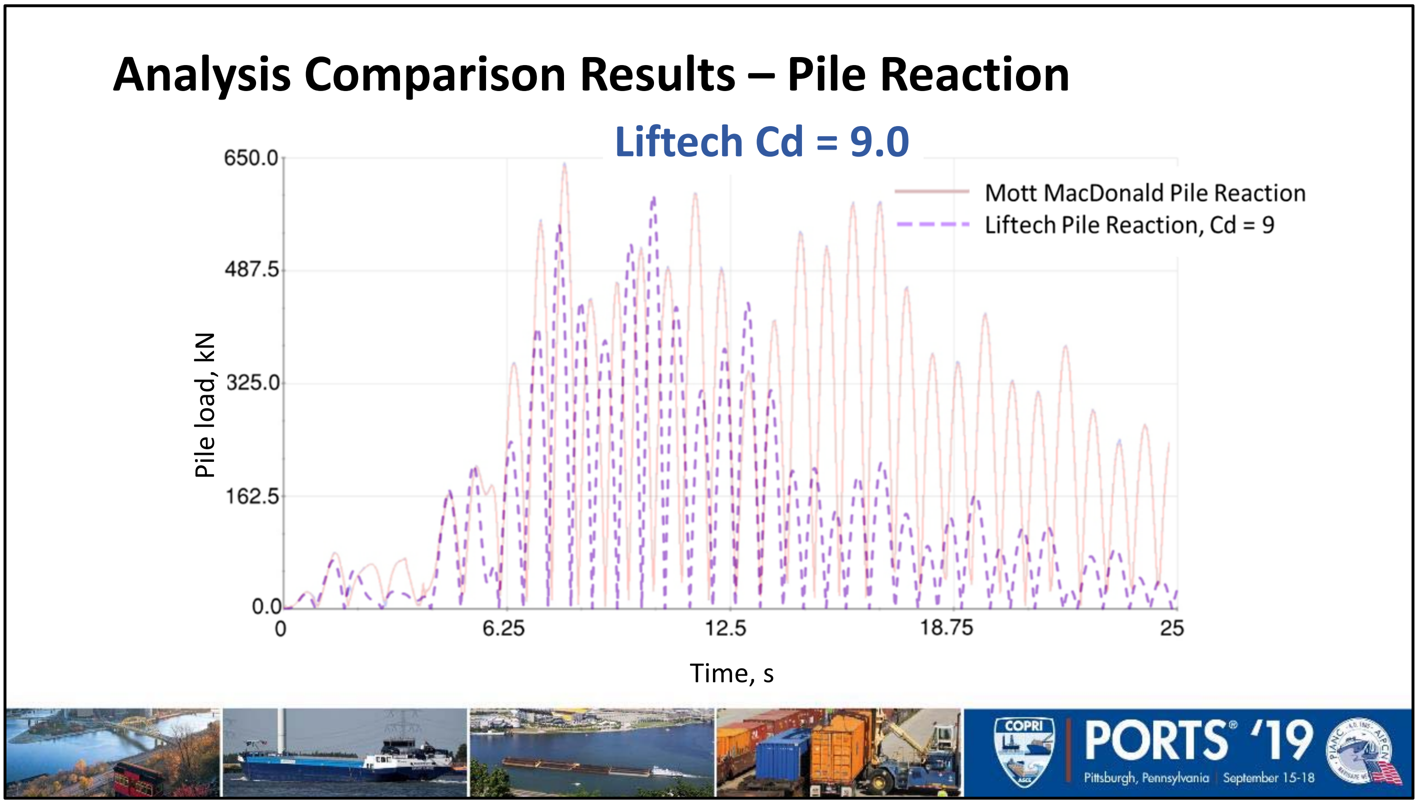
For comparison, a separate analysis was made for one of the earthquakes to compare the estimated pile reactions.

## Analysis Comparison Results – Pile Reaction





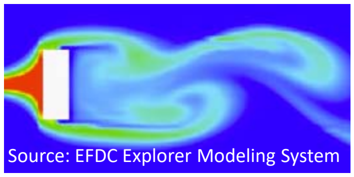
The Liftech calculated pile reactions with a Cd = 0.9 (and then amplified by 1.5) are slightly more than those in the fluid dynamic analysis by Mott MacDonald.




The Liftech calculated pile reactions with a Cd = 9 (and then amplified by 1.5) are less than those in the fluid dynamic analysis by Mott MacDonald.

## Sensitivity – Water Resistance and Soil Damping
## Average of angled maximum pile reactions for seven earthquakes

Ratio of applied / estimated water resistance


Source: EFDC Explorer Modeling System

Pile reactions all normalized by dividing by reaction with no water resistance and soil with 5% damping

Low sensitivity to water resistance

Similar results for float motion

| Applied / Estimated | | System 1 | | | |
|---|---|---|---|---|---|
| Water Resistance → | | 0 | 1 | 2 | 10 |
| | $\xi$ soil | | | | |
| | 5% | | 0.96 | 0.94 | 0.81 |
| $F_{piling}$ | 10% | 0.82 | 0.81 | 0.80 | 0.72 |
| | 15% | 0.73 | 0.71 | 0.70 | 0.64 |
| | 20% | 0.65 | 0.64 | 0.63 | 0.58 |

See next slide for other Systems and data


We wanted to check sensitivity of the pipe reactions to water resistance and soil damping. This slide is a key for understanding the sensitivity of pile reactions to water resistance and to soil damping. Refer to the next page for more data.

Calculated pile reactions are normalized to better visualize the relative effects of the water resistance and the soil damping. Normalization is with respect to zero water resistance and 5% soil resistance. For example:

> Doubling the estimated water resistance (comparing applied / estimated water resistance of "1" and "2") only reduces the pile reaction from 0.96 of reaction with zero resistance to 0.94 of the reaction with zero resistance. Even if the water resistance is ten times the estimated, the pile reaction is still 0.81 times the reaction with zero resistance.
>
> The effect of the soil damping is more significant.

# Sensitivity – Water Resistance and Soil Damping
## Average of Angled Maximum Pile Reactions for Seven Earthquakes

| Applied / Estimated | | System 1 | | | | System 2 | | | | System 3 | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Water Resistance → | | 0 | 1 | 2 | 10 | 0 | 1 | 2 | 10 | 0 | 1 | 2 | 10 |
| | ξ soil | | | | | | | | | | | | |
| $F_{piling}$ | 5% | | 0.96 | 0.94 | 0.81 | 1.00 | 0.98 | 0.96 | 0.85 | 1.00 | 0.99 | 0.98 | 0.93 |
| | 10% | 0.82 | 0.81 | 0.80 | 0.72 | 0.82 | 0.81 | 0.80 | 0.72 | 0.88 | 0.87 | 0.87 | 0.82 |
| | 15% | 0.73 | 0.71 | 0.70 | 0.64 | 0.70 | 0.69 | 0.68 | 0.63 | 0.78 | 0.78 | 0.77 | 0.74 |
| | 20% | 0.65 | 0.64 | 0.63 | 0.58 | 0.61 | 0.61 | 0.60 | 0.56 | 0.71 | 0.71 | 0.70 | 0.67 |
| $A_{Float}$ | 5% | 1.00 | 0.97 | 0.95 | 0.83 | 1.00 | 0.98 | 0.96 | 0.79 | 1.00 | 1.00 | 1.00 | 0.94 |
| | 10% | 0.85 | 0.83 | 0.81 | 0.75 | 0.84 | 0.83 | 0.82 | 0.73 | 0.89 | 0.89 | 0.89 | 0.83 |
| | 15% | 0.76 | 0.76 | 0.75 | 0.69 | 0.73 | 0.72 | 0.71 | 0.66 | 0.83 | 0.83 | 0.83 | 0.78 |
| | 20% | 0.71 | 0.71 | 0.69 | 0.64 | 0.67 | 0.66 | 0.54 | 0.61 | 0.78 | 0.78 | 0.78 | 0.78 |
| $x_{ground} - x_{float}$ | 5% | 1.00 | 0.96 | 0.94 | 0.82 | 1.00 | 0.98 | 0.96 | 0.85 | 1.00 | 0.99 | 0.99 | 0.93 |
| | 10% | 0.83 | 0.82 | 0.81 | 0.73 | 0.83 | 0.82 | 0.81 | 0.74 | 0.89 | 0.88 | 0.87 | 0.83 |
| | 15% | 0.73 | 0.73 | 0.72 | 0.66 | 0.72 | 0.71 | 0.71 | 0.65 | 0.79 | 0.79 | 0.79 | 0.76 |
| | 20% | 0.66 | 0.65 | 0.64 | 0.59 | 0.64 | 0.63 | 0.63 | 0.59 | 0.72 | 0.72 | 0.72 | 0.70 |

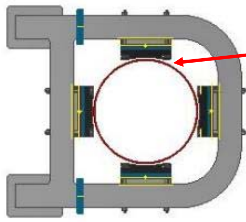
Note: Normalized to No Water Resistance and $\xi$ = 5%


Typical:

Reactions are not extremely sensitive to water resistance

More sensitive to soil damping

## Sensitivity – Pile Gap and Soil Damping
## Average of Angled Pile Reaction Maximums for Seven Earthquakes



*Pile Plan View*

Pile-float gap, mm (each side)

| | System 1 | | | |
|---|---|---|---|---|
| | 0 | 25.4 | 50.8 | 127 |
| ξ soil | | | | |
| 5% | | 1.00 | 0.97 | 1.04 |
| 10% | 0.84 | 0.84 | 0.87 | 0.88 |

See next slide for other Systems and data

Pile reactions all normalized by dividing by reaction with no pile gap and soil with 5% damping

Low sensitivity to pile-float gap (mostly)

Similar results for float motion


We also wanted to check sensitivity to the gap between the pile and float. This slide is a key for understanding the sensitivity of pile reactions to pile gap and to soil damping. Refer to the next page for more data.

## Sensitivity – Pile Gap and Soil Damping
## Average of Angled Maximum Pile Reactions for Seven Earthquakes

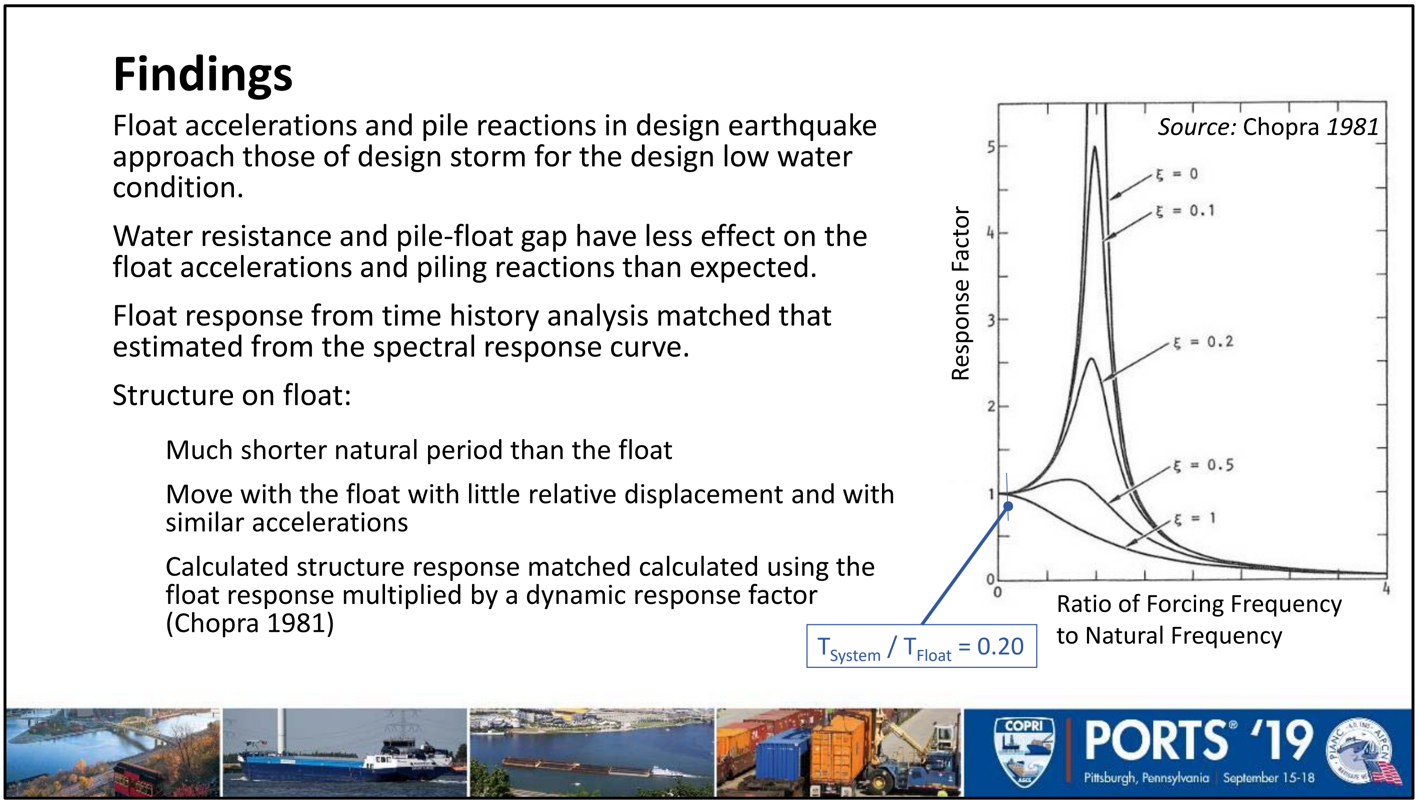
| | | System 1 | | | | System 2 | | | | System 3 | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Pile-Float Gap, mm → | | 0 | 25.4 | 50.8 | 127 | 0 | 25.4 | 50.8 | 127 | 0 | 25.4 | 50.8 | 127 |
| | $\xi$ soil | | | | | | | | | | | | |
| $F_{piling}$ | | 1.00 | 1.00 | 0.97 | 1.04 | 1.00 | 1.00 | 1.05 | 1.01 | 1.00 | 1.00 | 1.00 | |
| | 10% | 0.84 | 0.84 | 0.87 | 0.88 | 0.84 | 0.82 | 0.81 | 0.83 | 0.89 | 0.88 | 0.85 | 0.57 |
| $A_{Float}$ | 5% | 1.00 | 1.00 | 0.98 | 1.05 | 1.00 | 1.00 | 1.05 | 1.03 | 1.00 | 1.06 | 1.06 | 0.88 |
| | 10% | 0.86 | 0.86 | 0.89 | 0.91 | 0.85 | 0.84 | 0.82 | 0.85 | 0.94 | 0.94 | 0.94 | 0.65 |
| $x_{ground} - x_{float}$ | 5% | 1.00 | 1.05 | 1.02 | | 1.00 | 1.08 | 1.20 | 1.26 | 1.00 | 1.07 | 1.14 | 1.11 |
| | 10% | 0.84 | 0.89 | 0.95 | 1.11 | 0.84 | 0.84 | 0.83 | 0.94 | 0.89 | 0.94 | 0.99 | 0.90 |
| Note: Normalized to No Pile Gap and and $\xi$ = 5% | | | | | | | | | | | | | |


Typical:

Reactions are not sensitive to pile-float gap

Some sensitivity to soil damping

Gaps are 0, 1 in, 2 in, and 5 in.




1. Water resistance has less effect on the float response than expected.
2. Float accelerations and pile lateral reactions in design earthquakes are significant, approaching those of the design storm for the ground motions considered for the design low-water condition.
3. The structures on deck have much shorter natural periods than the float and move with the float with little relative displacement and with similar accelerations. The calculated structure response matched that calculated using the float response multiplied by a dynamic response factor (Chopra 1981).
4. The pile-float gap magnitude does not have a significant effect on float motions or piling reactions.
5. Float response from time history analysis matched that estimated from the spectral response curve.
6. Related to Chopra reference (see slide):

   $\mathbf{T_{system} / T_{float} = 0.20}$

## Conclusions

Pile moored floats can experience significant seismic movement, so earthquake float motions should be considered for pile moored float system design in areas of high seismicity, particularly if floats are sheltered with mild storm loads.

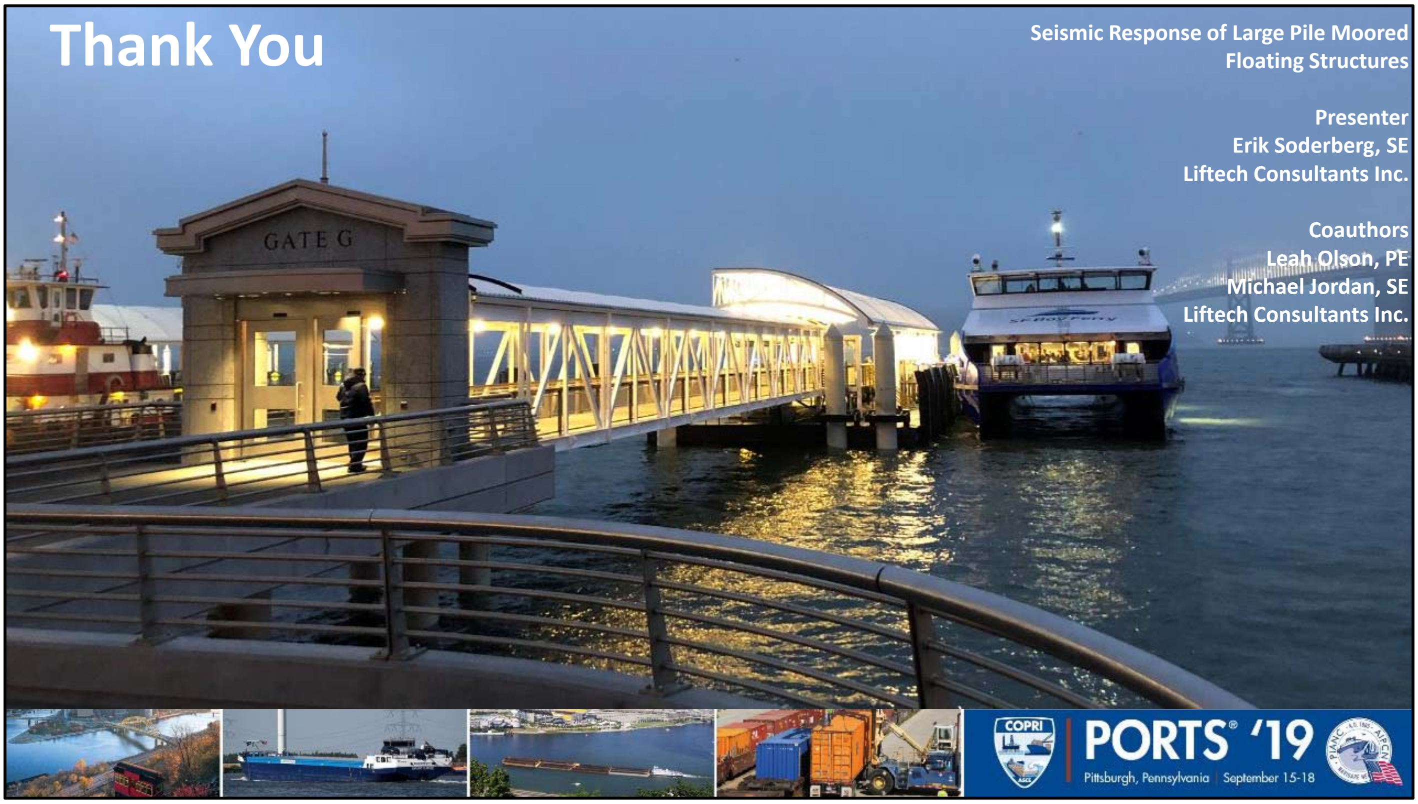
Surrounding water may not significantly resist or dampen the motion.

For float analysis, it is reasonable to assume:

- No pile-float gaps
- Structures on the floats are fixed to the float, if the structure periods are significantly shorter than the float-pile system

Float response can be determined from the ground motion response spectra and the float-pile period.


1. Pile moored floats can experience significant movement during a design earthquake. The surrounding water did not significantly resist or dampen the motion.
2. Design earthquake float motions should be considered in the design of pile moored float systems in areas of high seismicity, in particular when the float is sheltered with mild storm loads.
3. For float analysis, it is likely reasonable to simplify by assuming there are no pile-float gaps, and by assuming the structures on the floats are fixed to the float if the structures have periods significantly shorter than the float-pile system.
4. The float response can be determined from the ground motion response spectra and the float-pile period.




Coauthors Leah Olson and Michael Jordan, from Liftech, helped contribute to the paper and presentation.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