Seismic Response of Large Pile Moored Floating Structures

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ABSTRACT

Pile moored floats, such as floats for ferry terminals, ferry maintenance facilities, and other floating waterfront structures, often rely on long vertical piling to provide lateral support while allowing the floating structures to move up and down with changing water levels. These structures are often considered seismically isolated due to water resistance and are often designed without seismic evaluation.

Simplified spreadsheet time history analyses were made to analyze the seismic response of several pile moored floats designed for the San Francisco Bay Area. The analyses show that water resistance does not significantly reduce float response, such that seismic evaluation of these structures is recommended for high seismic regions, particularly if the float is sheltered and storm loading conditions are not severe.

INTRODUCTION

Pile moored floats are usually not analyzed for seismic motions, since they are often thought to be mostly isolated from ground motions due to the flexibility of the piles and the resistance of the surrounding water.

To confirm this assumption for several projects, the authors performed simplified time history analyses on multiple floats to study the effects of water resistance, soil damping, and the gap between the pile and float.

FLOAT SYSTEMS

Figures 1–3 show the three float systems (Systems) that were analyzed.

Figure 1. Concrete ferry float—System 1

Figure 2. Steel ferry float—System 2

Source: Shah Kawasaki Architects

Figure 3. Steel float with building on deck—System 3

ANALYSIS

The analysis method used the simplified pile-float system shown in Figure 4. Time history analyses of each System were made for seven design earthquakes with ground motions in two orthogonal directions. The analyses included a structure on the float, a pile-float gap, water resistance, and soil damping, with the parameters shown in Tables 1A and 1B. The following key simplifications were made:

1. Effect of the gangway on the float is ignored
2. Ballast is fixed to the float
3. No float roll or pitch
4. Constant drag coefficients for the piles and float moving through the water
5. Constant soil damping
6. No effective water mass
7. Participating piling mass is ignored

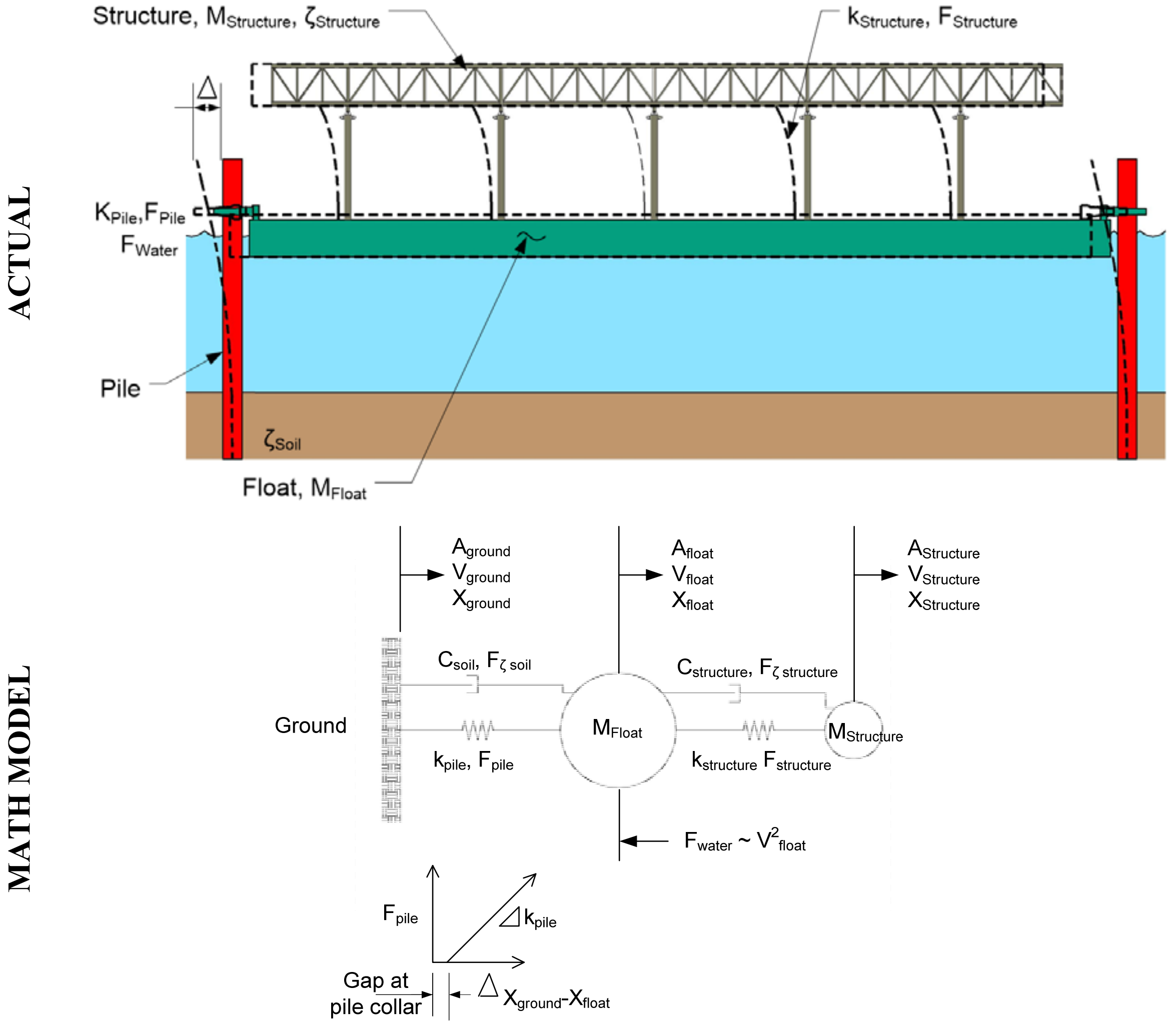

Figure 4. Pile-float simplified system

Table 1A. Key Analysis Parameters (*US Customary Units*)

System	Float					Piling				Soil	Structure on Float			
												Lateral Stiffness		
	Width ft	Length ft	Depth ft	Draft ft	Weight kip	#	OD in	t wall in	Lateral Stiffness kip/ft	ξ %	Weight kip	0˚ kip/in	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

Table 1B. Key Analysis Parameters (*SI Units*)

System	Float					Piling				Soil	Structure on Float			
												Lateral Stiffness		
	Width m	Length m	Depth m	Draft m	Weight t	#	OD mm	t wall mm	Lateral Stiffness kN/m	ξ %	Weight t	0˚ kN/mm	90˚ kN/mm	ξ %
1	13.7	35.1	3.2	2.3	1,114	4	1,067	25.4	8,760	5	44	13	30	0.5
2	12.8	41.2	1.6	0.8	366	6	914	31.8	8,410	5	44	13	30	0.5
3	29.0	52.7	2.7	1.2	893	4	1,524	30.0	7,008	5	805	127	96	5.0

Note: *1 Metric tonne (t) = 1,000 kg = 2.2 kip = 2,204 lb*

Earthquake Ground Motions

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 et al 2018), probable earthquakes, and estimated location of pile fixity.

Float Mass

The float mass was based on its water displacement. The structure weight on the float was accounted for separately.

Float-Piling System Stiffness

The stiffness of the float-piling system varies significantly depending on water level. Analyses were made for both the design low-water and high-water conditions. Low-water results in the maximum piling forces and high-water controls the maximum float displacements.

Estimated Water Resistance

We could not find guidance for estimating the water resistance to an object that is moving back and forth in water over short distances. The guidance we used applies to barges being moved by a ship, which behave differently (Nowacki et al 1968). Therefore, we based the water force on the float on the velocity of the float squared, multiplied by a drag coefficient of 0.6 to account for the geometry of the float moving through the water, multiplied by 1.5 to account for the back and forth movement and additional resistance on the piles. Our approach could be refined; however, as discussed later, the calculated motions were relatively insensitive to the water resistance.

Soil Damping

The analysis was not detailed enough to obtain an accurate understanding of soil damping. For System 3, the soil damping energy (product of force and displacement in the time history analysis) was compared with the energy absorbed by the soil in the LPILE pile-soil interaction analysis, conservatively assuming an elastic soil response. Based on this approach, 5% damping was reasonable and likely conservative, and a soil damping of 5% of critical was used for all systems. We expect that this damping is reasonable for small float movements with elastic soil deformations, but small for the large movements with plastic soil deformations. We also expect additional damping due to water pumping into and around the changing gaps between the soil and piling. No adjustment was made for potential water pumping.

Pile-Float Gap

The pile-float gap used was typically 1 in (25 mm) in each direction, 2 in (50 mm) total.

Structure on Deck

Systems 1 and 2 had canopy structures and 0.5% damping was assumed based on Liftech 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.

ANALYSIS RESULTS

Responses and forces were calculated for each earthquake in two orthogonal directions and for the angled direction. Minimum, maximum, and average responses were consolidated for design.

Graphs of calculated motions and reactions are provided below for System 3 in the design low water condition for one design earthquake, “Landers 1992,” in one orthogonal direction (“345”) and the angled direction. This earthquake resulted in the most severe float motions of the seven design earthquakes.

System 3 Responses—*One Orthogonal Direction*

The following graphs show System 3 displacements, reactions, and accelerations for the Landers 1992-345 earthquake for one orthogonal direction.

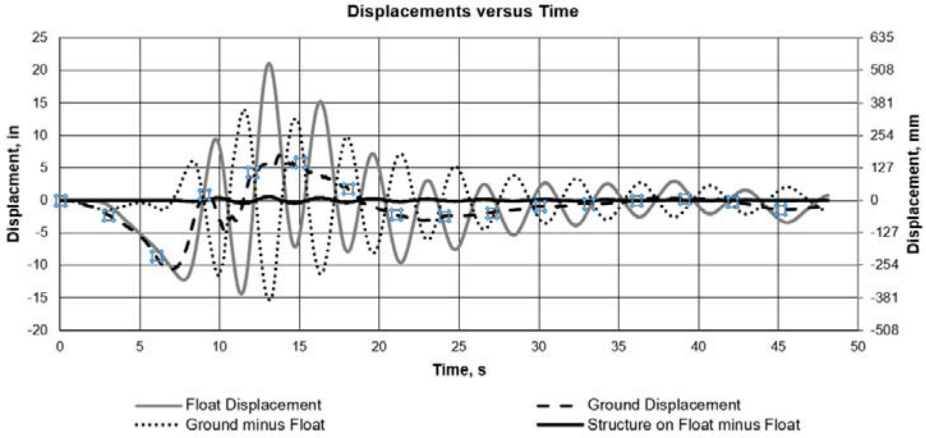

Figure 5. Displacements (System 3, Landers, one orthogonal direction)

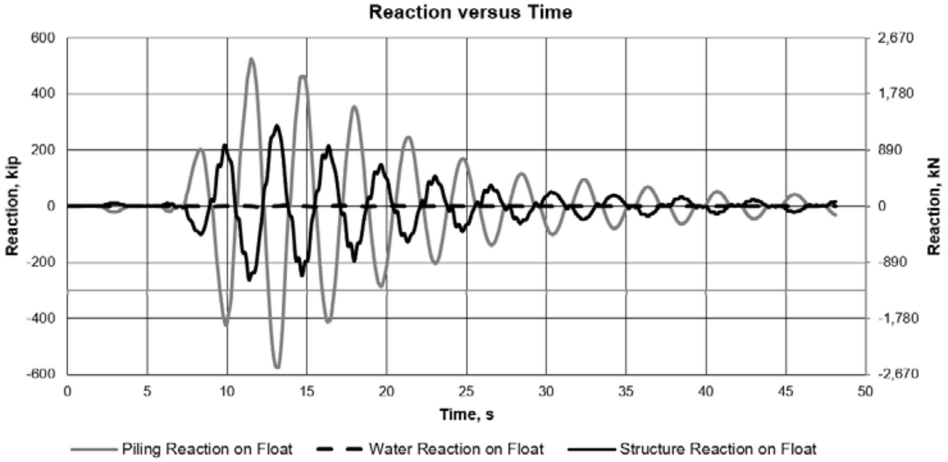

Figure 6. Reactions (System 3, Landers, one orthogonal direction)

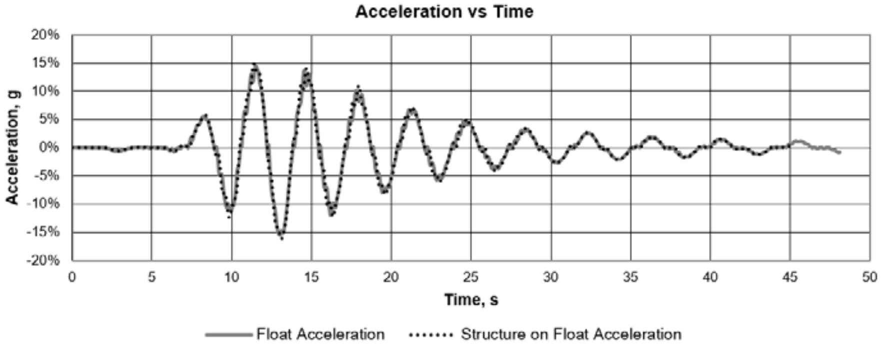

Figure 7. Accelerations (System 3, Landers, one orthogonal direction)

System 3 Responses—*Angled Reactions and Accelerations*
The following graphs show System 3 angled piling reactions and float accelerations for the Landers 1992-345 earthquake.

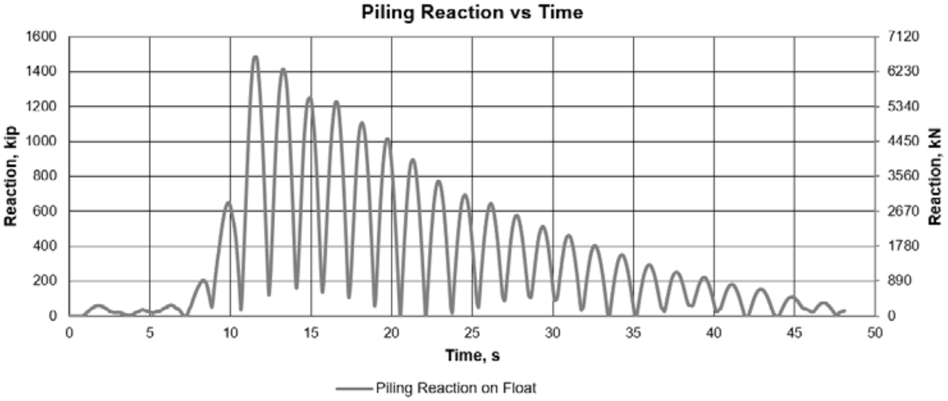

Figure 8. Piling reactions (System 3, Landers, angled)

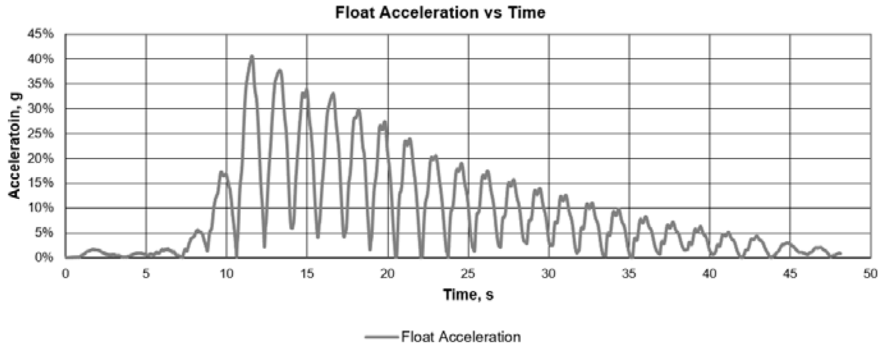

Figure 9. System 3: Float accelerations (System 3, Landers, angled)

Sensitivity – Water Resistance and Soil Damping (All Systems)
To determine the effect of water resistance and soil damping on the float response, the water resistance was varied from no resistance to 10 times that estimated for design. The soil damping was also varied, from 5% to 20%. Float gap was assumed to be 1 in (25 mm). Refer to Tables 2A, 2B, and 3, below, for calculated piling reactions, float accelerations, and relative float-to-ground movements as an average of the seven design earthquakes considered.

Analyses indicate that our design water resistance reduces the float motions and pile reactions up to about 4%. If the water resistance is two times the design water resistance, the reduction is up to about 6%. Similarly, if the water resistance is five times the design values used, the reduction is up to about 13%, and if ten times, up to about 19%.

Analyses indicate that, as expected, increasing soil damping has a significant effect on float motions and accelerations.

All structures had reasonably stiff lateral systems resulting in periods much smaller than the float-piling system, so the structures mostly move with the float and have only slightly larger motions and accelerations than the float.

Table 2A. Piling Reaction, Float Acceleration, and Float Movement for Varying Water Resistance and Soil Damping (*US Customary Units*)

Applied / Estimated Water Resistance →	ξ soil	System 1				System 2				System 3			
		0[1]	1	2	10	0	1	2	10	0	1	2	10
F_{Piling}, kip	5%	1,495	1,442	1,402	1,214	880	862	845	744	652	646	640	604
	10%	1,233	1,213	1,194	1,075	721	710	700	636	571	568	564	536
	15%	1,084	1,068	1,053	962	617	608	599	554	509	508	504	484
	20%	965	953	942	864	541	535	530	496	461	460	456	440
A_{Float}, g	5%	0.59	0.57	0.56	0.49	0.98	0.96	0.94	0.77	0.18	0.18	0.18	0.17
	10%	0.50	0.49	0.48	0.44	0.82	0.81	0.80	0.72	0.16	0.16	0.16	0.15
	15%	0.45	0.45	0.44	0.41	0.72	0.71	0.70	0.65	0.15	0.15	0.15	0.14
	20%	0.42	0.42	0.41	0.38	0.66	0.65	0.53	0.60	0.14	0.14	0.14	0.14
$x_{ground} - x_{float}$, in	5%	31.3	30.2	29.4	25.6	19.7	19.4	19.0	16.8	17.4	17.3	17.2	16.2
	10%	26.0	25.6	25.2	22.8	16.4	16.2	16.0	14.6	15.4	15.3	15.2	14.5
	15%	23.0	22.7	22.4	20.6	14.2	14.0	13.9	12.9	13.8	13.8	13.7	13.2
	20%	20.6	20.4	20.1	18.6	12.6	12.5	12.4	11.7	12.6	12.6	12.5	12.1

Note 1: Ratio of applied to estimated water resistance; 0 = no water resistance.

Table 2B. Piling Reaction, Float Acceleration, and Float Movement for Varying Water Resistance and Soil Damping (*SI Units*)

Applied / Estimated Water Resistance →	ξ soil	System 1				System 2				System 3			
		0[1]	1	2	10	0	1	2	10	0	1	2	10
F_{Piling}, kN	5%	6,651	6,415	6,237	5,401	3,915	3,835	3,759	3,310	2,901	2,874	2,847	2,687
	10%	5,486	5,397	5,312	4,783	3,208	3,159	3,114	2,830	2,540	2,527	2,509	2,385
	15%	4,823	4,752	4,685	4,280	2,745	2,705	2,665	2,465	2,265	2,260	2,242	2,153
	20%	4,293	4,240	4,191	3,844	2,407	2,380	2,358	2,207	2,051	2,047	2,029	1,958
A_{Float}, g	5%	0.59	0.57	0.56	0.49	0.98	0.96	0.94	0.77	0.18	0.18	0.18	0.17
	10%	0.50	0.49	0.48	0.44	0.82	0.81	0.80	0.72	0.16	0.16	0.16	0.15
	15%	0.45	0.45	0.44	0.41	0.72	0.71	0.70	0.65	0.15	0.15	0.15	0.14
	20%	0.42	0.42	0.41	0.38	0.66	0.65	0.53	0.60	0.14	0.14	0.14	0.14
$x_{ground} - x_{float}$, mm	5%	795	767	747	650	500	493	483	427	442	439	437	411
	10%	660	650	640	579	417	411	406	371	391	389	386	368
	15%	584	577	569	523	361	356	353	328	351	351	348	335
	20%	523	518	511	472	320	318	315	297	320	320	318	307

Note 1: Ratio of applied to estimated water resistance; 0 = no water resistance.

Table 3. Table 2 Values Normalized to 5% Soil Damping and No Water Resistance

Applied / Estimated Water Resistance →	ξ soil	System 1				System 2				System 3			
		0	1	2	10	0	1	2	10	0	1	2	10
F_{piling}	5%	1.00	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 ξ = 5%

Results of varying pile-float gaps are provided in Tables 4A, 4B, and 5.

Table 4A. Piling Reaction, Float Acceleration, and Float Movement for Pile-Float Gap and Soil Damping (*US Customary Units*)

		System 1				System 2				System 3			
Pile-Float Gap, inch →	ξ soil	0	1	2	5	0	1	2	5	0	1	2	5
F_{Piling}, kip	5%	1,441	1,442	1,402	1,501	862	862	904	870	648	646	647	510
	10%	1,214	1,213	1,250	1,269	728	710	730	723	578	568	554	367
A_{Float}, g	5%	0.57	0.57	0.56	0.60	0.96	0.96	1.01	0.99	0.17	0.18	0.18	0.15
	10%	0.49	0.49	0.51	0.52	0.82	0.81	0.83	0.84	0.16	0.16	0.16	0.11
$x_{ground} - x_{float}$, in	5%	28.8	30.2	29.4	36.5	18	19.4	21.6	22.7	16.2	17.3	18.4	18
	10%	24.3	25.6	27.5	32	15.2	16.2	17.9	21.4	14.4	15.3	16.1	14.5

Notes:
1. Design water resistance is applied to all conditions
2. Pile-float gap is with the pile centered, total gap = twice the value shown.

Table 4B. Piling Reaction, Float Acceleration, and Float Movement for Pile-Float Gap and Soil Damping (*SI Units*)

		System 1				System 2				System 3			
Pile-Float Gap, mm →	ξ soil	0.0	25.4	50.8	127.0	0.0	25.4	50.8	127.0	0.0	25.4	50.8	127.0
F_{Piling}, kN	5%	6,411	6,415	6,237	6,678	3,835	3,835	4,022	3,871	2,883	2,874	2,878	2,269
	10%	5,401	5,397	5,561	5,646	3,239	3,159	3,248	3,217	2,572	2,527	2,465	1,633
A_{Float}, g	5%	0.57	0.57	0.56	0.6	0.96	0.96	1.01	0.99	0.17	0.18	0.18	0.15
	10%	0.49	0.49	0.51	0.52	0.82	0.81	0.83	0.84	0.16	0.16	0.16	0.11
$x_{ground} - x_{float}$, mm	5%	732	767	747	927	457	493	549	577	411	439	467	457
	10%	617	650	699	813	386	411	455	544	366	389	409	368

Notes:
1. Design water resistance is applied to all conditions
2. Pile-float gap is with the pile centered, total gap = twice the value shown.

Table 5. Table 4 Values Normalized to 5% Soil Damping and No Pile-Float Gap

		System 1				System 2				System 3			
Pile-Float Gap, in →		0	1	2	5	0	1	2	5	0	1	2	5
Pile-Float Gap, (mm) →	ξ soil	(0.0)	(25.4)	(50.8)	(127.0)	(0.0)	(25.4)	(50.8)	(127.0)	(0.0)	(25.4)	(50.8)	(127.0)
F_{piling}	5%	1.00	1.00	0.97	1.04	1.00	1.00	1.05	1.01	1.00	1.00	1.00	0.79
	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	1.27	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 ξ = 5%

Analyses indicate that increasing the commonly used 0.5 in to 1.5 in (13 mm to 38 mm) gaps has little effect on the float response. As expected, the float movement typically increases if the gap is increased. Although usually not used, a large gap of 5 in (125 mm) resulted in significant reductions in pile forces and float motions for the System 3 site-specific design earthquakes. Such a large gap is typically impractical as the float would move around unacceptably in operating conditions.

FINDINGS

The following are our main findings:

1. Float accelerations and pile lateral reactions in design earthquakes are significant, with the averages of the seven design earthquakes in the low water condition approaching those of the design storm for the locations considered in the San Francisco Bay. For some earthquake ground motions, the pile reactions exceed those of the design storm, but the average of the seven design earthquakes is less than the design storm. For some of the seven design ground motions, plastic deformations may occur in the float system, i.e., the pile, pile collar, and structure on the float deck.
2. Water resistance has less effect on the float response than expected.
3. The structures on deck have natural periods much lower than the float and mostly move with the float with little relative displacement and only slightly larger accelerations. For the float response, it would have been reasonable to analyze them as fixed to the float.
4. The structure response calculated in the time history analysis matched that calculated using the calculated float response, multiplied by a dynamic response factor based on harmonic motion and the ratio of the structure and float periods (Chopra 1981).
5. The pile-float gap magnitude does not have a significant effect on float motions and piling reactions for commonly used gaps, less than 1 in (25 mm) average, 2 in (50 mm) total.

CONCLUSIONS

Pile moored floats will experience significant movement in design earthquakes. The water provides some resistance to float motions but is not as significant as the effect of soil damping. Design earthquake float motions should be considered in the design of pile moored float systems in areas of high seismicity, particularly for sheltered locations with mild design storms.

For the float analysis, it is reasonable to simplify the analyses of these systems 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.

The float response can be determined from the ground motion response spectra and the float-pile system period. It is then reasonable to base the response spectra for a structure on the float on the float response amplified by "Response Factors," based on harmonic excitation and the ratio of the structure and float-pile period (Chopra 1981).

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