

Experimental Study on Suction Pile Heave Resonance during Lowering Operations

L. Huang¹, D. Young¹, J. Zhang¹, R. Randall¹, and B. Wilde²

1 Ocean Engineering Program, Zachry Department of Civil Engineering,
Texas A&M University, College Station, Texas, 77843-3136
2 Intermoor Inc, 900 Threadneedle, Suite 300, Houston, Texas, 77079

ABSTRACT

One of the challenges of installing a suction pile is the occurrence of the heave resonance of the pile-cable system during the pile lowering process. To predict and possibly mitigate the resonance of the system, it is crucial to accurately estimate the natural frequency from the total added-mass of the system. The objective of this study is to determine the total added-mass coefficient of a suction pile through model tests.

KEY WORDS: Added-mass coefficient; damping coefficient; heave resonance; suction pile; lowering operation; model test; flow visualization.

INTRODUCTION

Suction piles are a common method of anchoring vessel mooring lines at the seafloor. A suction pile usually consists of a hollow steel cylinder, open at the bottom but closed at the top except for vent valves and a suction port. One of the challenges of installing a suction pile is the occurrence of the heave resonance of the pile-cable system during the pile lowering process. A suction pile is typically lowered to the seafloor on a wire rope cable deployed from a surface vessel's anchor winch or crane. When the heave and/or pitch frequency of the vessel matches the natural frequency of the pile-cable system, the heave resonance of the system may occur, resulting in large oscillations of the pile and thus significantly increasing loads on the lowering cable and device. To predict and possibly mitigate the resonance of the pile-cable system during the lowering process, it is crucial to estimate the natural frequency of the pile-cable system accurately, which in turn needs an accurate estimate the mass of entrapped water inside the pile as well as added-mass water outside the pile. It should be noted that "the mass of entrapped water inside the pile" does not mean the mass of water filling the inside the pile but the mass of water inside the pile moving at the same velocity (or acceleration) as the pile. The objective of this study is to determine the total added-mass coefficient of a pile (including the mass of entrapped water inside and added mass of water outside the pile) through model tests.

The model tests employ an electric motor (actuator) to induce the heave excitation of a pile-cable model in water at certain range of frequencies which cover the resonant frequency of the model. Within the range of frequencies, we determine the resonant (natural) frequency of the pile-cable system depending upon when the model experiences the largest heave. Since the

stiffness of the cable is known from the calibration, the natural frequency of the system will reveal the added-mass coefficient of the pile.

EXPERIMENTAL SETUP

Test Tank Facility

The dredge/tow tank in the Haynes Coastal Engineering Laboratory at Texas A&M University was used for the tests. The tank shown in Fig. 1 is 149.5 ft (45.57 m) long, 12 ft (3.66 m) wide and has a 10 ft (3.05 m) maximum water depth. The sediment pit is an additional 5 ft (1.52 m) deep and is 24.8 ft (7.56 m) long and located about 41 ft (12.5 m) from the weir end of the tank. There is an observation well with windows for observation and video recording. Fig. 2 (left) shows the dredge/tow carriage and the model suction pile actuator that was attached to the front of the dredge/tow carriage.

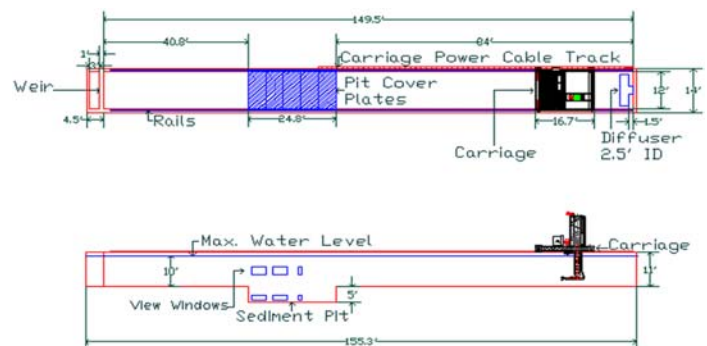


Fig. 1 Elevation and plan view of dredge/tow tank in the Haynes Coastal Engineering Laboratory at Texas A&M University

Actuator and DAQ

The actuator built by Premium Solutions was used for heave excitation of the models while in the tank. As shown in Figure 2

(upper right), it consists of a 220 volt variable speed electric motor, a 20:1 reduction gearbox and the actuating spindle that is attached to the gearbox. The spindle has holes for adjusting the heave stroke to 3 in (7.6 cm), 4 in (10.2 cm), 5 in (12.7 cm), 6 in (15.2 cm), 7 in (17.8 cm), 8 in (20.3 cm), and 9 in (22.9 cm). The actuator assembly was supported by the frame attached to the dredge carriage.

To control the variable speed motor, a voltage regulator was employed. It is a Lenze (AC Tech) SCM Series Sub-Micro drive provided by InterMoor and shown in Figure 2 (lower right). The voltage controller was mounted on a bracket that was situated on the dredge carriage for easy access. The sub-micro drive is equipped with a remote; the drive system has the ability to slowly ramp up the motor.



Fig. 2 Dredge/tow carriage (left), setup of actuator (upper right) and variable speed motor controls (lower right)

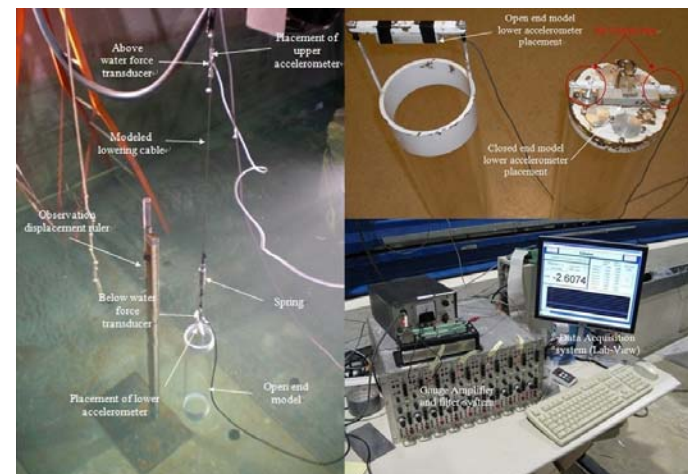


Fig. 3 Model pile with cable assembly (left), accelerometer placement on model suction piles (upper right) and Data acquisition and amplifier setup (lower right)

The cable assembly contains an upper and lower force transducer, upper and lower accelerometer and a spring. The force transducers are 250 lb (113.4 kg) in-line strain gauges and

are water submersible. The accelerometers are single directional accelerometers. The first force transducer was placed close to the actuating arm and the second was placed right above the model suction pile cap as shown in Figure 3 (left). This setup was used to determine the different loads in the cable above and below the spring. A spring was inserted in the middle of the cable to simulate the stiffness of an approximately prototype 6,560 ft (2,000 m) cable used for lowering a suction pile to the sea floor so that the model pile may have the equivalent resonant heave period following the Froude number similarity.

For the two accelerometers, the first was placed at the force transducers U-bolt connection and the second at the top of the model as shown in Figure 3 (left). The purpose for the two accelerometers placed at these two locations is to measure the acceleration above the spring and the acceleration of the model suction pile below the spring, which are different as anticipated. In Figure 3 (upper right), the placement of the lower accelerometer can be seen for the open and close ended models. For the open ended model the accelerometer was attached by using electrical tape on the connection bar for the cable assembly, and for the closed ended model, the accelerometer was attached by using a fabricated acrylic bracket that was attached to the connection for the cable assembly.

Lastly, an observation displacement ruler was put in the tow tank for visually observing the displacement of the model suction pile while it was undergoing oscillation. This visual observation is accomplished by looking through the observation window of the tow tank. The oscillation of the model suction pile was videoed to make sure that the accelerometers were recording correctly.

The force transducers and accelerometers were powered and the output signal amplified to render a good signal. This was done using a strain gauge amplifier shown in Figure 3 (lower right). The strain gauge amplifier is also capable of filtering the high-frequency noise. To record the output signal from the two force transducers and accelerometers, a program called Lab-View was used which recorded the voltage reading into a text file.

Model Parameters

The two suction pile models are shown in Fig. 4 (left) and their basic parameters listed in Table 1. The model scale is 1:32, thus the prototype pile size is 16 ft (4.88 m) in diameter and 96 ft (29.26 m) in length. The main difference between the two models is one with the cap and the other without the cap (open end). There are six pairs of valves with different diameters located on the cap. When all valves are completely sealed, the model is referred as the closed end model. When some or all of these valves are open, the model is referred as partially open end model. For the convenience of description, the valves are numbered from the smallest to the largest in diameter and shown in the Figure 4 (right). The specifications of these valves are summarized in the Table 2. It is noted that a pair of ring reducers can be mounted on the pair of #2 valves to decrease the valve diameter from 1 in (2.5 cm) to 3/4 in (1.9 cm). The latter

are named #2' valves. Also modeled was a simulation of a new generation vent valve called the PS valve. The closure plates for this type valve were mounted above the pair of #2' valves as shown in the Figure 3 (upper right). In the standard configuration, the orifices in the pile's top plate are meant to simulate butterfly valves.

Table 1. Basic parameters of two suction pile models

Parameter	Open End Model	Closed End Model
Cylinder length	3 ft (0.91 m)	3 ft (0.91 m)
External diameter	6 in (15.2 cm)	6 in (15.2 cm)
Wall thickness	0.25 in (0.635cm)	0.25 in (0.635cm)
External area	28.274 in ² (182.413 cm ²)	28.274 in ² (182.413 cm ²)
Internal area	23.758 in ² (153.277 cm ²)	23.758 in ² (153.277 cm ²)
External volume	1017.9 in ³ (16680.4 cm ³)	1017.9 in ³ (16680.4 cm ³)
Internal volume	855.3 in ³ (14015.9 cm ³)	855.3 in ³ (14015.9 cm ³)
Weight of water inside pile	30.9 lb (14.02 kg)	30.9 lb (14.02 kg)
Weight of water displaced by pile plus water inside pile	36.8 lb (16.69 kg)	36.8 lb (16.69 kg)
Dry weight	14.5 lb (6.58 kg)	16 lb (7.26 kg)
Wet weight	8.5 lb (3.86 kg)	9.6 lb (4.35 kg)
Weight of model accessories*	1.06 lb (0.48 kg)	1.06 lb (0.48 kg)
Total dry weight	15.57 lb (7.06 kg)	17.06 lb (7.74 kg)
Gravity center from top	1.29 ft (0.393 m)	1.27 ft (0.387 m)
Buoyancy center from top	1.50 ft (0.457 m)	1.40 ft (0.427 m)

*model accessories include a spring, an underwater force transducer, an underwater accelerometer, a section of cable and connections between the spring and the model.

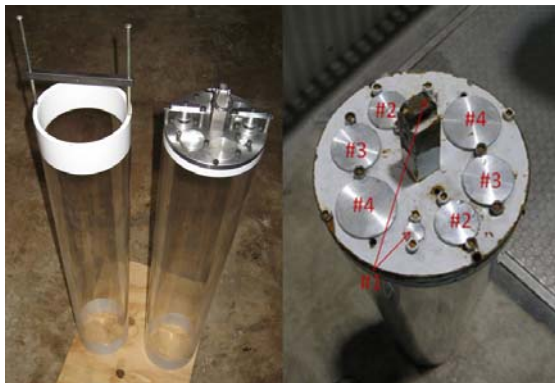


Fig. 4 Two suction pile models (left) and valve pair number for the closed end model (right)

Table 2. Specifications of the valves on the cap

Model Valve Pair No.	Prototype Valve Diameter	Model Valve Diameter	Area of Model Valve Pair
#1	12 in (30.48 cm)	0.375 in (0.953 cm)	0.221 in ² (1.426cm ²)
#2	32 in (81.28 cm)	1.0 in (2.54 cm)	1.571 in ² (10.135cm ²)
#2'	24 in (60.96 cm)	0.75 in (1.91 cm)	0.884 in ² (5.703cm ²)
PS Valve	24 in (60.96 cm)	0.75 in (1.91 cm)	0.884 in ² (5.703cm ²)
#3	40 in (101.6 cm)	1.25 in (3.18 cm)	2.454 in ² (15.832cm ²)
#4	48 in (121.92 cm)	1.5 in (3.81 cm)	3.534 in ² (22.780cm ²)

Dye Injection Procedure

The purpose of the dye injection is to visualize whether or not and how fast the water inside the suction pile model moved with the model while it oscillates. The dye was injected through a ¼ inch plastic hose and a syringe was used to pump the dye from a storage vessel into the plastic hose, as shown in Figure 5. During all tests, dye was released from the end of the hose which was attached to the inside wall of the pile model, as shown in Figure 5. In the case of the closed end model, in addition to the hose attached the inside wall, there was an additional hose also placed inside the model but near the upper cap. The locations of the two hoses in the closed ended model suction pile are shown in Figure 5 (lower right).

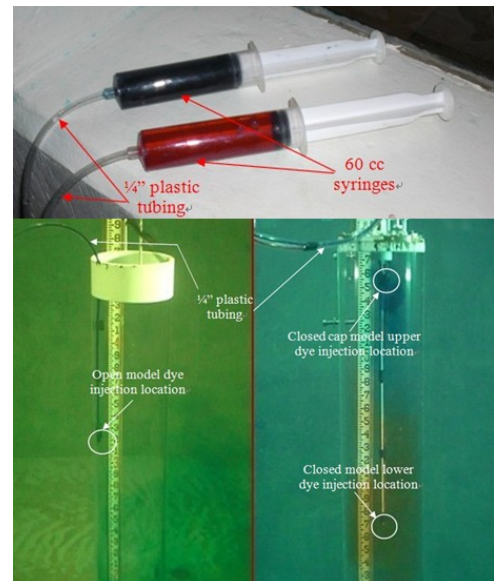


Fig. 5 Device for injecting dye (upper), dye injection layout for open (lower left) and closed (lower right) models

In the case of the open-ended model, a streak of dye from the open end of the plastic hose was observed. Since the open end of the hose was attached the pile model, the dye streak indicates the water inside the pile did not move with the model. However, in the case of the closed end model, no dye streak was observed inside the model, indicating the water moves at the same velocity of the model. In all cases of model testing, the inside of a pile model was always filled with water and no cavitations were observed.

THEORETICAL ANALYSIS

Dynamic System Analysis

To understand the dynamics of its heave, the pile-cable system is simplified and modeled as a single degree of freedom (SDOF) system, which can be described by Eq. (1).

$$M\ddot{X} + C\dot{X} + KX = F(t) \quad (1)$$

where X , \dot{X} , \ddot{X} stand for the heave displacement, velocity and acceleration, respectively, M the total mass of the system (the mass of pile plus the entrained water inside the pile and added mass of water outside the pile), C the equivalent damping coefficient, K the stiffness of the spring, and $F(t)$ the external force. The external force is a function of time and so are the displacement, velocity and acceleration. The overhead dot and dots stand for the derivative with respect to time.

The damped natural frequency ω_d is the real-part solution to the homogenous equation of (1),

$$\omega_d = \omega_n \sqrt{1 - \zeta^2} = \sqrt{\frac{K}{M} - \frac{C^2}{4M^2}} \quad (2)$$

where $\omega_n = \sqrt{\frac{K}{M}}$ is the un-damped natural frequency of the system and $\zeta = \frac{C}{2M\omega_n}$ the damping ratio of the system. In general, ζ is very small and less than 0.2 in the case of the open and closed end models, and hence, in these cases the damped natural frequency is very close to the un-damped natural frequency. When the external force is periodic and of an amplitude A_a and frequency ω , the heave amplitude of the pile is equal to,

$$A_p = \frac{A_a}{K - M\omega^2 + iC\omega} \quad (3)$$

Eq. (3) shows that when the frequency of the external force is smaller than the un-damped natural frequency the heave of the pile (the underwater acceleration A_2) is in phase of the external

force (the above water acceleration defined as A_1). On the other hand, when the frequency of the external force is greater than the un-damped natural frequency, the heave of the pile (the underwater acceleration) is out of phase of the external force (the above water acceleration). When the frequency of the external force is close to the un-damped natural frequency, the phase relation between the heave of the pile and the external force depends on the damping coefficient and the difference between ω_n and ω .

In two cases, the measured above water acceleration (A_1) can be quite different from that induced at the actuator. They are discussed here for better understanding the test results. First, when $\omega > \omega_n$ the external force and heave of the pile are out of phase. Therefore, when the pile is moving up and the cable near the actuator is moving down, the spring is compressed so much that the tension in the spring can reduce to its initial tension. Consequently, the measured acceleration above the spring is smaller than that induced by the actuator. In addition, the tension in the cable below the spring may reach zero, which may hinder the upward motion of the pile and induce the pitch motion of the pile. Secondly, when $\omega \approx \omega_n$, the heave amplitude of the pile becomes significantly greater than the amplitude induced by the actuator. When the pile is moving up and even the actuator is moving up or out of phase by 90 degrees, the spring again is compressed so much that its tension can reach to its initial tension. Consequently, the pile 'pushes up' the spring. If the actuator is almost in phase with the pile, then the measured above water acceleration can be greater than that induced at the actuator. These 'push up' phenomena were observed in the cases of open and closed model near their related resonant frequencies.

Testing Frequency Range

The range of frequencies for testing a model pile is intended to cover its 'unknown' heave resonant frequency. Thus, rough estimate of the resonant frequency of a model pile was made using Eq. (2). Since the total added-mass coefficient (C_a) of each model was not known at this stage, we empirically determined that it was 1.1 for the closed end model and 0.1 for the open end model. The total added-mass coefficient is defined below.

$$C_a = \frac{M_a}{M_0} \quad (4)$$

where M_a is the total added water mass of the system (mass of water displaced by the structure, trapped water mass and added mass) and M_0 is the total mass of the pile (mass of water displaced by the structure plus trapped water mass). The latter was given in Table 1. It is found in calibration procedure of spring that the spring stiffness (K) is 1.5063 lb/in (0.27 kg/cm) and the initial (minimum) tension is 2.222 lb (1 kg). Based on the spring stiffness, the estimated results for both open end and

closed end models are given in Table 3. Note that M_1 is the mass of open ended model in air, and M_2 is the mass of closed ended model in air.

Table 3. Theoretical calculation of resonance frequency both in air and in water

	Total mass of the system		f_n	
	Open ended model	$M_1 =$ (in air)	15.57 lb (7.06 kg)	0.97
$M_1 + 0.1M_0 =$ (in water)		19.25 lb (8.31 kg)	0.87	Hz
Closed ended model	$M_2 =$ (in air)	17.06 lb (7.74 kg)	0.93	Hz
	$M_2 + 1.1M_0 =$ (in water)	57.54 lb (26.10 kg)	0.51	Hz

It is expected that the resonant frequencies of pile models of a cap with some or all open valves are between the resonant frequencies of the open end model and the closed end one. The range of frequencies for the tests of a model was hence set at

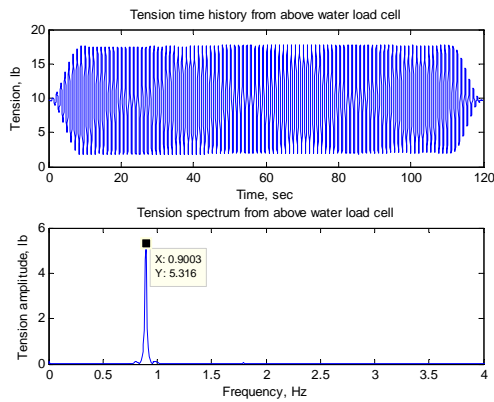
about ± 0.2 Hz with respect to the related estimated resonant frequency.

Measurement Analysis

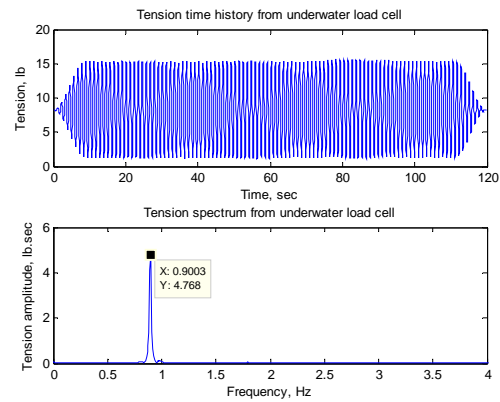
The procedures of analyzing measurements of each case of pile model are virtually the same. For an example, the procedures for analyzing the open end model are described below.

After the heave of the open end model reached the steady state, the signals of four sensors (two force transducers and two accelerometers) were recorded for a period of 120 s. Before applying Fast Fourier Transform (FFT) to a time series of measurements, it is multiplied by a unit (height) trapezoidal window function with a ramp of 15 s at both ends. Since the duration of record is 120 s, the frequency resolution is limited to

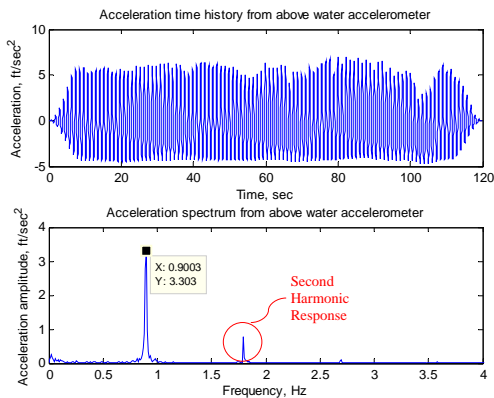
$\Delta f = \frac{1}{T} = \frac{1}{120} \approx 0.0083 \text{ Hz}$. Fig. 6 shows the measured forces and accelerations in both time and frequency domains for the case of the actuator excitation frequency of 0.89 Hz (near resonance).



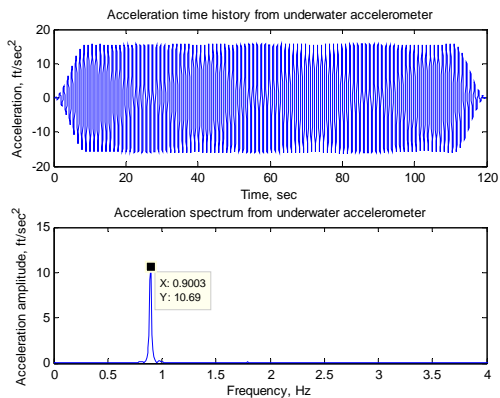
(a) Tension signal from the above water force transducer



(b) Tension signal from the underwater force transducer



(c) Acceleration signal from the above water accelerometer



(d) Acceleration signal from the underwater accelerometer

Fig. 6 A 120 second signal record both in time domain and frequency domain at the input frequency $f = 0.89$ Hz (near resonance)

In these cases, the peak frequency (f_p) for the forces and accelerations are virtually equal to the corresponding excitation frequency of the actuator, which is expected. Considering the energy leaking due to limited duration of the record used in the FFT, the amplitude at the peak frequency is calculated based on 'equivalent' energy concept. That is, the square of the 'equivalent' amplitude is equal to the sum of the square of individual amplitudes nearby the peak frequency. Hence, the equivalent amplitude is greater than that at the peak frequency shown in the figures.

The dynamic tension amplitude above the spring is similar to but slightly greater than the corresponding one below the spring. It is because the tension above the spring also includes the contribution from the spring. However, the acceleration above the spring is significantly smaller than the corresponding one below the spring, especially in the case that the excitation frequency ($f = 0.89$ Hz) of the actuator is very close to the resonant frequency. This is also expected that the heave amplitude of the model is greatly amplified near its resonant frequency.

It is observed in Figure 6(c) that the measured acceleration by the above water accelerometer is asymmetric (higher positive magnitude and relatively lower negative magnitude) in the time domain. The asymmetry results in a minor peak in the frequency domain, which is located at the frequency twice of that of the major peak and known as the second harmonic response. The asymmetry in the above water acceleration is caused by the 'pushing up' of the pile model. The 'pushing up' occurs when the pile model moves up much more than the cable above the spring and the tension in spring reaches its initial tension (or minimum tension). The 'pushing up' results in greater heave amplitude at the location of the above water accelerometer than that at the actuator. Because of the 'pushing up', the cables above and below the spring can be slack at the moment, which was observed during the tests.

RESULT ANALYSIS

Open End Case

There are slight differences between the frequency of the external force (input frequency) and the measured peak heave frequency of the pile model. The tiny difference is probably caused by the limited frequency resolution in FFT (~ 0.01 Hz) as well as that of actuator controller. The calculated heave amplitudes are obtained by dividing the acceleration amplitudes by the corresponding frequencies. It is shown that the acceleration amplitude at the pile model is much greater than that at the above water accelerometer, especially near the resonant frequency. The calculated heave amplitude above water gradually decreases with the increase in frequency, especially when the excitation frequency is greater than the resonant frequency. However, the calculated heave amplitude very close to the natural frequency can be greater than that at the actuator

because of the 'pushing up' by the pile. It is known that the heave amplitude at the actuator remains constant (0.125 ft) and is independent of the excitation frequency. Therefore, the largest calculated heave amplitude at the pile model indicates that the related input frequency is closest to the resonant frequency. The largest heave amplitude in this case is about 4 times of that at the actuator from video record. The calculated heave amplitudes of the open pile model are plotted as a function of peak frequencies in Fig. 7, showing that the resonant frequency is 0.905 Hz.

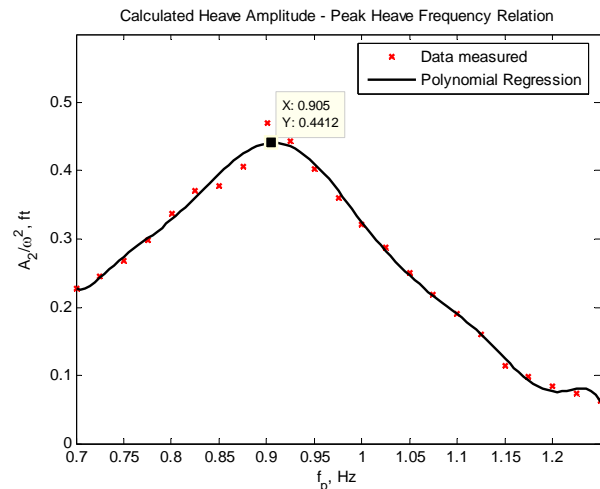


Fig. 7 Relation of calculated heave amplitudes to peak heave frequencies for the open end model tests

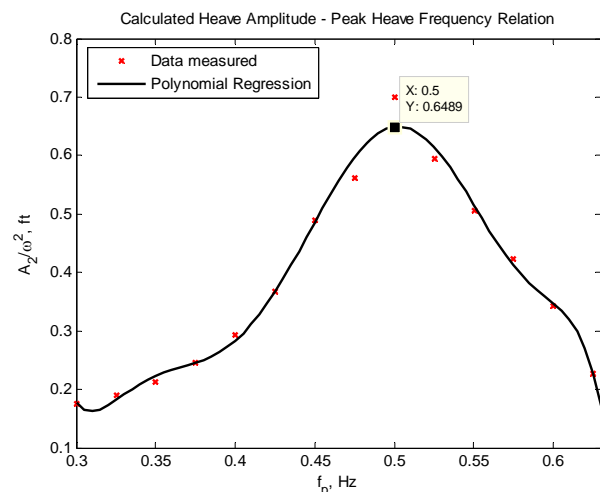


Fig. 8 Relation of calculated heave amplitudes to peak heave frequencies for the closed end model tests

Closed End Case

Similar to the open end model, the calculated heave amplitude above the spring is smaller than that at the actuator for the excitation frequencies significantly greater than the natural frequency. Near the natural frequency, the calculated heave amplitude above the spring is greater than that at the actuator,

which is caused by the ‘pushing up’ of the pile model. Near the natural frequency, the heave amplitude of the pile model is almost 6 times as that at the actuator from video record. The calculated heave amplitude of the pile model is plotted as a function of the peak frequency in Fig. 8, showing that the resonant frequency is 0.5 Hz.

Partial Open End Cases

By opening various pairs of orifices (i.e. simulated valves), eight different pile top opening areas plus the special PS valve case could be studied for a total of nine tests. Table 4 summarizes the details of these cases. The most important factor to distinguish these partially open models is the opening area at the cap and presented in the third column. The ratios (γ) of an opening area to the inner cross section area of the pile $A = 23.758 \text{ in}^2$ (153.277 cm^2) are given in the fourth column. For brevity, only the results of Case 5 and Case 9 are presented here.

Table 4. Nine testing cases of partially open end model conducted in the laboratory

Case No.	Valve Pair Opening	Opening Area	γ
Case 1	#1	0.221 in ² (1.426 cm ²)	0.9%
Case 2	#2'	0.884 in ² (5.703 cm ²)	3.7%
Case 3	PS Valve Pair	0.884 in ² (5.703 cm ²)	3.7%
Case 4	#3	2.454 in ² (15.832 cm ²)	10.3%
Case 5	#4	3.534 in ² (22.780 cm ²)	14.9%
Case 6	#1, #2, #3	4.246 in ² (27.393 cm ²)	17.9%
Case 7	#2, #4	5.105 in ² (32.935 cm ²)	21.5%
Case 8	#1, #3, #4	6.210 in ² (40.064 cm ²)	26.1%
Case 9	#1, #2, #3, #4	7.780 in ² (50.193 cm ²)	32.7%

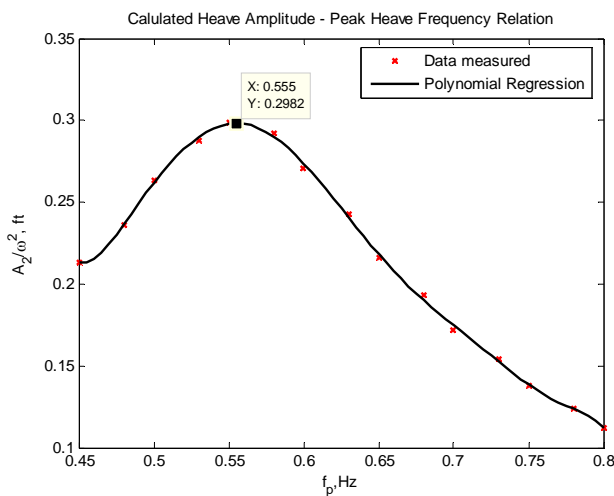


Fig. 9 Relation of calculated heave amplitudes to peak heave frequencies for the partially open end model tests (Case 5)

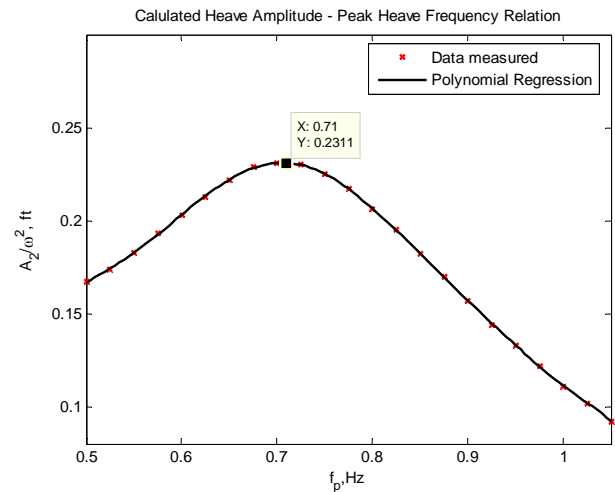


Fig. 10 Relation of calculated heave amplitudes to peak heave frequencies for the partially open end model tests (Case 9)

Because of these pile top openings (vent valves), the flow through these openings induces vortices near the cap which significantly dampen the heave of the pile model, especially near their corresponding natural frequencies. The maximum heave amplitudes are about twice of that at the actuator from video records. Because the heave amplitudes of the pile model in these two cases are small in comparison with those in the previous two cases, the ‘pushing up’ from the pile model to the spring no longer occurs. Consequently, the heave amplitude above the spring monotonically decreases with the increase in the excitation frequency. During the tests of these two cases, the phenomena of ‘slack cable’ and the pitch of the models were not observed when the excitation frequency was close to the related natural frequency. The heave amplitudes of these two cases are plotted as a function of peak frequencies in Fig. 9 and Fig. 10, showing that the resonant frequencies are 0.555 Hz and 0.71 Hz respectively.

Summary of All Cases

The open and closed end models can be viewed as special cases among the partially open cases. That is, $\gamma=1$ for the open end model and $\gamma=0$ for the closed end model. All the results of the eleven cases are summarized in Table 5. The resonance frequency (f_{res}) and the resonance circular frequency (ω_{res}) for partially open end cases are determined by the same way as illustrated in open and closed end cases. The total weight of the system (W'), is calculated from the resonance frequency using the following relationship:

$$W' = \frac{K}{\omega_{res}^2} g \quad (5)$$

The weight of model pile (W_{pile}), weight of water inside model pile (W_{in}), and weight of water displaced by pile plus interior entrapped water (W_o) are identical except the open end model, shown in Table 1. The total added water weight ($W_a = W' - W_{pile}$),

is given in Column 4. The exterior added water weight ($W_{a,ex}=W'-W_{pile}-W_{in}$), and exterior added-mass coefficient ($C_{a,ex}=W_{a,ex}/W_0$) are given in Column 5 and Column 6. Assume $C_{a,ex}$ are constant for closed end model and partially open end

models. The interior entrapped water weight ($W_E= W'-W_{pile}-W_{a,ex}$), and entrainment ($E= W_{a,in} /W_{in}$) are given in Column 7 and Column 8. If E is less than zero, let E is equal to zero and recalculate the exterior added mass coefficient.

Table 5. Summary of results of all the model test cases

γ	f_{res}	W'	W_a	$W_{a,ex}$	$C_{a,ex}$	W_E	E	TR	Note
0.000	0.5 Hz	58.91 lb (26.72 kg)	41.85 lb (18.98 kg)	10.95 lb (4.97 kg)	0.298	30.90 lb (14.02 kg)	1.000	5.4	Pile top closed
0.009	0.505 Hz	57.75 lb (26.19 kg)	40.69 lb (18.46 kg)	10.95 lb (4.97 kg)	0.298	29.74 lb (13.49 kg)	0.962	5	
0.037	0.51 Hz	56.62 lb (25.62 kg)	39.56 lb (17.94 kg)	10.95 lb (4.97 kg)	0.298	28.61 lb (12.98 kg)	0.926	4.8	
0.103	0.54 Hz	50.51 lb (22.91 kg)	33.45 lb (15.17 kg)	10.95 lb (4.97 kg)	0.298	22.50 lb (10.21 kg)	0.728	4.2	
0.149	0.555 Hz	47.81 lb (21.69 kg)	30.75 lb (13.95 kg)	10.95 lb (4.97 kg)	0.298	19.80 lb (8.98 kg)	0.641	3.2	
0.179	0.585 Hz	43.03 lb (19.52 kg)	25.97 lb (11.78 kg)	10.95 lb (4.97 kg)	0.298	15.03 lb (6.82 kg)	0.486	3	
0.215	0.61 Hz	39.58 lb (17.95 kg)	22.52 lb (10.21 kg)	10.95 lb (4.97 kg)	0.298	11.57 lb (5.25 kg)	0.374	2.9	
0.261	0.64 Hz	35.96 lb (16.31 kg)	18.90 lb (8.57 kg)	10.95 lb (4.97 kg)	0.298	7.95 lb (3.61 kg)	0.257	2.85	
0.327	0.71 Hz	29.22 lb (13.25 kg)	12.16 lb (5.52 kg)	10.95 lb (4.97 kg)	0.298	1.21 lb (0.55 kg)	0.039	2.8	All valves open
1.000	0.905 Hz	17.98 lb (8.16 kg)	2.41 lb (1.09 kg)	2.41 lb (4.97 kg)	0.066	0.00 lb (0.00 kg)	0.000	6.4	Fully open
0.037	0.505 Hz	57.75 lb (26.19 kg)	40.69 lb (18.46 kg)	10.95 lb (4.97 kg)	0.298	29.74 lb (13.49 kg)	0.962	5	PS valves used

The 9th column lists the Transmissibility (TR) which is defined as the ratio of the heave amplitude of pile at resonance observed from video records to the heave amplitude at the actuator (1.5 inches (3.81 cm) heave amplitude throughout all the tests). The last row lists the results of the case of only the PS valve opening. Although the opening PS valve ratio ($\gamma=0.037$) is greater than that of the case of opening Valve #1 ($\gamma=0.009$), their natural frequencies and the added-mass coefficient are identical. This is because the PS valves have closure plates hanging about one inch above the orifice. The closure plates hinder the flow through the orifice and effectively reduce the opening area ratio. In general, the larger the opening area ratio is, the smaller the added-mass coefficient is, and consequently, the larger the natural (resonant) frequency is. The related results are plotted in Figs. 11, 12 and 13, respectively. The trend observed in these two figures is as expected. That is, a larger opening ratio results in less mass of water moving with the same velocity as the pile model.

CONCLUSIONS

Based on the results of model tests, several preliminary conclusions were derived and are given below.

1) Due to the presence of the openings at the cap, part of the water inside the pile model flows through the openings and hence does not move at the same velocity and acceleration with the pile. The larger the opening ratio is, more flow passes through the openings or less mass of water is entrapped (or moves with pile). Hence, the total mass of a model reduces with the increase of the opening ratio. Consequently, the natural frequency of a model increases with the increase of the opening ratio. In the case of the closed end model, the water inside the pile is 100% entrapped within the pile. Hence, its natural frequency is the lowest.

The entrained water ratio varied from near 100% for the closed pile top case, to 96% with a pair of 24 in (61 cm) (prototype size) valves opened, 65% with a pair of 48 in (122 cm) valves opened and 4% when four pairs of [12 in (30.5 cm), 32 in (81.3 cm), 40 in (101.6 cm) and 48in (122 cm)] valves were opened. However, this calculation of the mass of entrapped water is based on the assumption that the outside added mass coefficient ($C_{a,ex}$) remains constant when the open area ratio changes. As we know, the flow pattern around the upper end of the pile may change due to the presence of opening valves. It is likely that the outside added mass coefficient may decrease with the increase in the opening area ratio.

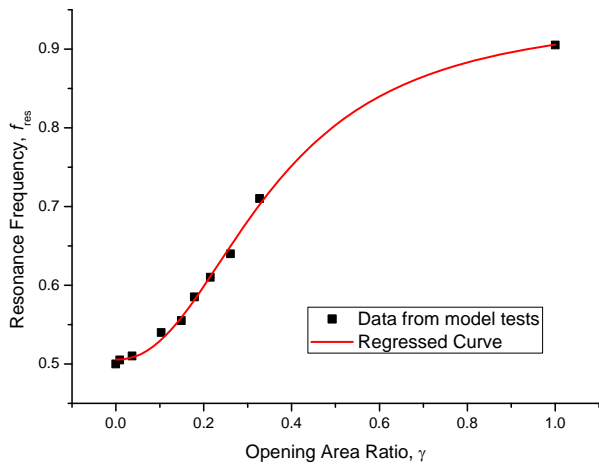


Fig. 11 Relation of opening area ratio to resonance frequency

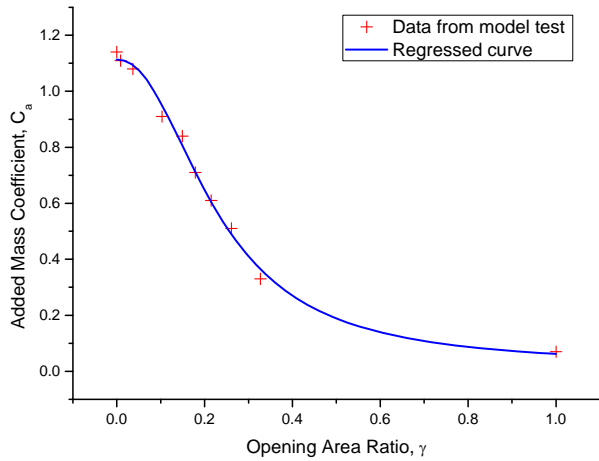


Fig. 12 Relation of opening area ratio to total added mass coefficient

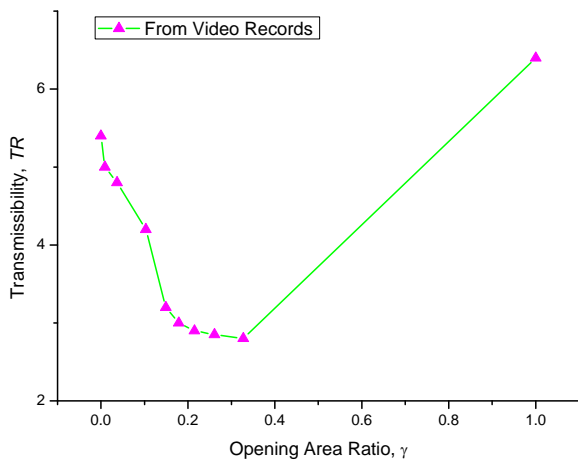


Fig. 13 Relation of opening area ratio to transmissibility

2) Due to the presence of the openings at the cap of the pile, water flows through them when the pile is oscillating. This flow generates vortices above and below the cap and hence results in additional resistances to the heave of the pile. Consequently, the resonance heave amplitudes for the partially open models are significantly smaller than that of either open or closed model. However, in order to significantly reduce the resonant heave amplitude the opening ratio has to be greater than 0.15.

For the closed pile top case, the critical damping ratio was found to be 9.4%. This increased to 16.5% when both 48 in (122 cm) (prototype size) valves were opened. With the pairs of 12 in (30.5 cm), 32 in (81.3 cm), 40 in (101.6 cm) and 48 in (122 cm) opened, the critical damping ratio peaked at 19.1%.

3) The greatest resonant heave amplitude was observed in the tests of open and closed models when the excitation frequency is closed to the related natural frequency. The large heave amplitude results in the ‘push up’ phenomenon when the pile model pushes up the spring and cable. The ‘push up’ by the pile may significantly reduce the tension in spring and cable. The reaction force from the spring and cable may hinder the upward motion of the pile model and hence may induce pitching of the pile.

4) Increased damping that reduces resonant response would be viewed as a desirable feature when the ratio of the system natural period to the peak excitation period called beta ($\beta = T_n/T_p$) is less than the square root of 2. When lowering relative low mass objects such as well control Christmas trees, this would be the case.

ACKNOWLEDGEMENTS

This study was sponsored by the InterMoor Inc. and conducted at the Haynes Coastal Engineering Laboratory at Texas A&M University. We gratefully acknowledge the approval of publication of this study by the InterMoor Inc. We also thank the Premium Solutions Inc for building the actuator and testing models, and laboratory technician John Reed and graduate student John Henrikson for technical help of electronic equipments.

REFERENCES

CHOPRA, A. *Dynamics of Structures*. New Jersey: Prentice-Hall, 2001.