



The Response of Pile-Guided Floats Subjected to Dynamic Loading Volume I Final Report

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Pile-Guided floats can be a desirable alternative to stationary berthing structures. Both floats and guide piles are subjected to dynamic forces such as wind generated waves and impacts from vessels. This project developed a rational basis for estimating the dynamic response of pile-guided floating structures. The Dynamic Analysis Method (DAM) was used to model the response of the system. MATLAB was used to compute the analytic and numerical values obtained from the dynamic models. ANSYS AQWA was used to validate the dynamic analysis models used in this study.				
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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
LENGTH				
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
AREA				
in ²	square inches	645.2	square millimeters	mm ²
ft ²	square feet	0.093	square meters	m ²
yd ²	square yard	0.836	square meters	m ²
ac	acres	0.405	hectares	ha
mi ²	square miles	2.59	square kilometers	km ²
VOLUME				
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft ³	cubic feet	0.028	cubic meters	m ³
yd ³	cubic yards	0.765	cubic meters	m ³
NOTE: volumes greater than 1000 L shall be shown in m ³				
MASS				
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
TEMPERATURE (exact degrees)				
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
ILLUMINATION				
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m ²	cd/m ²
FORCE and PRESSURE or STRESS				
lbf	poundforce	4.45	newtons	N
lbf/in ²	poundforce per square inch	6.89	kilopascals	kPa
APPROXIMATE CONVERSIONS FROM SI UNITS				
LENGTH				
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
AREA				
mm ²	square millimeters	0.0016	square inches	in ²
m ²	square meters	10.764	square feet	ft ²
m ²	square meters	1.195	square yards	yd ²
ha	hectares	2.47	acres	ac
km ²	square kilometers	0.386	square miles	mi ²
VOLUME				
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m ³	cubic meters	35.314	cubic feet	ft ³
m ³	cubic meters	1.307	cubic yards	yd ³
MASS				
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
TEMPERATURE (exact degrees)				
°C	Celsius	1.8C+32	Fahrenheit	°F
ILLUMINATION				
lx	lux	0.0929	foot-candles	fc
cd/m ²	candela/m ²	0.2919	foot-Lamberts	fl
FORCE and PRESSURE or STRESS				
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in ²

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.
(Revised March 2003)

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Abstract

Pile-guided floats can be a desirable alternative to stationary berthing structures. Both floats and guide piles are subjected to time varying (dynamic) forces such as wind-generated waves and impacts from vessels. There is little design information available concerning the dynamic load environment to which the floats will be subjected. So far, the most widely acceptable method used in offshore structure design is the Kinetic Energy Method (KEM). It is a simplified method that is based on the conservation of energy. This approach is straightforward and easy to implement. However, in spite of its simplicity and straightforwardness, the method lacks accuracy.

This project developed a rational basis for estimating the dynamic response of floating pile-guided structures, providing necessary insight into design requirements of the guide-piles. In this study, the Dynamic Analysis Method (DAM) was used to model the dynamic responses of the system. MATLAB codes are written to help calculate the analytic and numerical values obtained from the dynamic models.

For the purpose of validation, results from the two systems were compared to a comprehensive dynamic analysis model created with the ANSYS AQWA Software.

Executive Summary

In this study, the responses of the berthing system under dynamic loading have been analyzed. Previous works from other authors regarding floating structures have been reviewed. However, little design information is available and empirical data is often highly site specific. The responses of the floating system under the impact of the vessel are analyzed by two different methods: the Kinetic energy Method (KEM) and the Dynamic Analysis Method (DAM). The KEM is a quasi-static analysis and uses the principle of conservation of energy. DAM is based on dynamic models that represent the key features of the dynamic system, thus deriving the governing differential equations that describe the motion of the system. The responses of the berthing system can be obtained by solving the governing differential equations. The procedures to obtain responses of the berthing system are given in detail in the study and the results from the two methods obtained are interpreted and compared.

In addition to dynamic loading from the vessel, wave loading can generate forces within the guide piles. The responses of the system under wave loading are analyzed only by the DAM, and the results are interpreted.

The following list is a summary of conclusions of the study.

For the responses of the berthing system under vessel impact analyzed by the KEM:

- The response of the berthing system is directly proportional to the kinetic energy of the approaching vessel.

- The responses of the spring elements heavily depend upon the stiffness of the elements. Softer elements will lead to smaller reaction forces but larger displacements.
- The stiffness ratio of the spring elements (the fender and the piling system) determines the distribution of the kinetic energy from the vessel. If the stiffness of one element is large compared with the other, the displacement of the more rigid element will tend to be small and the reaction forces will converge to some value as the element becomes rigid. However, the kinetic energy absorbed by the more rigid element is smaller compared to the softer element.
- The mass of the float and the damping effects from the structures are not considered in the KEM.

For the responses of the berthing system under vessel impact analyzed by the DAM:

- The characteristics of the responses share the same first three trends as in the KEM.
- The DAM accounts for the damping effects and the mass of the float.
- Higher damping ratios may reduce the response of the berthing system considerably.
- The mass ratio of the vessel to the float and the stiffness ratio of the fender to the piling system have significant effects on the responses of the system under vessel impact.
- The general trend is that, for the float that is massive compared to the vessel, the responses tend to be larger than if the float is less massive.

- If the mass of the float is negligible, the responses of the system tend toward responses obtained from KEM, given a small damping ratio. A high damping ratio will reduce the response.
- If the piling system is very rigid compared to the fender, the responses of the piling system will tend to converge with the results obtained from the KEM regardless of the mass of the float.
- Comparing the results obtained from two methods, it can be concluded that the responses of the piling system by the DAM can be greater than the responses by the KEM. The difference is m when the float is massive (compared to the vessel), the damping is small or negligible, or eccentricity exists.

For the responses of the floating system under wave loading analyzed by the DAM:

- The responses of the piling system will increase as the period of the wave increases. However, the rate of increase will approach zero if the period of the wave is very long (and very long period waves are rare in nature).
- If the period of the wave is very close to the natural period of the floating system in any direction, resonance will occur; the responses of the piling system will grow significantly. Therefore, resonance should be avoided in design.
- If the incoming angle of the wave is 0 or 45 degrees with respect to the surge direction of the floating system, the wave loading only has effects in the surge direction. Therefore,

the floating system should be oriented accordingly, to avoid coupled effects that may result in excitation in the yaw direction.

Annexes B and C contain “response plots” for numerous vessel, float, approach velocity, pile stiffness and damping combinations. These figures are intended to be design aids to assist the end-user of this report with assessing response (force and deflection) of guide piles in pile-guided float construction. Annex B contains responses for single-degree-of-freedom configurations in which the center-of-rigidity of the pile group and center-of-mass of the vessel are coincident during berthing. Annex C provides theoretical response for eccentric configurations in which the center-of-mass of the vessel and center-of-rigidity of the float are not coincident. Annex C is intended to represent the extreme of what might be constructed in practice with respect to the degree of eccentricity. It is reasonable to interpolate between plots when necessary.

Chapter 1 Introduction

1.1 Problem Statement

Alaska Department of Transportation & Public Facilities (AKDOT&PF) has used pile-guided floats at certain ferry terminals and is considering the future use of floating piers at a number of other Alaska Marine Highway System (AMHS) terminals. The floats are supported laterally by guide-piles, but are allowed to translate vertically to accommodate the extreme tidal characteristic of Alaska. These floats will be subjected to dynamic (time-varying) forces from both vessels and wave action. The design loads for guide-piles that support these floats are not apparent in current practice or associated literature. Besides, given the dynamic nature of the system, static analyses may not be appropriate. Because of this, AMHS Engineers seek the means to reasonably estimate the forces in the guide piles under service conditions.

1.2 Problem Background

The major advantage of pile-guided floats is that vessels may be left unattended during the extreme tidal changes that occur commonly in Alaska. Due to the extreme tidal gap in Alaska, moored ships held by fixed docks, which is the case for most of the facilities in service right now in Alaska, require continuous monitoring which results in a significant labor cost. However, since the guide-piles support the float laterally but allow free vertical movement, the float will move freely as the tide changes. In such case, monitoring is no longer needed; consequently, considerable labor cost will be spared.

Pile-guided floats are constantly subjected to time-varying loads, such as impact loads from vessels and dynamic loads from waves. Quasi-static analysis can be used to calculate the responses of pile-guided floats; the Kinetic Energy Method (KEM) falls into quasi-static analysis, and it is easy to implement. However, quasi-static analysis does not take into account the effects of inertial and damping forces, which, in pile-guided floats, can be quite significant. Besides, it cannot capture the dynamic nature of time-dependent system responses, such as displacements or reaction forces. Therefore, using the Dynamic Analysis Method (DAM) is more appropriate for pile-guided floats.

The following provides a summary of the basic concepts involved in this study.

Simple Structures

Simple structures are called *simple* because they can be idealized as a concentrated lumped mass m supported by a massless structure with stiffness k in the lateral direction (Anil K. Chopra, 2006). Figure 1.1 is a simple structure with mass m and stiffness k . The structure can be considered as a lumped mass m mounted on top of a column with stiffness k , with the mass translating only in the horizontal direction.

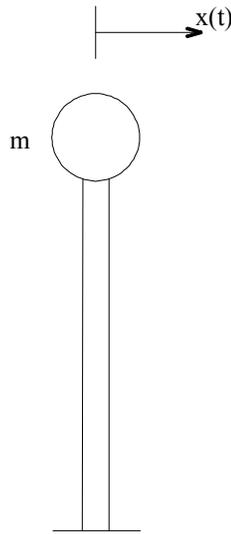


Fig. 1.1 Simple Structure

Degree of Freedom (DOF)

The number of independent displacements required to define the displaced positions of all the masses relative to their original position is called the number of *degrees of freedom* (DOF) for dynamic analysis (Anil K. Chopra, 2006). Therefore, a system with only one DOF is called a *single degree of freedom* (SDF) system. Fig. 1.2 is an example of SDF system. A system with more than one DOF is called a *multi-degree of freedom* (MDF) system. Fig. 1.3 shows a system with two DOFs.

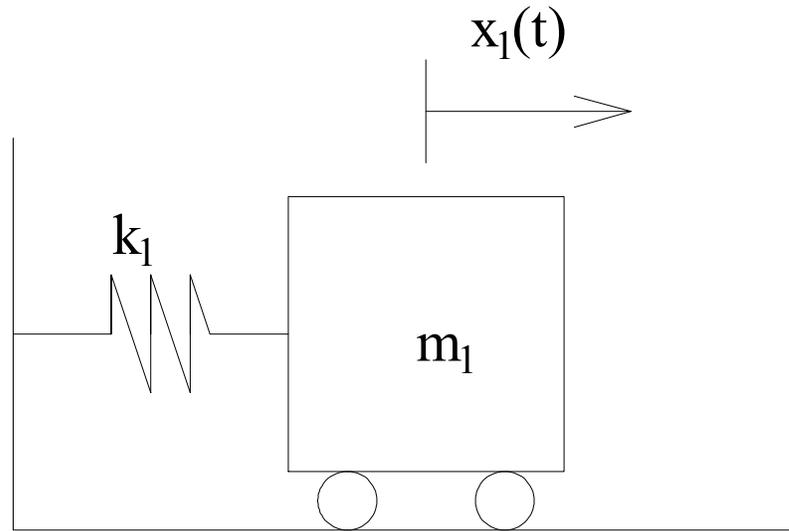


Fig. 1.2 Single Degree of Freedom (SDF) System

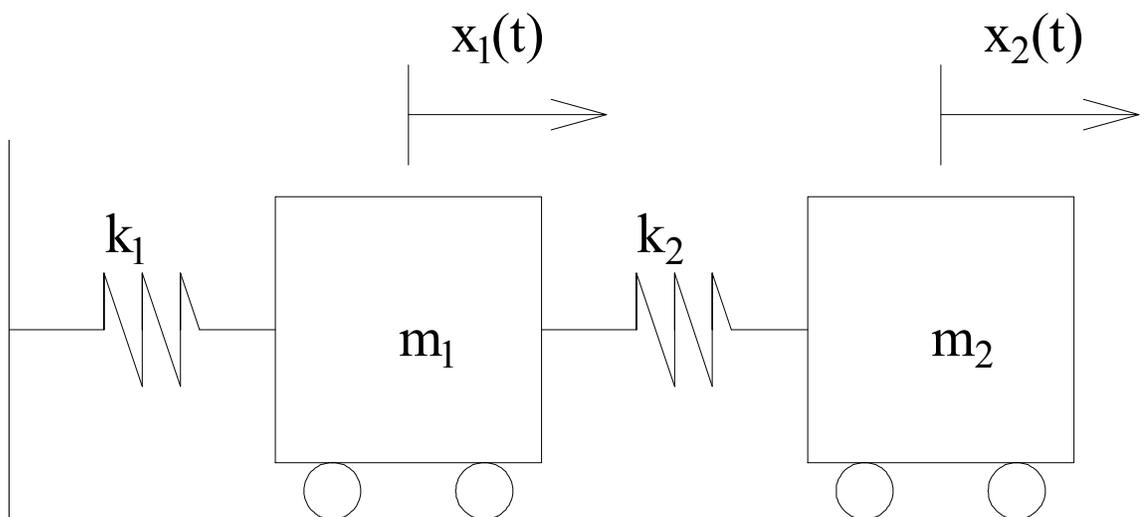


Fig. 1.3 Multi-degree of Freedom (MDF) System

Mass or Inertia Elements

The mass or inertia element is assumed to be a rigid body; it can gain or lose kinetic energy whenever the velocity of the body changes. From Newton's second law of motion, the product of the mass and its acceleration is equal to the force applied to the

mass. Work is equal to the force multiplied by the displacement in the direction of the force, and the work done on a mass is stored in the form of the mass's kinetic energy (Singiresu S. Rao, 2004). Fig. 1.4 shows a MDF system with three mass elements connected with springs.

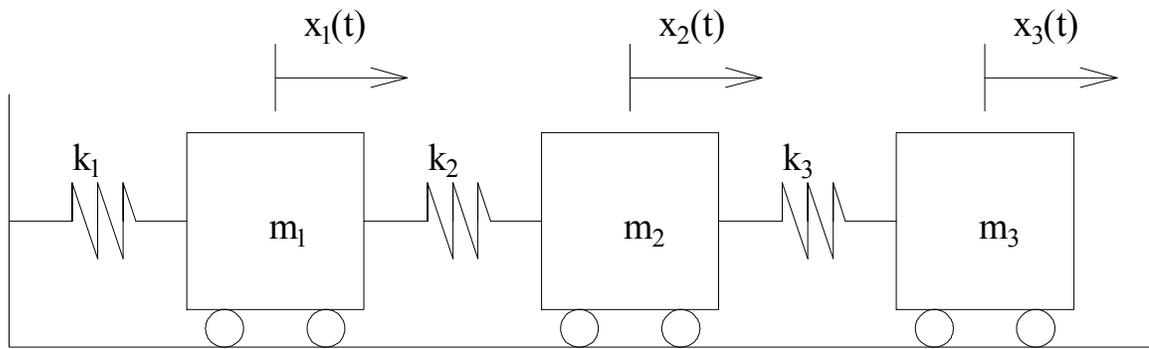


Fig. 1.4 MDF System with Three mass elements

Spring Elements

A linear spring is a type of mechanical link that is generally assumed to have negligible mass and damping. A force is developed in the spring whenever there is relative motion between the two ends of the spring (Singiresu S. Rao, 2004). The spring force is proportional to the amount of deformation and is given by

$$F = kx \quad (1-1)$$

Where F is the spring force, x is the deformation (displacement of one end with respect to the other), and k is the *spring stiffness coefficient* or *stiffness constant*. The work done, U ,

in deforming a spring is stored as strain or potential energy in the spring, and it is given by

$$U = \frac{1}{2}kx^2 \quad (1-2)$$

Actual spring elements may act nonlinearly or only act linearly within a certain point. For a system where the relationship between force F and deformation x is linear, the system is said to be elastic; we call this type of system *linear elastic system* (Anil K. Chopra, 2006). If the relationship between F and x is nonlinear, the system is considered as *inelastic*.

Damping Elements

In practical systems, the vibrational energy is gradually converted to heat or sound (Singiresu S. Rao, 2004). Due to the reduction in the energy, the response, such as the displacement of the system, gradually decreases. The mechanism by which the vibrational energy is gradually converted into heat or sound is known as *damping*. In damping, the energy of the vibrating system is dissipated by various mechanisms, and often more than one mechanism may be present at the same time. It seems impossible to mathematically identify or describe all the energy-dissipating mechanisms in an actual system.

As a result, the damping in actual systems is usually represented in a highly idealized manner. For many purposes the actual damping in a system can be idealized satisfactorily by a linear viscous damper or dashpot (Singiresu S. Rao, 2004). This

idealization is therefore called *equivalent viscous damping*. The damping force F is related to the velocity \dot{x} for a linear viscous damper by

$$F = c\dot{x} \quad (1-3)$$

where c is the *damping coefficient* or *damping constant*.

Governing Equations of Motion

For dynamic systems, the governing equations of motion can be derived with the principles of dynamics. In the study, the project undertaken involves pile guided floats subjected to dynamic loading, and it can be treated as a dynamic system with time varying loading. The responses are time-dependent, due to the nature of the system. From the perspective of principles of dynamics, the system can be modeled as a MDF system. The governing equations of motion are expressed as follows:

$$[m]\{\ddot{x}(t)\} + [c]\{\dot{x}(t)\} + [k]\{x(t)\} = \{F(t)\} \quad (1-4)$$

where:

$[m]$ = mass matrix of the dynamic system

$[c]$ = damping coefficient matrix of the dynamic system

$[k]$ = stiffness coefficient matrix of the dynamic system

$\{x(t)\}$ = displacement vector of the dynamic system

$\{F(t)\}$ = external forcing vector of the dynamic system

Added mass and added mass coefficient

When an object is moving in the water, some water is entrained with the object; the mass of the water is called added mass or virtual mass. Added mass can be represented by added mass coefficient for an object, C_m , which equals the ratio of the added mass plus the actual mass of the object to the actual mass of the object.

Considerable work has been done on added mass due to hydrodynamic effect. Expressions for C_m are given by explicit equations in Unified Facilities Criteria: Design Piers and Wharves (Donald L. Basham, P.E. et al., 2005), as well as Alexandr I. Korotkin (2007) and C. E Brennen (1982), have pioneered the work on such topics. A more detailed explanation will be given in the literature review section.

Hydrodynamic damping and damping from structure components

The dynamic system will be subjected to damping during motion. In the study, the damping consists of hydrodynamic damping and damping from structure components such as fenders and piling systems. It is important to investigate the responses of the dynamic system-the forces and displacements imparted on the system by a berthing vessel. Unfortunately, very few studies have investigated the determination of damping effects, particularly hydrodynamic damping. In the study, different damping coefficients will be chosen to calculate the response of the dynamic system. Subsequently, the results

will be compared in order to determine the effects of different damping values on the system. A more elaborate explanation will be given in the literature review section.

Dynamic Loading from Wave Action

It is generally understood that wind-generated waves can heavily influence the design of marine structures (Merritt, 1983). Strictly speaking, wave action is a very complex phenomena and difficult, if not impossible, to precisely model. However, a number of approaches are in use by AMHS that appear to produce credible results (Miller, 1998). A commonly used approach has been to model waves as static forces on a structure, while neglecting the temporal aspects of wave-action.

The response of a structural system to harmonic loading, as wave-action is often modeled is heavily dependent on the ratio of the natural period of the structure to the period of the forcing function; $\frac{T_n}{T_w}$ (Clough and Penzien, 1993). The natural period of the structure is calculated with the relationship:

$$T_n = 2\pi \sqrt{\frac{m}{k}} \quad (1-2)$$

where:

m = the mass of the structure

k = the stiffness of the structure

For a relatively (laterally) rigid structure (i.e., k is relatively large), like pile-supported structures that incorporate battered piles (traditionally used by AMHS), the ratio of $\frac{T_n}{T_w}$ becomes small. When this ratio becomes small, the dynamic amplification (the increase in load applied to a structure due to dynamics of the system) approaches 1.0, essentially a static condition. This is the traditional approach when designing structures to resist wave forces.

Guide piles used to provide lateral support to floating docks are inherently flexible as compared to traditional construction, relying on beam action for support as opposed to axial forces generated in battered piles. Increasing the stiffness of the guide-piles to that of a battered piling system is either economical or necessary given the appropriate analysis. A decrease in stiffness results in an increase in T_n . As the natural frequency of the structure approaches that of the forcing function (the wave period) the dynamic amplification increases to a point of resonance when the ratio is unity. Dynamic amplification can be significant as the ratio approaches unity. For this reason, it is important that the effects of dynamic loads be accounted for in the proposed ferry landing designs.

Conversely, if the structure is designed to be *soft* by allowing the stiffness to become small and $\frac{T_n}{T_w}$ to be well above 1.0, the dynamic amplification can decrease dramatically resulting in the loads applied to the structures that are less than the static condition. The consequence of this condition is significantly increased deflection.

Vessel Impulse Loads

Fixed mooring structures (docks) are traditionally designed under the assumption that an impacting vessel imparts a quasi-static load on the structure. The analysis model resolves vessel impulse into kinetic energy (Gaythwaite, 2004). This is often justified when the structure is relatively rigid. It is often necessary to consider dynamic effects in fixed structures that exhibit a higher degree of lateral flexibility (Barltrop and Adams, 1991). The pile-guided floats above more closely emulate the latter condition.

The systems will be subjected to vessel impulse loads. As with wave-action, these time-varying loads can also induce dynamic lateral responses in the pile-guided floats. Relatively rigid guide piles will result in larger loads from berthing. Designing the guide-piles to be more flexible will decrease the load supported by the structure but will increase the deflection. Excessive deflections can negatively affect or damage means of egress to the shoreline (bridges, walkways, etc.). The condition is very similar to that encountered with wave-action. The result is that the guide-piles must be designed for two very different dynamic load environments, the response of which shall be dictated by, among other parameters (like damping), the stiffness of the guide-piles. A basis or set of guidelines that account for both types of loads is necessary for the successful design of pile guided floats.

1.3 Objectives

The primary objective of this study is to develop a rational method for estimating the design demands placed on guide-piles used in the construction of floating concrete

piers. It is the intent of this study to develop and perform dynamic analysis for both the SDF systems and MDF systems. Development of the dynamic equations will require the estimation of mass, stiffness and damping parameters.

Damping coefficients are not trivial to define. This study shall include a thorough literature search, including resources related to defining damping characteristics of floating structures. Damping coefficients shall be included in the analyses to the greatest extent possible. Analyses shall be performed for the damped and undamped condition: the undamped case representing a conservative, upper bound of response.

Summary of Objectives:

- Literature search on topics related to the study
- Estimation of practical mass, stiffness and damping coefficients based on available literature. A SDF analysis of the system subjected to a steady-state forcing function representing wave-action and an impulse forcing function representing vessel loading. This analysis shall be executed for both damped and undamped systems. The result shall produce an estimated response in the system, subsequently allowing for the calculation of guide-pile forces.
- A similar MDF analysis shall also be performed, also resulting in system response
- Dissemination of results in a format readily implemented by AMHS Engineers

1.4 Limitation and Scope

The primary limitation of the study is the assumption of linearity within the dynamic model. The mass, damping, and stiffness coefficients are considered constant during the whole berthing process in order to simplify the analysis. In addition, the wave forcing function is simplified into a sinusoidal function based on the linear wave theory. Moreover, the system is simplified into a discrete SDF and MDF system. Therefore, while the model is not geometrically exact, it can still produce accurate results. Berthing vessels are only considered when they are berthing in surge direction towards the float.

Chapter 2 Literature Review

2.1 Study Review

Many floating docks, piers and wharves are used around the world. For example, the 124m by 109m floating dock in Texas Shipyard built by Bethlehem Marine Construction Group in 1985. Floating structures are ideal for piers and wharves as the ships can come alongside them and their positions are constant with respect to the waterline. An example of a floating pier is the one located in Hiroshima, Japan. Vancouver also has a floating pier designed for car ferries. Car ferry piers must allow smooth loading and unloading of cars and the equal tidal rise and fall of the pier. Ferries are indeed advantageous for this purpose. A floating type pier was also designed for berthing the 50000ton container ships in Valdez, Alaska. The floating structure was adopted due to the great water depth (E. Watanable, C.M. Wang 2004).

There are design criteria for floating berthing structures such as piers and wharves, the detailed design analysis is written in Unified Facilities Criteria (UFC).

Selection of floating berthing structures over fixed berthing structures is determined by the water level fluctuation of the site. Floating structures are preferred where the tidal range or seasonal water level range is 3 feet or more (Donald L. Basham, P.E. et al., 2005). Considering the extreme tidal fluctuations in Alaska, which could be as large as 30 feet, floating berthing structures are indeed advantageous.

For analyzing the responses of floating structures under dynamic loading, several methods can be applied (James C. Dalton, P.E. et al., 2009). In general, there are three different methods:

1. Empirical method or statistical method, based on the data that has already been collected and through direct field measurements to predict the responses of the float.
2. Scaled model or similitude method is to use a small scaled model to approximate the real physical phenomenon. The tests are conducted in a well-equipped lab, simulating the physical scenario by satisfying both the geometric similitude, which means the ratio of the model to the prototype is the same everywhere and dynamic similitude, which means the ratio of all forces acting on the model to the prototype is the same.
3. Analytical method, building governing differential equations to capture the motions of the maritime structure that is under concern (Donald L. Basham, P.E. et al., 2005).

There are both advantages and disadvantages associated with the three methods mentioned above. However, in the literature review, only studies that are related to the analytical method will be discussed due to lack of data on model tests.

The classical analytical method often used to calculate the response of maritime structures under dynamic loading, such as the loading from berthing vessels or progressive waves, is the Kinetic Energy Method (KEM), which uses the kinetic energy from a berthing vessel to calculate the response of the system. During a vessel berthing, the kinetic energy is transferred into elastic, or potential energy, primarily by the

displacement of the berthing structure. The method is written in detail in Unified Facilities Criteria: Design Piers and Wharves (Donald L. Basham, P.E. et al., 2005). It has been a widely accepted method for the design of piers and wharves for naval facilities. Explicit equations are given to calculate the kinetic energy from the vessel, and the energy will be absorbed completely by the fender or piling system during berthing. Several coefficients are given to account for different factors, such as contact angle, geometric configuration of the berthing vessel, deformation of the vessel and configuration of the piers or wharves (Donald L. Basham, P.E. et al., 2005). This method depends largely on the velocity and mass of the berthing vessel, even though it accounts for some other factors that are given above. The Kinetic Energy Method is a very simplified approach to a very complex dynamic process, and therefore does not always produce accurate results. However, it is still one of the most widely utilized methods due to its simplicity.

The energy equation can be written as:

$$E_{vessel} = \frac{1}{2} \frac{m}{g} v^2 \quad (2-1)$$

where

E_{vessel} = berthing energy of vessels

m = mass of vessels (in pound mass)

g = acceleration due to gravity (32.2ft/s)

v = berthing velocity normal to the berth (ft/s)

However, there are several factors that modify the actual energy to be absorbed by the fender system; the expression can be written as:

$$E_{fender} = C_b C_m E_{vessel} \quad (2-2)$$

where

E_{fender} = energy to be absorbed by the fender system

C_b = Berthing coefficient, equal to the product of: Eccentricity (C_e), geometric (C_g), deformation (C_d), and configuration (C_c) coefficients

$$C_m = 1 + 2 \frac{D}{B} \quad (2-3)$$

where

D = maximum draft of vessels

B = width of vessels

The above expressions are listed in the Unified Facilities Criteria, Design: Piers and Wharves (Donald L. Basham, P.E. et al., 2005). As berthing conditions become more and more complicated, the traditional method becomes less satisfactory (Erik Huang and Hamn-Ching Chen, 2003). This is especially the case when one or more of the following

conditions exist: shallow water, large ship, and floating pier. The Dynamic Analysis Method focuses on the dynamic motion of both the berthing vessels and the maritime structures under concern; the motion of the entire system, including both the vessel and the structure, is of great importance. When describing complex dynamic berthing events, such as vessels berthing to offshore piers and wharves, the dynamic analysis method can produce significantly more accurate results than the Kinetic Energy Method. However, due to the inherent complexity of the Dynamic Analysis Method, it is not easy to implement. The Dynamic Analysis Method captures the oscillatory motion of the system during berthing. The motion is represented by a series of governing differential equations.

The earliest known study on oscillating vessel motion dates back to the 1950s. Weinblum and St. Denis presented a comprehensive review of the state of knowledge at the end of what we may call the “classical” period in research on sea keeping. However, the earliest work should be attributed to Cummins (1962). He developed the Impulse Response Function to calculate the vessel motion when the system is subjected to external forces, which can then be applied to describe the interaction between a berthing vessel and the associated offshore structure. In his study, he used convolution integral to capturing the exciting force with what is called Impulse Response Function appearing as the kernel (W.E. Cummins, 1962). He also applied the convolution integral to hydrodynamic studies in order to calculate complex hydrodynamic effects, such as added mass and damping. In his study, he assumed linear equations of motion and the coefficients for both the added mass and damping are constant, i.e. the system is under steady state motion. He also decoupled the factors separately in order to simplify the

problem. Therefore, the equation of motions is an approximation rather than a real physical reflection, since both the added mass and damping effects are coupled in reality.

The displacement function due to an external forcing function is given as:

$$x_i(t) = \sum_{j=1}^6 \int_0^t F_j(\tau) R_{ij}(t-\tau) d\tau \quad (2-4)$$

where

$x_i(t)$ = displacements in the one of the six degree of freedom, ($i = 1, 2, 3, 4, 5, 6$)

x_1 = displacement in surge direction

x_2 = displacement in sway direction

x_3 = displacement in heave direction

x_4 = displacement in roll direction

x_5 = displacement in pitch direction

x_6 = displacement in yaw direction

$F_i(\tau)$ = external forcing function in i direction

$R_{ij}(t)$ = the response in direction i to a unit impulse at $t = 0$ in direction j , or Impulse

Response Function

The expression uses the classic Convolution Integral Method to solve the time-dependent transient responses due to external forces.

In the study, Cummins also pointed out that $R_{ij}(t)$ can be determined experimentally.

The governing equation of motions can be expressed as:

$$\sum_{j=6}^6 \left[(m_i + a_{ij}m_j) \ddot{x}_i(t) + b_{ij} \dot{x}_i(t) + c_{ij} x_i(t) \right] = F_i(t) \quad (2-5)$$

where

m_i = mass of the vessel in i direction

a_{ij} = hydrodynamic or added mass from water

b_{ij} = hydrodynamic damping coefficient

c_{ij} = hydrodynamic and structure stiffness coefficient

Until the era of modern digital computers, when more knowledge on numerical methods such as Finite Element Method became known, most of the literature published was based on Cummins' Impulse Response Function method and linearization system assumption.

Glenn B. Woodruff (1962) was able to give explicit equations to calculate both the kinetic energy of the berthing vessel being absorbed and the response of the piling system during berthing and wave forcing. The equations were based on empirical observation and direct response measurements. He pointed out that the induced moments caused by eccentricity from the wave forcing with the angle of attack of 0 and 90 degree were negligible. The moments reach their maximum when this angle is approximately 45 degrees. However, the equations were “ship and site specific”.

Shu-t'ien Li (1962) was able to describe the response of a moored vessel based on the energy method. He used the kinetic energy of the moored vessel caused by the progressive waves to calculate the mooring forces, given the properties of the system. The kinetic energy is converted into the strain energy of the system. However, no experimental data was given to validate the empirical equations.

The kinetic energy (K. E.) is expressed as:

$$K.E. = \frac{1}{2} M' V'^2 \quad (2-6)$$

where

$$M' = M \left(1 + \frac{B}{16D} \right) \quad (2-7)$$

$$V' = \frac{Ag}{\omega D} \frac{\sinh(kd) - \sinh(ks)}{\cosh(kd)} \frac{\sin(kB)}{\frac{kB}{2}} \sin(\theta) \quad (2-8)$$

where

$K.E.$ = kinetic energy of the vessel

M' = combined mass of the vessel (actual mass and added mass)

V' = variable velocity in sway direction (ft/s)

B = width of the vessel

D = draft of the vessel

A = projected area in the current direction

g = acceleration due to gravity ($32.2ft/s$)

ω = angular frequency of the wave

s = clearance under the keel

θ = the incoming angle formed by the wave with respect to the sway direction

The kinetic energy must be converted to a force acting on the berthing structure (Shun-t'ien Li, 1962).

Fontijn (1980) was an early researcher to investigate the berthing motion of a ship to a jetty. He used the Cummins' Impulse Response Function method and linearization system assumption. Although he pointed out that the linear system assumption was not perfect, it is still a good approximation for real ships with small to moderate velocities.

He gave analytically calculated added mass and damping effects in sway and yaw directions for a chosen model ship under different berthing conditions. He also compared the results with experimentally determined values, and confirmed their consistency.

Vasco Costa (1965) studied the mechanics of berthing vessels. He used the same equation as the one given from the Unified Facilities Criteria: Piers and Wharves Design (Donald L. Basham, P.E. et al., 2005). He used the energy method with high added mass values in an early period. The high added mass values were acceptable, considering the overly conservative design at the time. He also addressed that keel clearance, currents, ship rotation, and approaching velocities all contribute to the berthing effect.

Saurin R. F (1965) conducted a series of tests in his laboratory, with scaled model observation; he used the energy equation for an approaching ship. He was also able to produce numerical values for complex birthing parameters. Brotsma, Hirs and Langeveld (1977) evaluated added mass coefficients; they found the added mass coefficients are affected by the submersed geometry of the ship, the stiffness of the fender system and its natural frequency, under keel clearance, and the shape of the berthing structure. A single value for the added mass coefficient that produces accurate results for all conditions seems infeasible.

Shashikala (1995) investigated the response of a barge elastically moored to a fixed support using the three dimensional Finite Element Method. He then compared the result with the model tests carried out in a wave flume for regular and random waves in a head sea condition. The influence of the mooring point's location and the mooring line's

flexibility was also addressed. He used a linearized Bernoulli equation to solve the wave diffraction problem in order to calculate the added mass and damping effects in 6 directions (surge, sway, heave, roll, pitch and yaw) with a frequency range of 0.35Hz to 1.0Hz in steps of 0.05Hz. When compared against experimental values, the results derived using the linearized Bernoulli equation matched very well. The barge used was 400mm wide, 2000mm long and 300mm tall. The barge was chosen to approximate normal shaped vessels. Both the added mass and damping coefficients were very low when the vessel was in surge direction compared with the values in heave and pitch direction, which makes perfect sense given the streamlined shape of the barge used in the experiments. His research demonstrated that the added mass and damping effects in the surge direction are almost negligible.

Schellin and Ostergaard (1993) discussed mooring vessel modeling in the surge direction. They assumed the added mass is 15% of the actual mass of the vessel and damping is 1-2% of the critical damping based on hydrodynamic simulation, linear wave theory and potential flow theory (T.E. Schellin and C. Ostergaard, 1993). Their assumptions were reasonable due to the streamline shape of the vessels and they coincide with the study done by Shashikala (1995). They also used the linearization system and time-invariant added mass and damping coefficients. The computed results they obtained were very close to the ones measured in the field.

William N. Seelig, P.E. and his colleagues (2010) conducted studies on added mass coefficients in the sway direction for mooring vessels, in accordance with the

Unified Facilities Criteria (Donald L Basham, P.E. et al., 2005). Their results were intended for use with the Kinetic Energy Method. However, they pointed out some important physical phenomena that were not covered in other studies. When the vessel is oscillating in the water, due to hydrodynamic effects, there are added mass or virtual mass effects from the water. The effect can be calculated and it is affected by different factors, such as the velocity of the vessel under keel clearance, etc. However, when the ship is berthing to the piers, some of the water will continue to move even after the vessel has stopped. Therefore, the real added mass during vessel berthing is smaller than it is when the vessels are oscillating in the water. Seelig and his colleagues were also able to plot added mass coefficients based on different vessel parameters and keel clearance. They compared their results with the experimental values, and the results matched well.

The equations to determine added mass coefficients are:

$$C_m = c_{m0} + (C_{m1} - C_{m0})\left(\frac{T}{d}\right)^{3.5} \quad (2-9)$$

$$C_{m0} = 1.3 + 1.5\left(\frac{T}{B}\right) \quad (2-10)$$

$$C_{m1} = F\left[12.4\left(\frac{T}{B}\right)^{0.3} - 50\left(\frac{T}{L}\right)\right] \quad (2-11)$$

where

C_m = the oscillating added mass coefficient

C_{m0} = added mass coefficient for $T/d = 0$, shallow water limit

C_{m1} = added mass coefficient for $T/d = 1$, deep water limit

T = vessel draft

d = water depth

F is a multiplier. It has different values due to different vessel geometries in the same year (2010), William N. Seelig, P.E. and his colleagues conducted another study on the dynamic modeling of ferry berthing. They used commercial software ANSYS AQWA to model the dynamic analysis. They were able to give both linearized hydrodynamic effects coefficients and frequency-dependent hydrodynamic effects. The added mass coefficients in the surge and sway directions differ greatly, with the added mass in the surge direction only about 10% of the actual mass of the vessel, while the added mass in sway direction can be several times larger than the actual mass of the vessel. The damping coefficients are given as frequency-dependent, and according to Seelig and his colleagues, they were very small in the surge direction. All of these results coincide with the studies done by previous researchers.

Willelijn H. Pauw, René H.M. Huijsmans and Arjan Voogt (2007) used diffraction computations on side-by side moored carriers. They used the lid method in diffraction code formulated by Chen (2005). They plotted both the calculated results based on the above method and the measured ones in the field, which were satisfactorily close.

Hamn-Ching Chen and Erick T. Huang (2003) conducted two separate studies on ship berthing at floating piers. In both their studies, the Reynolds-Averaged Navier-Stokes (RANS) simulation model was used, which was also formulated by Chen (1998, 2000 and 2002). The governing differential equations were the same as the ones developed by Cummins (1962). The only difference is that they were transient state equations of motion; therefore, all the coefficients were time-dependent, and thus more accurate. Chen and Huang plotted their results without any comparison to the experimental values. Nevertheless, their results were reasonably accurate.

2.2 Summary and Comments

While the classical Kinetic Energy Method is probably the easiest method for the design but it tends to oversimplify the problem. It is not accurate enough and most of the time it is overly conservative. The method is still being used for small facility construction with simple berthing conditions, but it is not suitable for large projects.

Analytical analysis with the linearization system assumption can be used as a reasonably good approximation for the response of the system. It is often a challenge to determine the hydrodynamic coefficients, such as added mass coefficients and damping effects. The coefficients are best determined by either commercial software or experiments. Literature related to identifying coefficients is also available.

Numerical analysis of the transient (time-dependent) state of motion is technically more accurate. However, due to its inherent complexity, both mathematically and

computationally, its usefulness is typically limited with using advanced commercial software, such as AWQA.

In this study, the linearization system assumption will be used, and selection of berthing coefficients will be based on results from the existing literature reviewed above.

Chapter 3 Response to Vessel Impact

3.1 Quasi-Static Analysis

The Kinetic Energy Method (KEM) is a well-accepted design method that utilizes the conservation of energy and is commonly used in practice. The KEM will be considered in this study. The approach used here will use varied key parameters of the berthing system: impact velocity, mass of the vessel and stiffness of the piling system and fender.

Figure 3.1 represents a simple pile-guided float structure and will serve as the basis for analysis. The system consists of a vessel which is moving towards the float, a fender element, a float which functions as a dock, and a piling system (also represented by a spring) which is used to provide lateral support to the dock.

Given the schematic description of the berthing system, the quasi-static model is needed to investigate the berthing responses of the fender and the piling system. Figure 3.2 shows a quasi-static model of the berthing system. In the figure, both the fender and the piling system are represented by spring elements, the float acts as a massless rigid connection between the fender and the piling system, and the vessel is berthing towards the fender connected with the float and the piling system. The float is considered massless because this is consistent with the generally accepted Kinetic Energy Method.

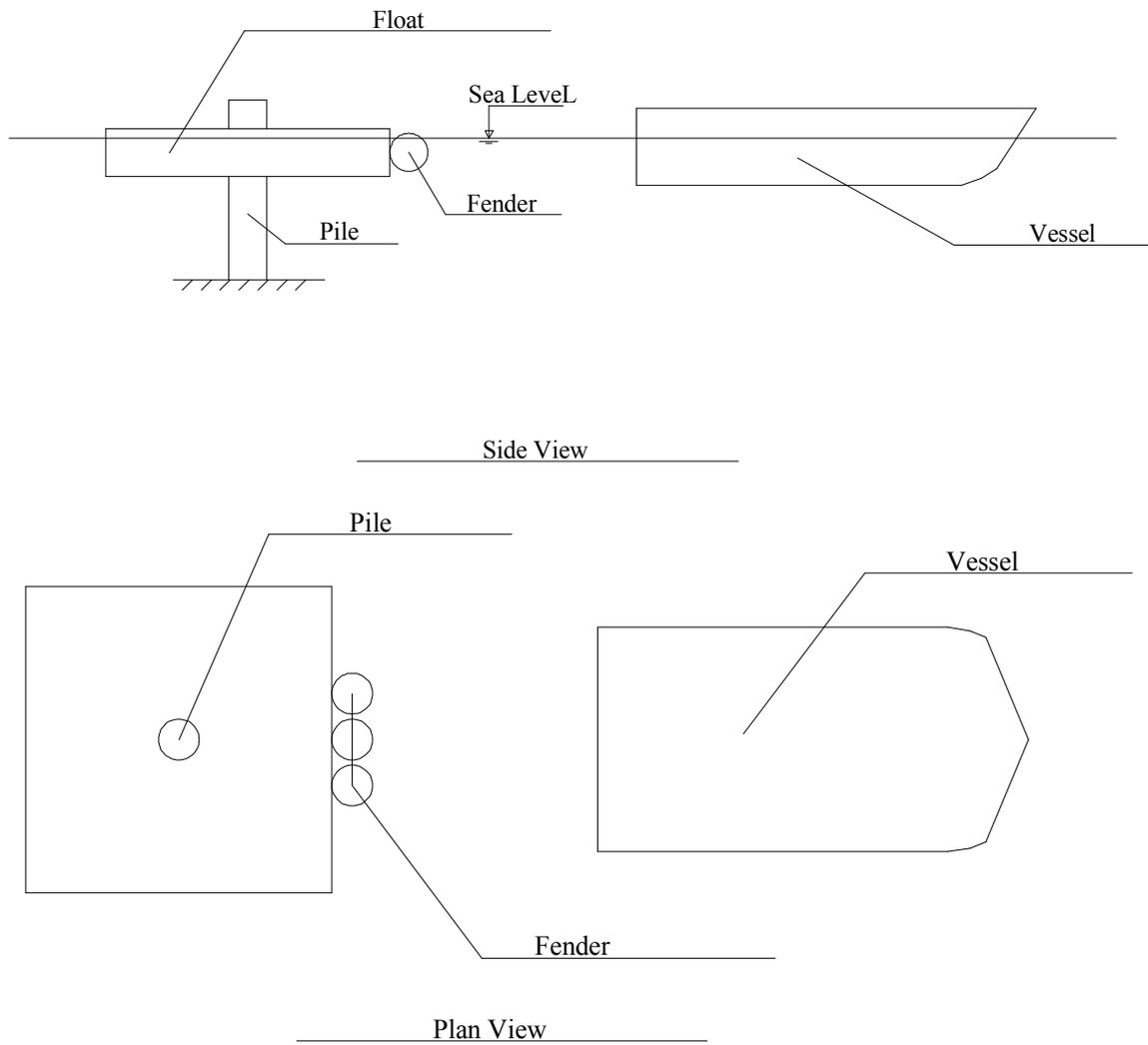


Fig. 3.1 Schematic of Pile-guided Float for Analysis

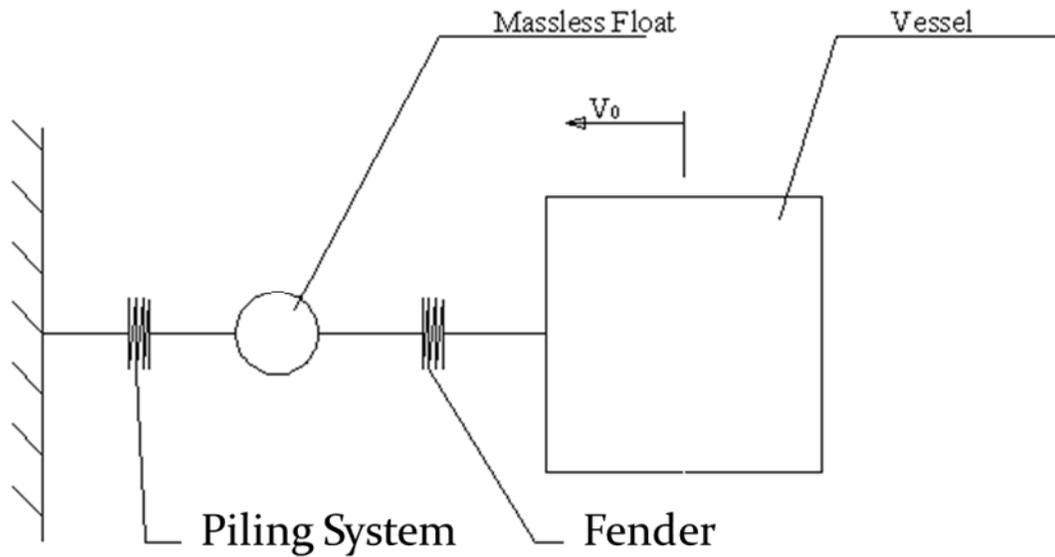


Fig. 3.2 Pile-guided Float model for a quasi-static analysis

A certain portion of the total kinetic energy of the vessel is converted to elastic strain energy of the structural system. The displacements of the spring elements are deformation and deflection of the fender and the piling system respectively. Therefore, by the principle of conservation of energy, the portion of the kinetic energy transferred to the dock should be equal to the sum of the elastic energy of the spring elements representing the fender and the piling system. The various berthing factors described previously account for energy loss and added mass, modifying the total (assumed) energy to represent the energy actually absorbed by the structure (Donald L. Basham, 2005). An equation representing the conservation of energy transferred to the structural system is represented by Eq. (3-1):

$$C_b C_m K_{vessel} = U_{fender} + U_{pile} \quad (3-1)$$

where:

K_{vessel} = kinetic energy of the vessel

C_b = berthing coefficient, used to account for the different berthing conditions

U_{fender} = elastic energy of the fender

U_{pile} = elastic energy of the piling system

C_m = added mass coefficient for the vessel

A practical range of values for the berthing coefficient is from 0.5 to 1.5.

The added mass coefficient is related to the projected area of the ship at the right angle to the direction of motion. Other factors, such as the form of the ship, water depth, berthing velocity and acceleration and deceleration of the ship will have some effect on the added mass coefficient (Donald L. Basham, 2005).

In the study, the vessel is always berthing in the surge direction towards the float. The value of the added mass coefficient will be chosen as 1.1 in accordance with the work done by Seelig and Lang (2010).

From statics:

$$F_{fender} = F_{pile} \quad (3-2)$$

where F_{fender} is the reaction force of the fender, F_{pile} is the reaction force of the piling system.

Assuming the reaction forces of the spring elements are linearly related to the displacements of the elements, the elastic energies of both spring elements can be represented by:

$$U_{fender} = \frac{1}{2} k_{fender} x_{fender}^2 \quad (3-3)$$

$$U_{pile} = \frac{1}{2} k_{pile} x_{pile}^2 \quad (3-4)$$

$$K_{vessel} = \frac{mV^2}{2} \quad (3-5)$$

where k_{fender} is the stiffness of the fender, k_{pile} is the stiffness of the piling system, x_{fender} is the displacement of the fender and x_{pile} is the lateral displacement of the piling system. m is the mass of the vessel and V is the approaching velocity of the vessel.

The responses under concern are displacements and reaction forces of the fender and the piling system with given stiffness of both spring elements and given vessel mass and velocity; therefore, combine Eq. (3-1) – Eq. (3-5), two equations can be obtained with substitution:

$$\frac{1}{2} C_b C_m m V^2 = \frac{1}{2} k_{fender} x_{fender}^2 + \frac{1}{2} k_{pile} x_{pile}^2 \quad (3-6)$$

$$k_{fender}x_{fender} = k_{pile}x_{pile} \quad (3-7)$$

Since

$$F_{fender} = k_{fender}x_{fender} \quad (3-8)$$

$$F_{fender} = k_{fender}x_{fender} \quad (3-9)$$

Solving Eq. (3-6) and Eq. (3-7), the displacements of the piling system and the fender can be expressed as:

$$x_{pile} = \sqrt{mV^2 C_b C_m \frac{k_{fender}}{k_{pile}^2 + k_{pile}k_{fender}}} \quad (3-10)$$

$$x_{fender} = \sqrt{mV^2 C_b C_m \frac{k_{pile}}{k_{fender}^2 + k_{pile}k_{fender}}} \quad (3-11)$$

The reaction forces can be expressed as:

$$F = \sqrt{mV^2 C_b C_m \frac{k_{fender}k_{pile}}{k_{pile} + k_{fender}}} \quad (3-12)$$

where F is the reaction force for both the fender and the piling system under the quasi-static assumption.

Given the different parameters, V , C_b , C_m , k_{fender} and k_{pile} , the quasi-static responses can be found. From Eq. (3-10), Eq. (3-11) and Eq. (3-12), it can be observed

that both the displacements and reaction forces are proportional to the square root of the energy transferred to the structure, $K_{vessel}C_bC_m$, which is to be absorbed by the spring elements. It is interesting to note that the combination of the stiffness of the spring elements may cause the responses to vary.

For quasi-static analysis, berthing coefficients are assigned as 0.5, 1 or 1.5, and the added mass coefficient is assigned as 1.1 for vessel berthing in the surge direction. (Seelig, P.E. and Lang 2010).

Figure 3.3 and Figure 3.4 give values of energy transferred to the structure, $K_{vessel}C_bC_m$, for a range of values for both m and V , respectively.

It can be observed from Fig. 3.3 that the transferred kinetic energy to be absorbed by the spring elements is increasing linearly with the mass of the vessel m , providing constant velocity V , and the berthing coefficient and added mass coefficient. The transferred kinetic energy also increases as the berthing coefficient becomes larger (from 0.5 to 1.5).

In Figure 3.4, the actual kinetic energy to be absorbed by the spring elements is increasing with increasing velocity V in a parabolic manner, with given mass of the vessel m .

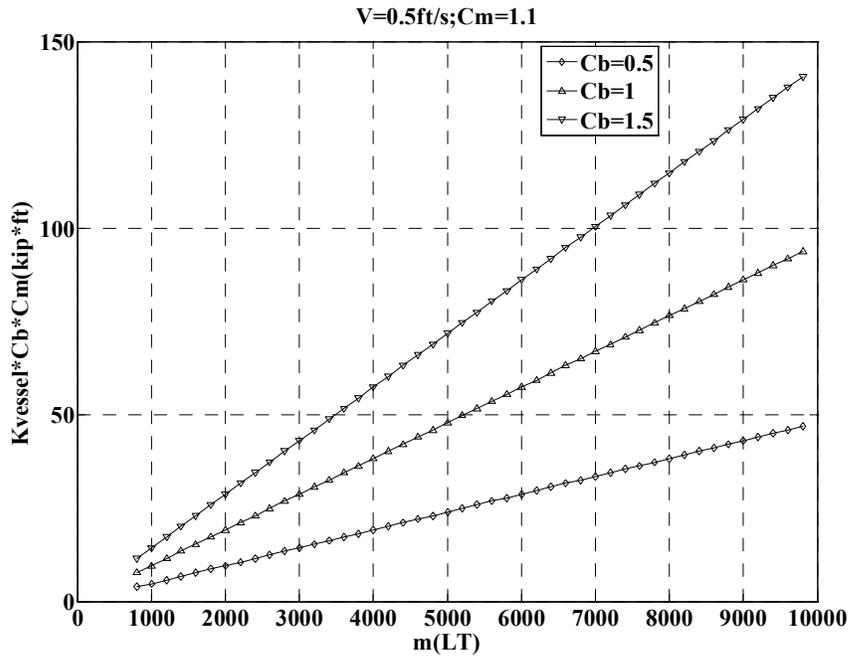


Fig. 3.3 Transferred Energy-1

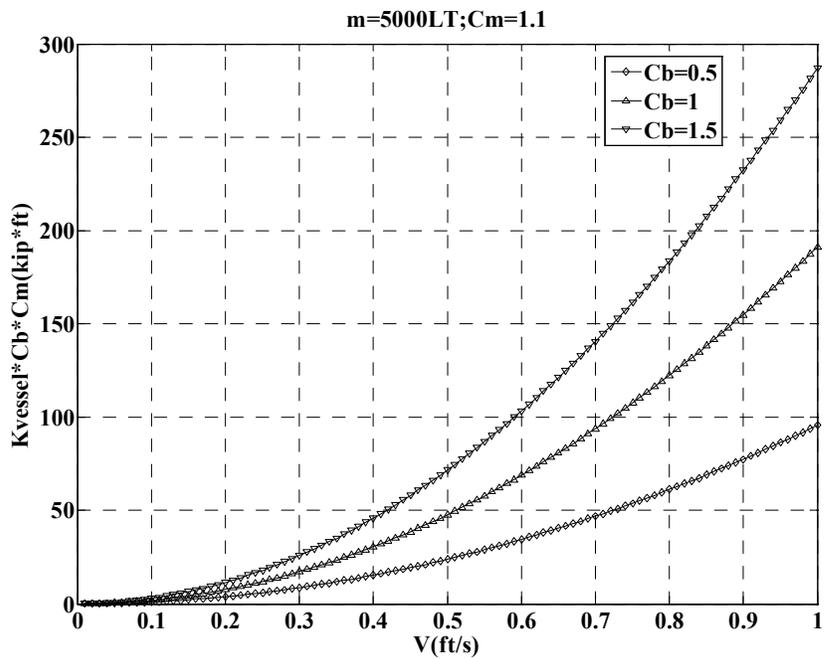


Fig. 3.4 Transferred Energy-2

Figure 3.5 to Figure 3.7 present the responses for given $K_{vessel}C_bC_m$ and k_{fender} .

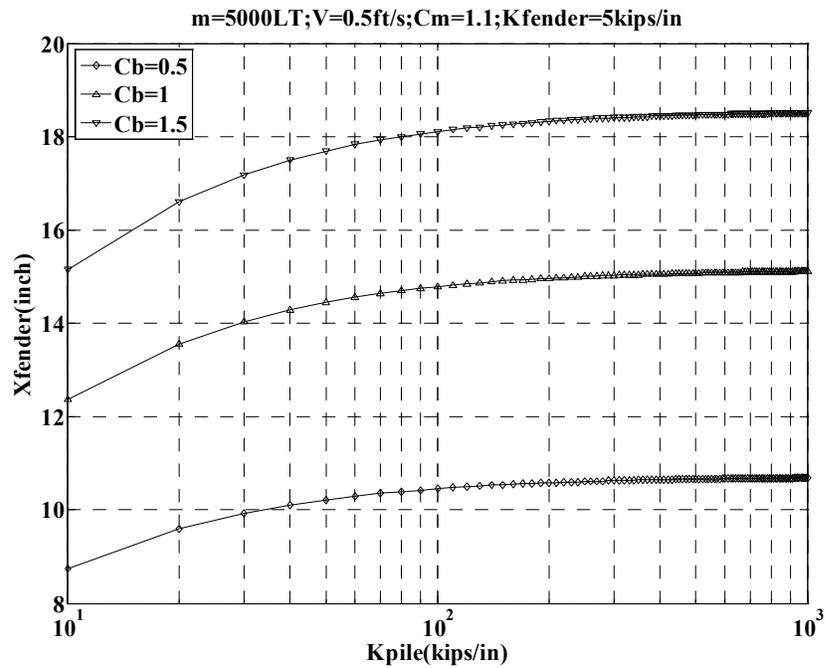


Fig. 3.5 Displacement of the Fender-1

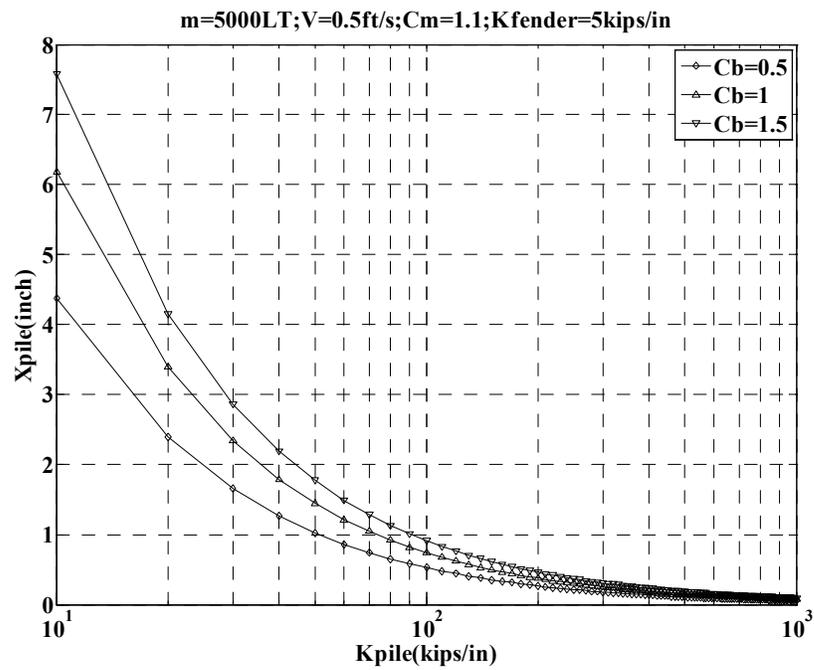


Fig. 3.6 Displacement of the Piling System-1

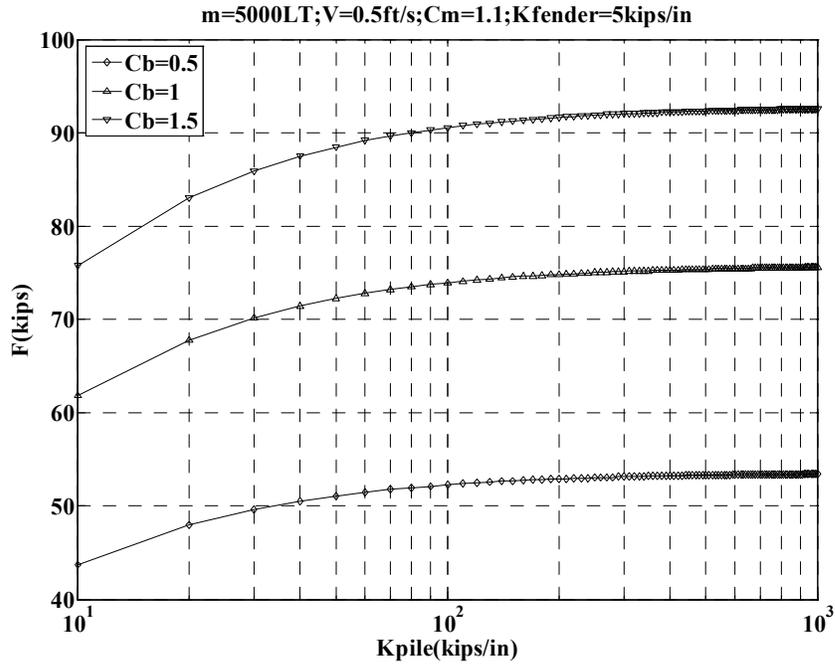


Fig. 3.7 Reaction Forces for both the Fender and Piling System-1

Figure 3.8 and figure 3.10 present the responses with same K_{vessel} , C_b and C_m but larger k_{fender} .

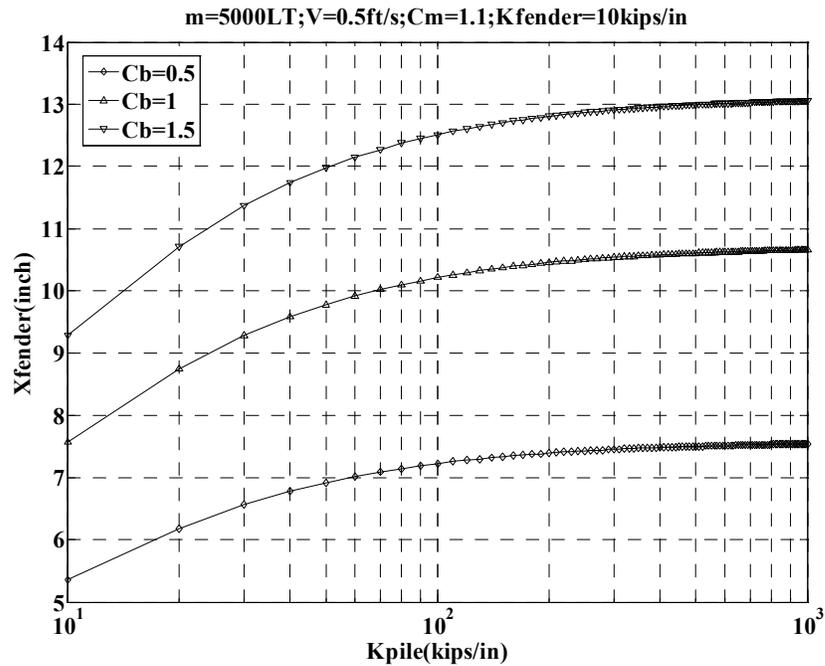


Fig. 3.8 Displacement of the Fender-2

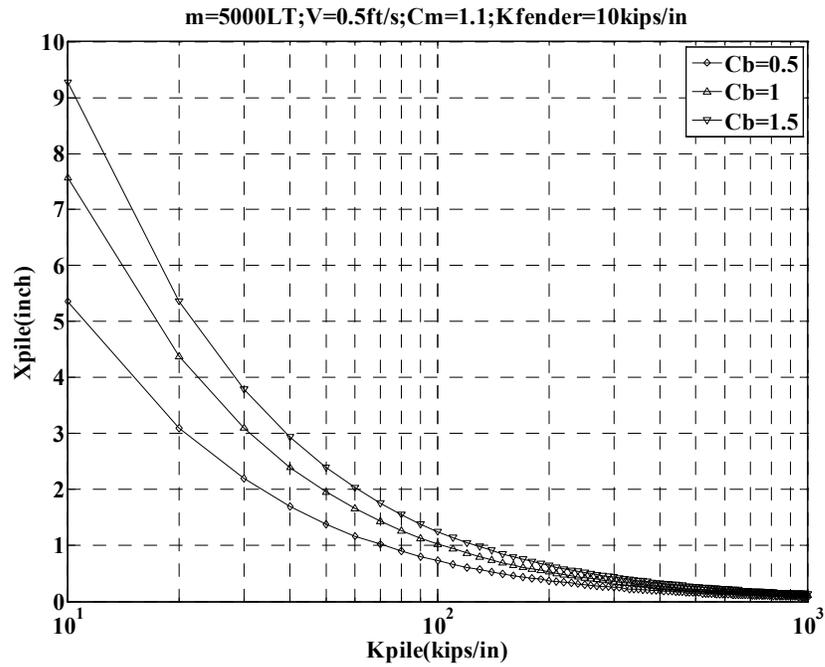


Fig. 3.9 Displacement of the Piling System-2

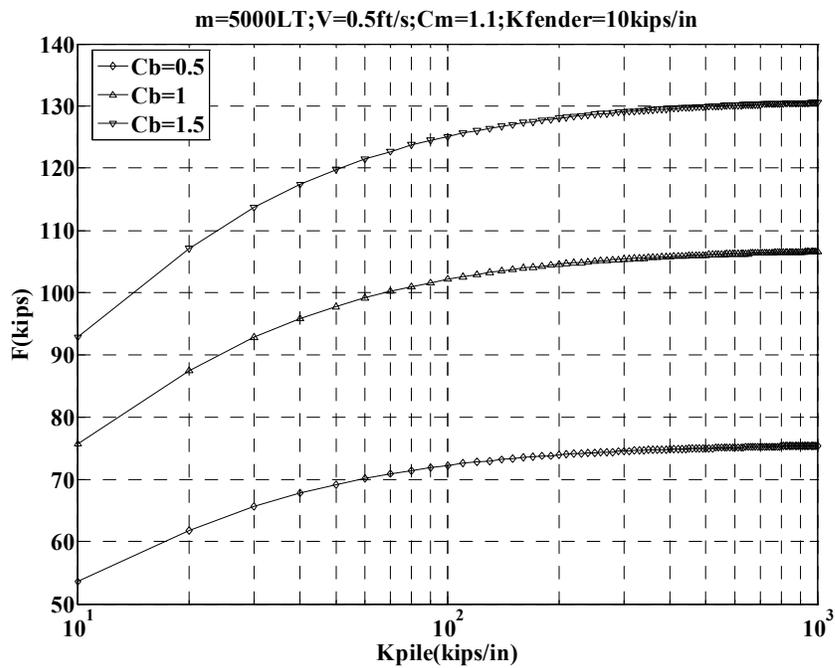


Fig. 3.10 Reaction Forces for both the Fender and Piling System-2

Figure 3.5 presents the displacements of the fender, with given kinetic energy and stiffness of the fender which is 5kips/in, and varying stiffness of the piling system. The displacements don't increase significantly with increasing k_{pile} , and when k_{pile} reaches to large values, the displacement is almost constant even though k_{pile} is still increasing. Given a very rigid piling system, the deflection, and therefore energy, is nearly entirely transferred to the relatively elastic fender system.

Figure 3.7 shows that the reaction forces for both spring elements are almost constant when the stiffness of the piling system becomes large or very rigid. This plot demonstrates the influence of pile stiffness on the force experienced by the structure.

Comparing Figures 3.8, 3.9 and 3.10 to Figures 3.5 3.6 and 3.7 demonstrates the influence of fender stiffness on the quasi-static response of the pile-guided float structure.

3.2 Dynamic Analysis

The DAM (Dynamic Analysis Method) is a method that captures the response of a dynamic system in the time domain, and it is technically more accurate than the KEM.

For comparison to the quasi-static analysis, the berthing system will be treated as a MDF system in this section. To simplify the analysis, both spring and damping elements will be treated as linear components. In this section, the system will be investigated in both one-dimension and two-dimensions and the section is divided into two subsections to cover each analysis. For one dimensional analysis, the responses of the system will be considered only in the surge direction. The analysis will be covered in

the first subsection. For two dimensional analysis, the responses of the system will be considered in the surge, sway and yaw direction, and it will be covered in the second subsection.

3.2.1 One Dimensional Analysis

The berthing system will be treated as a two DOFs system in this section, and both the vessel and the float will be treated as discrete lumped mass systems. The schematic of the two DOFs dynamic system is shown in Fig. 3.11. The dynamic model of the system is shown in Fig. 3.12.

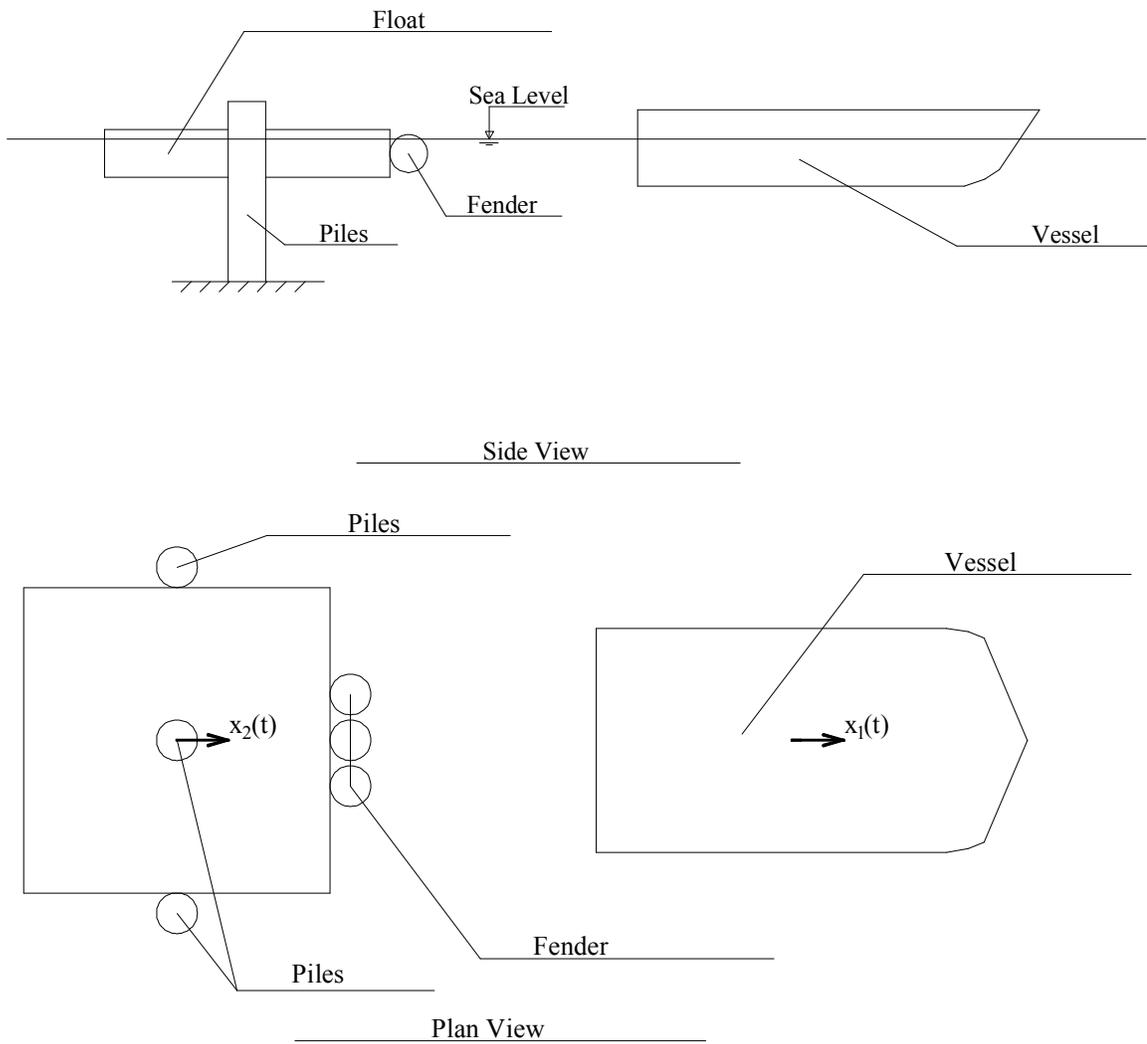


Fig. 3.11 Schematic of Two DOFs System

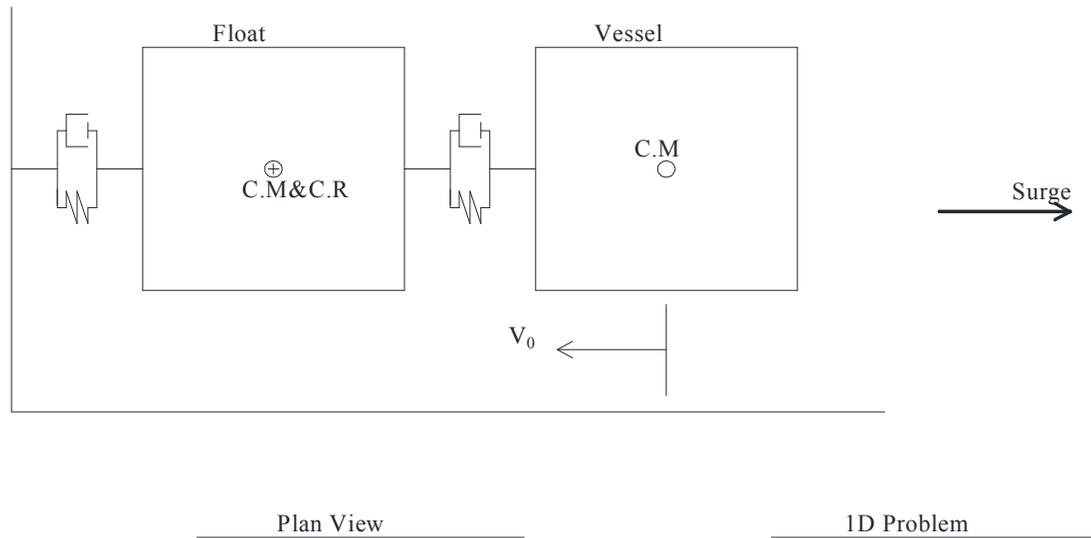


Fig. 3.12 Dynamic Model of Two DOFs System

The free body diagram of the system is shown in Figure 3.13.

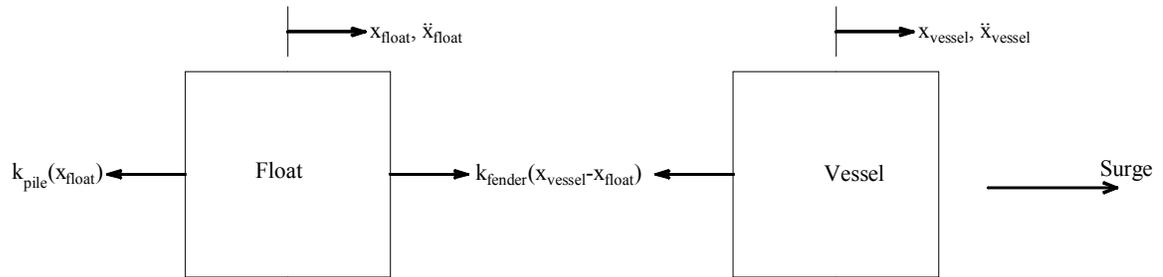


Fig. 3.13 Free Body Diagram for Two DOFs System (undamped)

x_{float} = displacement of the float

\ddot{x}_{float} = acceleration of the float

x_{vessel} = displacement of the vessel

\ddot{x}_{vessel} = acceleration of the vessel

$k_{pile}(x_{float})$ = reaction force from the pile

$k_{fender}(x_{vessel} - x_{float})$ = reaction force from the fender

The governing equations of motion for the berthing system can be expressed as:

$$m_{vessel}\ddot{x}_{vessel} = -k_{fender}(x_{vessel} - x_{float}) \quad (3-13)$$

$$m_{float}\ddot{x}_{float} = k_{fender}(x_{vessel} - x_{float}) - k_{pile}x_{float} \quad (3-14)$$

After arranging the left side of the equation to the right side, the equations can be expressed as:

$$m_{vessel}\ddot{x}_{vessel} + k_{fender}x_{vessel} - k_{fender}x_{float} = 0 \quad (3-15)$$

$$m_{float}\ddot{x}_{float} - k_{fender}x_{vessel} + k_{fender}x_{float} + k_{pile}x_{float} = 0 \quad (3-16)$$

The equations can also be put in matrix form:

$$\begin{bmatrix} m_{vessel} & 0 \\ 0 & m_{float} \end{bmatrix} \begin{Bmatrix} \ddot{x}_{vessel} \\ \ddot{x}_{float} \end{Bmatrix} + \begin{bmatrix} k_{fender} & -k_{fender} \\ -k_{fender} & k_{fender} + k_{pile} \end{bmatrix} \begin{Bmatrix} x_{vessel} \\ x_{float} \end{Bmatrix} = \begin{Bmatrix} 0 \\ 0 \end{Bmatrix} \quad (3-17)$$

where:

m_{vessel} = mass of the vessel

x_{vessel} = displacement of the vessel

m_{float} = mass of the float

x_{float} = displacement of the float

k_{fender} = stiffness of the fender

k_{pile} = stiffness of the piling system

The equations of motion can be condensed as:

$$[m]\{\ddot{x}(t)\} + [k]\{x(t)\} = \{0\} \quad (3-18)$$

which is the classical form of equations of motion without damping and external forces.

Damping Effects

The governing equations of motion derived in the last section represent the responses for an undamped system. However, as stated earlier, berthing responses will be affected by damping effects in reality. For simplicity, linear viscous damping will be used in the analysis. Because of the lack of information regarding damping in a structure such as pile-guided floats, a relatively wide range of damping values will be considered in this study. For this study, the damping matrix can be expressed as:

$$[c] = a[m] + b[k] \quad (3-19)$$

where a and b are constants. This type of damping is known as *proportional damping* because $[c]$ is proportional to a linear combination of $[m]$ and $[k]$ (Singiresu S. Rao 2004). By inserting Eq. (3-18) into Eq. (3-19), the equations of motion for the berthing system can be expressed as:

$$[m]\{\ddot{x}(t)\} + [a[m] + b[k]]\{\dot{x}(t)\} + [k]\{x(t)\} = \{0\} \quad (3-20)$$

Eigen Value Problems

For undamped MDF system without external forces, the governing equations of motion can be expressed as:

$$[m]\{\ddot{x}(t)\} + [k]\{x(t)\} = \{0\} \quad (3-20)$$

the solution of the equations of motion can be assumed to have the form

$$x_i(t) = X_i T(t), \quad i = 1, 2, \dots, n \quad (3-22)$$

where X_i is a constant and T is a function of time. T can be expressed as a linear sinusoidal function as:

$$T(t) = C \cos(\omega t + \phi) \quad (3-23)$$

where C and ϕ are constants, known as the amplitude and the phase angle, respectively.

The configuration of the system does not change its shape during motion, but its amplitude does. The configuration of the system, given by the vector

$$\mathbf{X} = \begin{Bmatrix} X_1 \\ X_2 \\ \cdot \\ \cdot \\ \cdot \\ X_n \end{Bmatrix} \quad (3-24)$$

Eq. (3-24) is known as the *mode shapes* of the system. Substituting Eq. (3-24) and Eq. (3-23) into Eq. (3-21), the equations obtained can be expressed as:

$$[[k] - \omega^2 [m]] \mathbf{X} = 0 \quad (3-25)$$

Since the mode shape of the system cannot be zero, the part of the equation that contains the stiffness matrix, mass matrix and frequencies must equal zero, such as:

$$[[k] - \omega^2 [m]] = 0 \quad (3-26)$$

Eq. (3-25) represents what is known as the *eigenvalue* or *characteristic value* problem,

Eq. (3-26) is called the characteristic equation, ω^2 is known as the *eigenvalue* or the *characteristic value*, and ω is called the *natural frequency* of the system.

The expansion of Eq. (3-26) leads to an n th order polynomial equation in ω^2 . The solution (roots) of this polynomial or characteristic equation gives n values of ω^2 (Singiresu S. Rao 2004).

Orthogonality of Mode Shapes

The mode shapes $\mathbf{X}^{(i)}$ satisfy an important property called *orthogonality* (Singiresu S. Rao 2004). The property can be expressed as:

$$\mathbf{X}^{(j)T} [m] \mathbf{X}^{(i)} = 0, \quad i \neq j \quad (3-27)$$

$$\mathbf{X}^{(j)T} [k] \mathbf{X}^{(i)} = 0, \quad i \neq j \quad (3-28)$$

Therefore, the mode shapes satisfy the following relations:

$$[M] = \begin{bmatrix} M_{11} & & & 0 \\ & M_{22} & & \\ & & \ddots & \\ 0 & & & M_{nn} \end{bmatrix} = [X]^T [m] [X] \quad (3-29)$$

$$[K] = \begin{bmatrix} K_{11} & & & 0 \\ & K_{22} & & \\ & & \ddots & \\ 0 & & & K_{nn} \end{bmatrix} = [X]^T [k] [X] \quad (3-30)$$

The mode shapes can be *normalized*, and the diagonal mass and stiffness matrices have the following forms if the normalized mode shapes are used, and that is:

$$[M] = [X]^T [m] [X] = [I] \quad (3-31)$$

$$[K] = [X]^T [k] [X] = \begin{bmatrix} \omega_1^2 & & & 0 \\ & \omega_2^2 & & \\ & & \ddots & \\ 0 & & & \omega_n^2 \end{bmatrix} \quad (3-32)$$

Modal Analysis

The governing equations of motion of an undamped MDF system are expressed as Eq. (3-21), and the equations are a set of ordinary differential equations. Solution of the equations of motion of an MDF system can be found by *modal analysis*. It is necessary to solve the eigenvalue problem first, which is given below:

$$\omega^2 [m] \mathbf{X} = [k] \mathbf{X} \quad (3-33)$$

in order to find the natural frequencies $\omega_1, \omega_2, \dots, \omega_n$ and the corresponding mode shapes $\mathbf{X}^{(1)}, \mathbf{X}^{(2)}, \dots, \mathbf{X}^{(n)}$. The solution vector of Eq. (3-21) can be expressed as a linear combination of the mode shapes.

$$\{x(t)\} = q_1(t) \mathbf{X}^{(1)} + q_2(t) \mathbf{X}^{(2)} + \dots + q_n(t) \mathbf{X}^{(n)} \quad (3-34)$$

where $q_1(t), q_2(t), \dots, q_n(t)$ are time-dependent generalized coordinates, also known as the principle coordinates or modal participation coefficients. By defining a modal matrix $[X]$ in which the j th column is the vector $\mathbf{X}^{(j)}$, Eq. (3-34) can be rewritten as:

$$\{x(t)\} = [X]\{q(t)\} \quad (3-35)$$

where:

$$\mathbf{q}(t) = \begin{Bmatrix} q_1(t) \\ q_2(t) \\ \cdot \\ \cdot \\ \cdot \\ q_n(t) \end{Bmatrix} \quad (3-36)$$

Since $[X]$ is not a function of time, from Eq. (3-35), the second derivative of the solution with respect to time can be expressed as:

$$\{\ddot{x}(t)\} = [X]\{\ddot{q}(t)\} \quad (3-37)$$

Using Eq. (3-29) and Eq. (3-30), Eq. (3-21) can be expressed as:

$$[m][X]\{\ddot{q}(t)\} + [k][X]\{q(t)\} = \{0\} \quad (3-38)$$

Premultiplying Eq. (3-38) by $[X]^T$, Eq. (3-39) can be obtained:

$$[X]^T [m][X]\{\ddot{q}(t)\} + [X]^T [k][X]\{q(t)\} = \{0\} \quad (3-39)$$

If the mode shapes are normalized, Eq. (3-40) can be obtained:

$$\{\ddot{q}(t)\} + [\boldsymbol{\omega}^2] \{q(t)\} = \{0\} \quad (3-40)$$

Eq. (3-40) denotes a set of n uncoupled differential equations of second order

$$\ddot{q}_i(t) + \omega_i^2 q_i(t) = 0 \quad (3-41)$$

The solution of Eq. (3-41) can be expressed as:

$$q_i(t) = q_i(0) \cos \omega_i t + \left(\frac{\dot{q}(0)}{\omega_i} \right) \sin \omega_i t \quad (3-42)$$

The initial generalized displacements $q_i(0)$ and the initial generalized velocities $\dot{q}(0)$ can be obtained from the initial values of the physical displacements $x_i(0)$ and physical velocities $\dot{x}_i(0)$ as

$$\{q(0)\} = [X]^T [m] \{x(0)\} \quad (3-43)$$

$$\{\dot{q}(0)\} = [X]^T [m] \{\dot{x}(0)\} \quad (3-44)$$

where $\{x(0)\}$ is the *initial displacement vector*, and $\{\dot{x}(0)\}$ is the *initial velocity vector*.

If the MDF system has proportional damping, such as the one shown in Eq. (5-7), by expressing the solution vector $\{x(t)\}$ as a linear combination of the mode shapes of the undamped system, which is given in Eq. (3-35), Eq. (3-21) can be rewritten as:

$$[m][X]\{\ddot{q}(t)\} + [a[m] + b[k]][X]\{\dot{q}(t)\} + [k][X]\{q(t)\} = \{0\} \quad (3-45)$$

Premultiplication of Eq. (3-45) by $[X]^T$ leads to:

$$[X]^T [m][X]\{\ddot{q}(t)\} + [X]^T [a[m] + b[k]][X]\{\dot{q}(t)\} + [X]^T [k][X]\{q(t)\} = \{0\} \quad (3-46)$$

If the mode shapes are normalized, Eq. (3-46) reduces to

$$[I]\{\ddot{q}(t)\} + [a[I] + b[\omega^2]]\{\dot{q}(t)\} + [\omega^2]\{q(t)\} = \{0\} \quad (3-47)$$

which is:

$$\ddot{q}_i(t) + (a + b\omega_i^2)\dot{q}_i(t) + \omega_i^2 q_i(t) = 0 \quad (3-48)$$

where ω_i is the i th natural frequency of the undamped system.

By writing

$$a + b\omega_i^2 = 2\zeta_i\omega_i \quad (3-49)$$

where ζ_i is called the modal damping ratio for the i th normal mode, Eq. (3-48) can be rewritten as:

$$\ddot{q}_i(t) + 2\zeta_i\omega_i\dot{q}_i(t) + \omega_i^2q_i(t) = 0 \quad (3-50)$$

It can be seen that each of the n equations represented by this expression is uncoupled from all of the others. The solution of Eq. (3-50), when $\zeta_i < 1$, can be expressed as:

$$q_i(t) = e^{-\zeta_i\omega_i t} \left\{ \cos\omega_{di}t + \frac{\zeta_i}{\sqrt{1-\zeta_i^2}} \sin\omega_{di}t \right\} q_i(0) + \left\{ \frac{1}{\omega_{di}} e^{-\zeta_i\omega_i t} \sin\omega_{di}t \right\} \dot{q}_i(0) \quad (3-51)$$

where:

$$\omega_{di} = \omega_i \sqrt{1-\zeta_i^2} \quad (3-52)$$

Therefore, with initial conditions and mass, stiffness matrices and modal damping ratio the solution of the governing equations of motion can be obtained.

However, although the damping matrix can be handily represented by a linear combination of mass and stiffness matrices, the modal damping ratio ζ_i is still unknown for each mode shape due to lack of data. Besides, the linearized damping effects are idealized conditions. Therefore, modal damping ratios will be chosen as from 0% to 20% in the study. 0% damping physically means there is no damping at all, and the system doesn't lose any energy during berthing. 20% damping is a considerable energy loss during berthing. According to the calculation by Schellin and Ostergaard (1993) based on hydrodynamic simulation, linear wave theory and potential flow theory, the damping

ratio accounting for hydrodynamic effects for fixed mooring systems could be chosen as 1-2%, which is quite small. In a dynamic analysis for ferry berthing report by William. N. Seelig. P.E. and Gerritt Lang, E.I.T. (2010), the hydrodynamic damping effects simulated with numerical analysis also turned out to be very little, given deep water condition.

Added Mass Effects

The added mass effects were introduced in the first chapter of this study. The mass components in the berthing system are the vessel and the float. When they are moving in the water, some water will be entrained with the components. However, unlike the vessel, which moves some of the water as it approaches with a considerable velocity, the float under investigation does not move until the vessel has impacted the float. In addition, the movement of the float is very small, and the amount of water that will be entrained by the float is almost negligible. Therefore, the added mass of the float will be ignored in the governing equations of motion. The added mass of the vessel can be numerically represented by the added mass coefficient C_m , which will be chosen as 1.1 (William. N. Seelig. P.E. and Gerritt Lang, E.I.T. 2010) in this study.

Solution of the Governing Equations of Motion

The solution of the equations of motion for the berthing system can be found by modal analysis as introduced above. The Fig. 3.14 and Fig. 3.15 are responses of the piling system in the time domain for a berthing system with a vessel weight of 800long tons, a float weight of 1000long tons, a fender stiffness of 5kips/in, a piling system stiffness of 10kips/in and 5% damping for all the mode shapes (the system has two mode

shapes since it has two DOFs). The mechanism of the whole berthing process works as such: assume the vessel and the float are uncoupled before the vessel has impacted the float. As soon as the vessel makes contact with the float, the system is assumed to become a coupled dynamic system with two mass components: the vessel and the float. Therefore, the initial condition will be: the displacements for both the vessel and the float are zero, the velocity of the vessel is 1 ft/s, and the velocity of the float is zero.

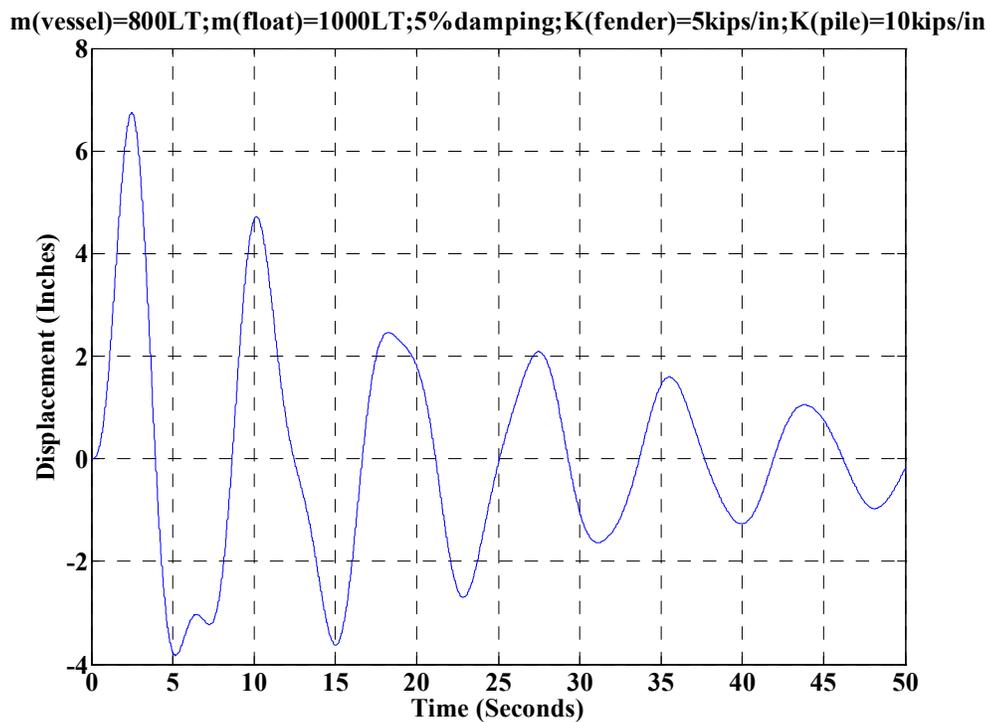


Fig. 3.14 Displacement of the Piling System in Time Domain

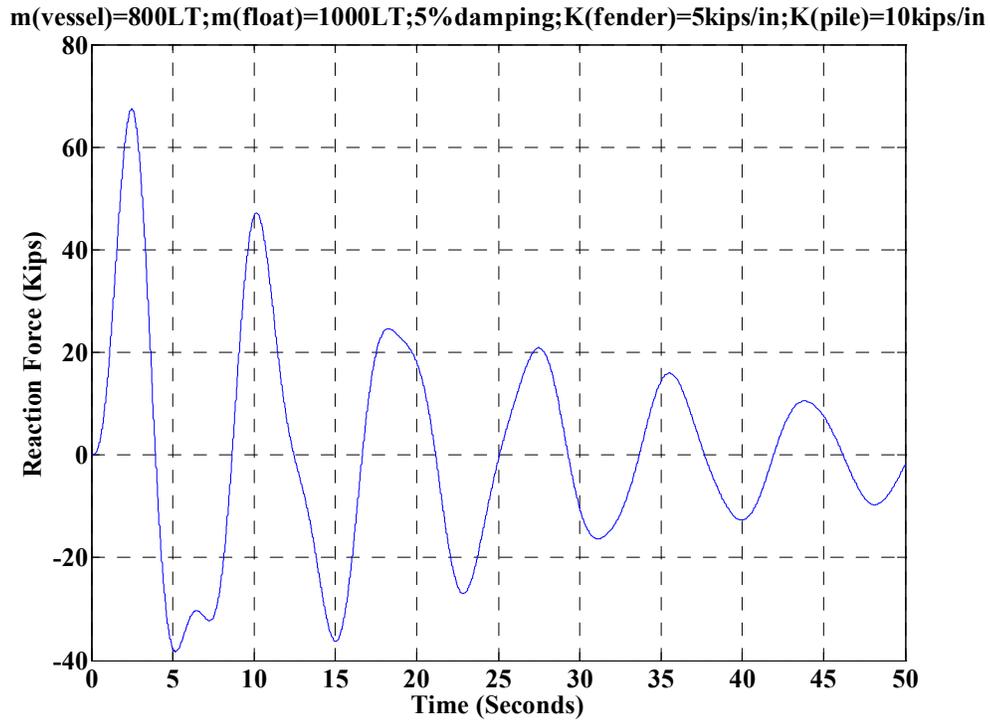


Fig. 3.15 Reaction Forces of the Piling System in Time Domain

The responses of the piling system shown above are the responses of the dynamic model representing the berthing system. However, since after the vessel impacts the float, the vessel will separate from the float; therefore, the vessel and the float are coupled for only half of the first cycle. Only the peak load and displacement will be encountered in the real berthing scenario, all the responses after the first half cycle have no physical meaning. The peak displacement and load are marked in Fig. 3.16 and Fig. 3.17, respectively.

$m(\text{vessel})=800\text{LT}; m(\text{float})=1000\text{LT}; 5\% \text{damping}; K(\text{fender})=5\text{kips/in}; K(\text{pile})=10\text{kips/in}$

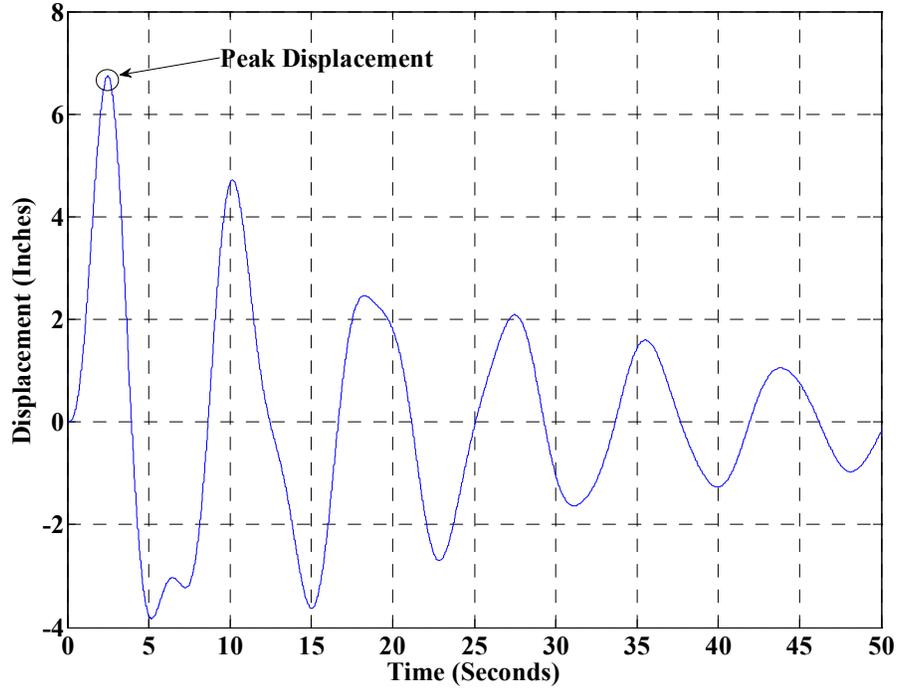


Fig. 3.16 Displacement of the Piling System

$m(\text{vessel})=800\text{LT}; m(\text{float})=1000\text{LT}; 5\% \text{damping}; K(\text{fender})=5\text{kips/in}; K(\text{pile})=10\text{kips/in}$

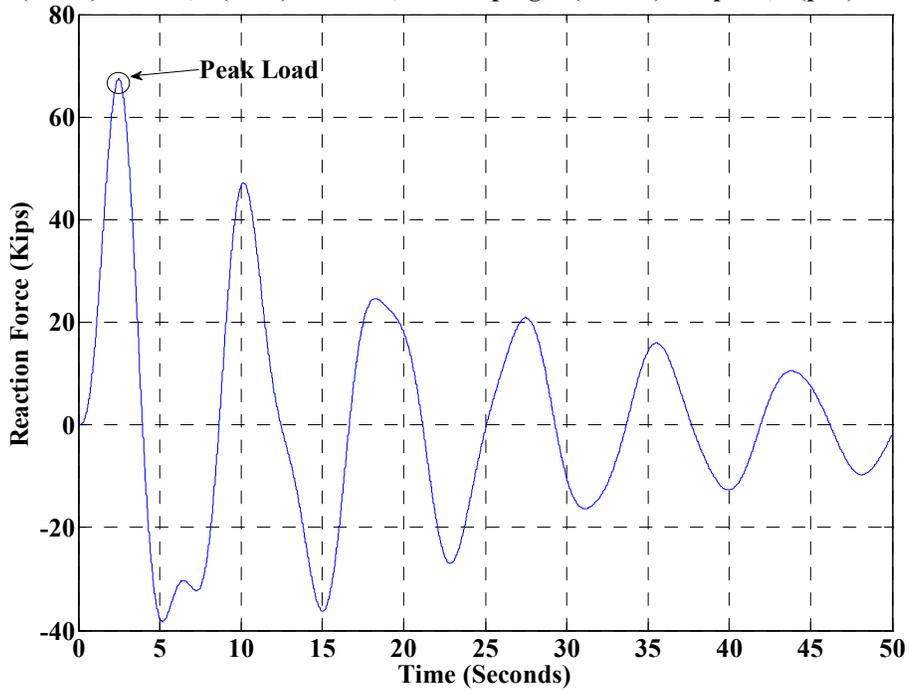


Fig. 3.17 Reaction Forces of the Piling System

In the results section of the chapter, peak responses will be calculated with different parameters, such as different masses of the vessel and the float, and different stiffness of the fender and the piling system. Peak responses will be plotted with varying parameters and will be graphically shown in figures.

Results for One Dimensional Analysis

The solutions of the governing equations of motion for the berthing system with proportional damping in one dimension are obtained by modal analysis. The solutions are the transient displacements of the float, which will cause the piling system to move with it. The responses of the piling system are the displacements and reaction forces of the piling system.

The responses of the piling system in one dimensional analysis are numerically calculated given the mass of the vessel and the float, the stiffness of the fender and the stiffness of the piling system fixed on the float. The float is scaled up or down according to the original float, which is chosen as 60ft by 60ft by 10ft with 8ft draft floating on sea water. In the analysis, the ratio of the mass of the vessel to the float is chosen from 0.1 to 100. The mass of the vessel is chosen as a specific value, from 800LT to 10,000LT, for a certain mass ratio. The stiffness of the fender is chosen as 10kips/in; the stiffness of a single pile ranges from 10kips/in to 1000kips/in. Therefore the stiffness of the piling system that consists of three piles ranges from 30kips/in to 3000kips/in. In the diagrams given below, the x-axis is chosen as the stiffness of each single pile of the piling system and the responses on the y-axis are for the single piles as well. The damping ratios are

chosen from 2% to 20% of critical damping. In comparison with the KEM, the corresponding responses calculated by the KEM will be shown on the plots as well. Some of the response diagrams of one dimensional analysis will be provided below. The more detailed results will be provided in the reference section of the study.

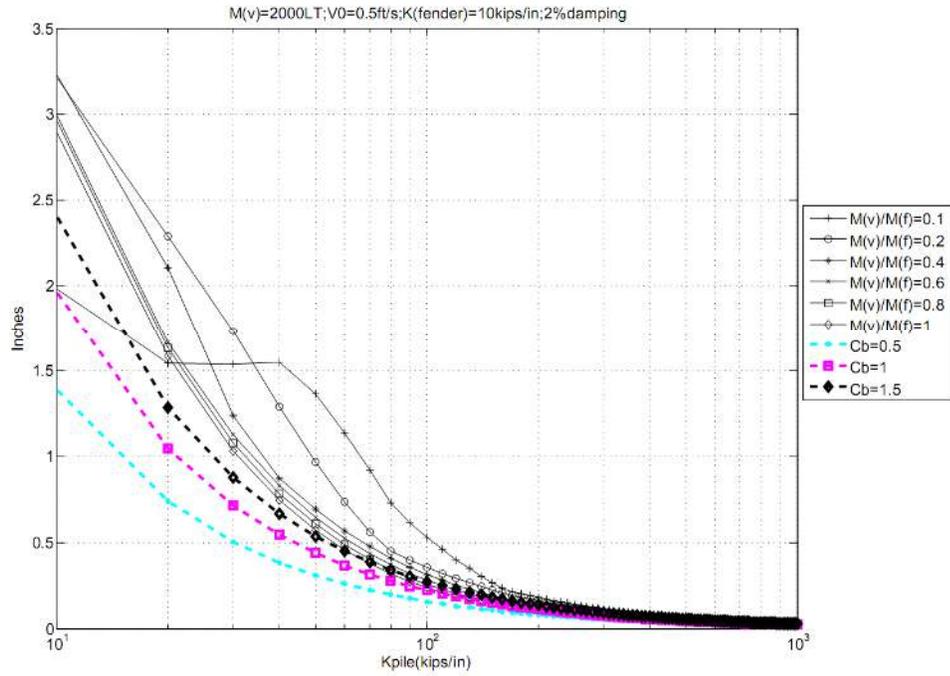


Fig. 3.18 Displacement of the Piling System 1D-a1

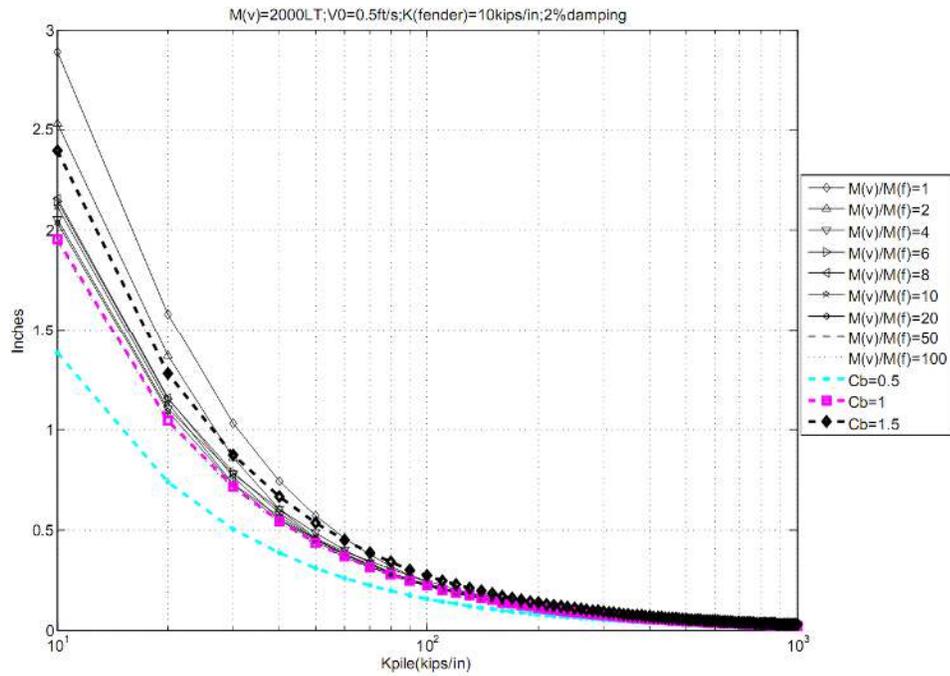


Fig. 3.19 Displacement of the Piling System 1D-a2

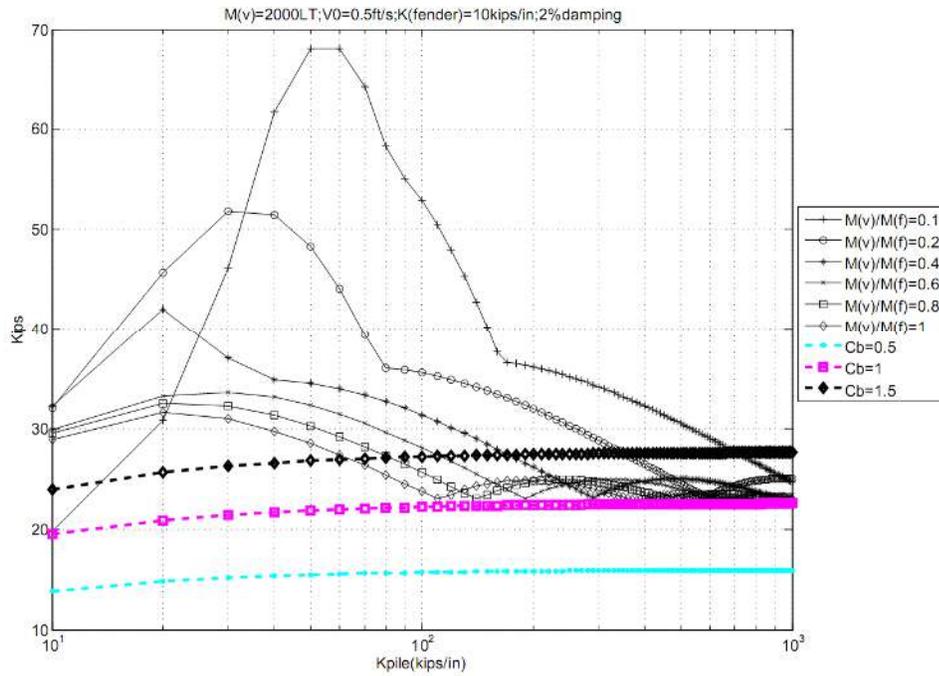


Fig. 3.20 Reaction Force of the Piling System 1D-a1

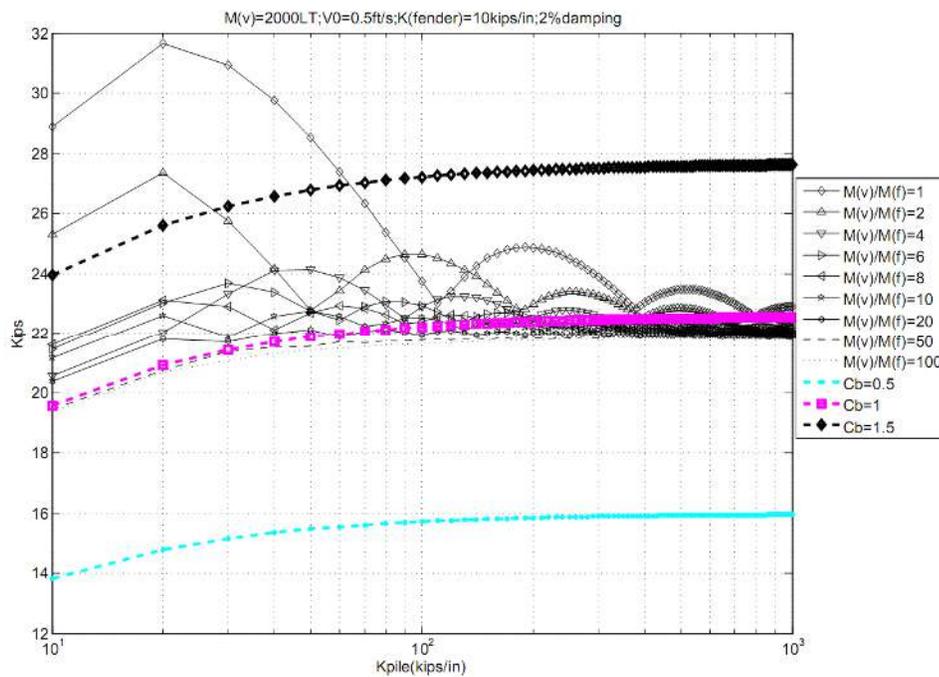


Fig. 3.21 Reaction Force of the Piling System 1D-a2

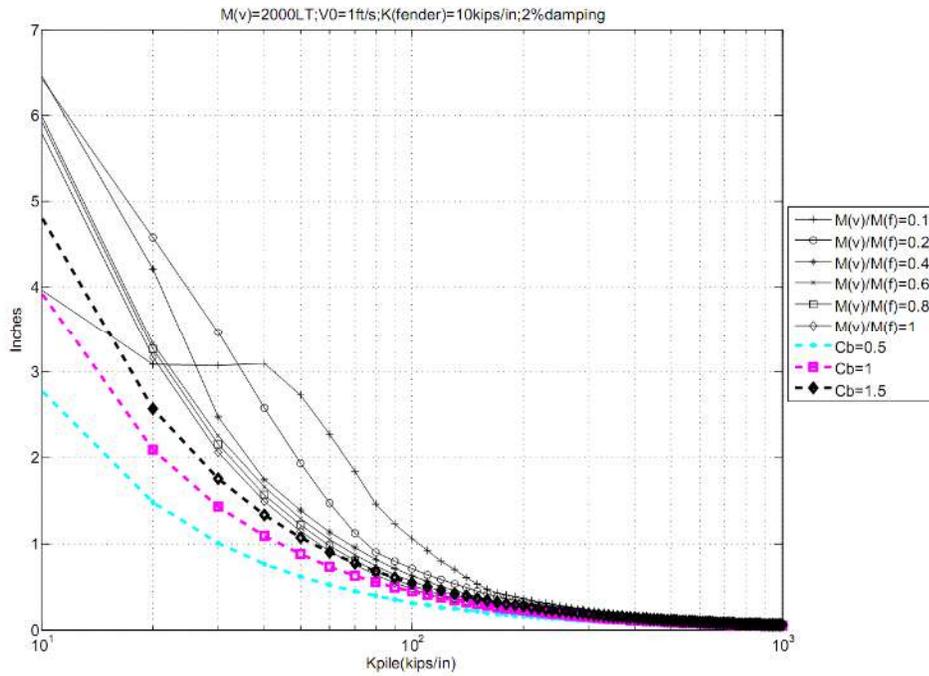


Fig. 3.22 Displacement of the Piling System 1D-b1

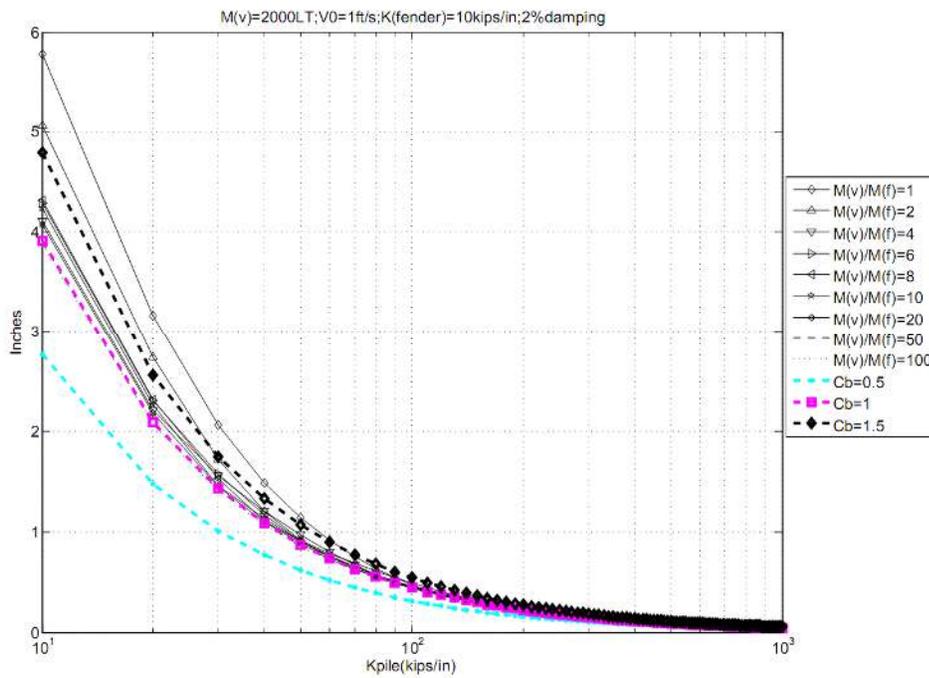


Fig. 3.23 Displacement of the Piling System 1D-b2

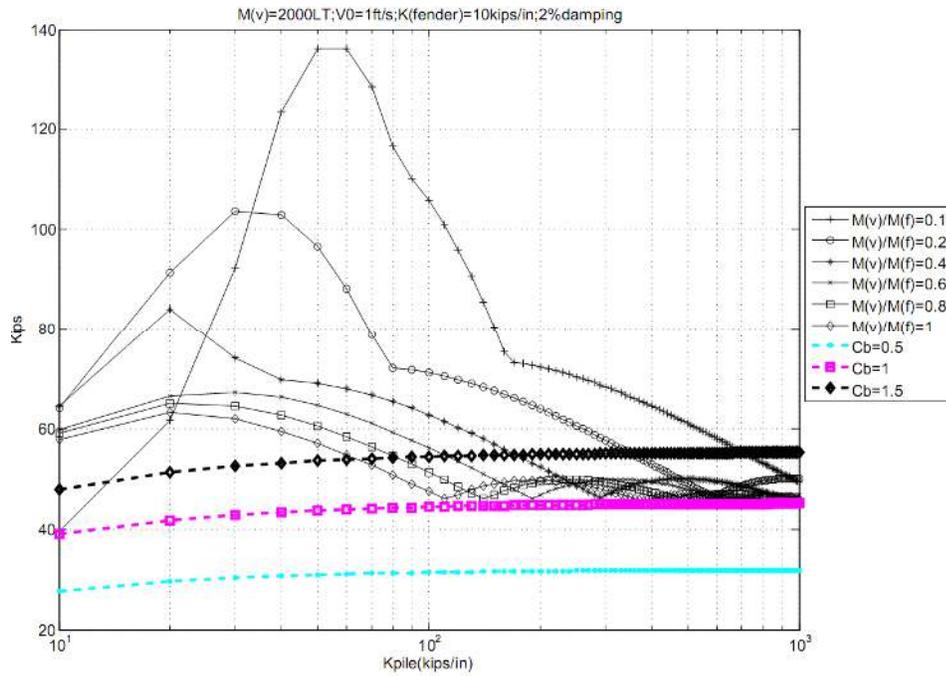


Fig. 3.24 Reaction Force of the Piling System 1D-b1

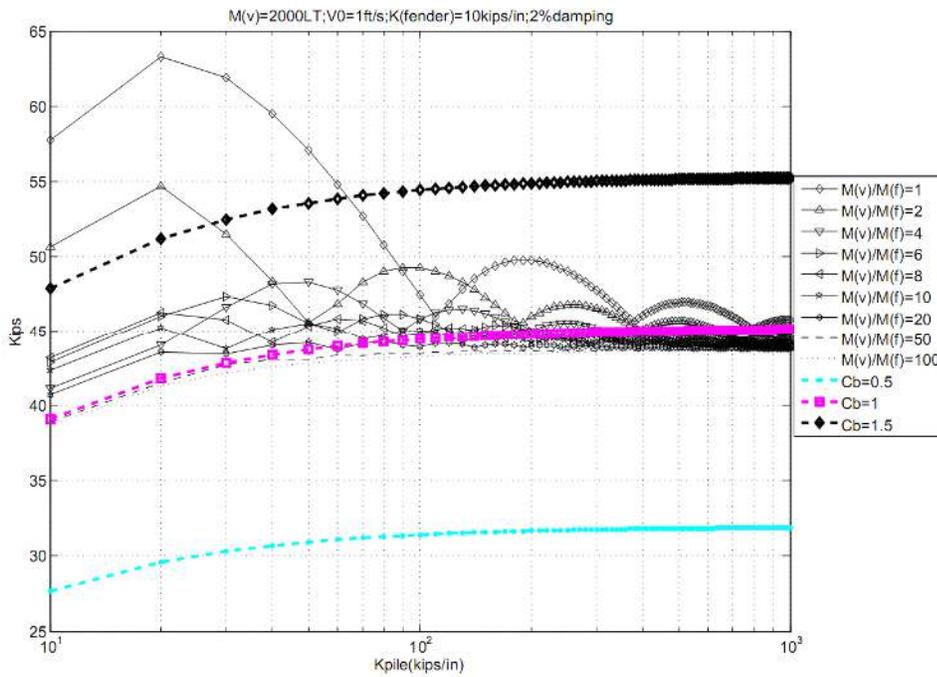


Fig. 3.25 Reaction Force of the Piling System 1D-b2

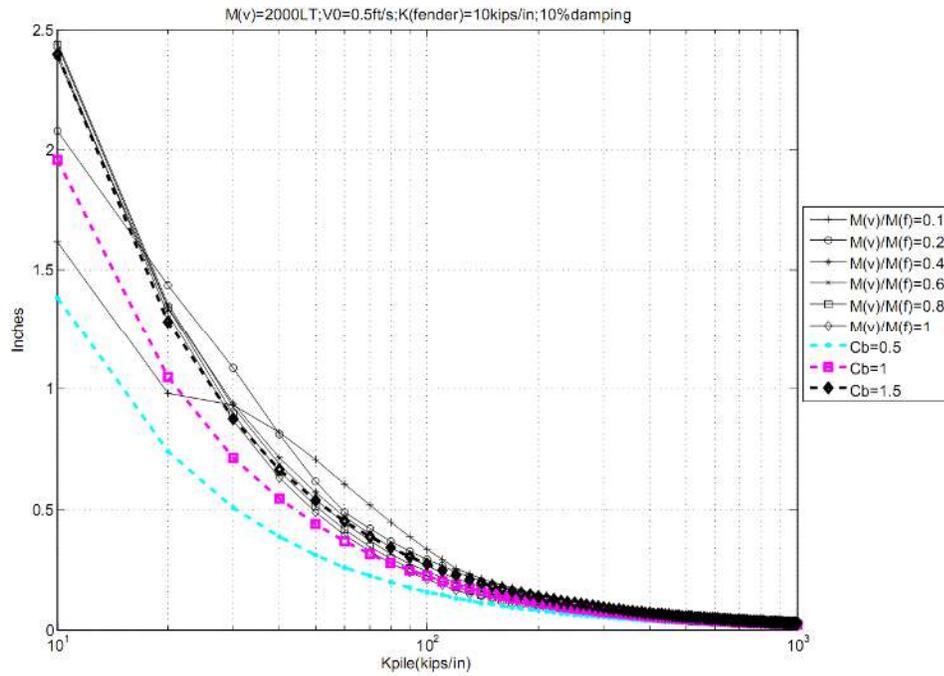


Fig. 3.26 Displacement of the Piling System 1D-c1

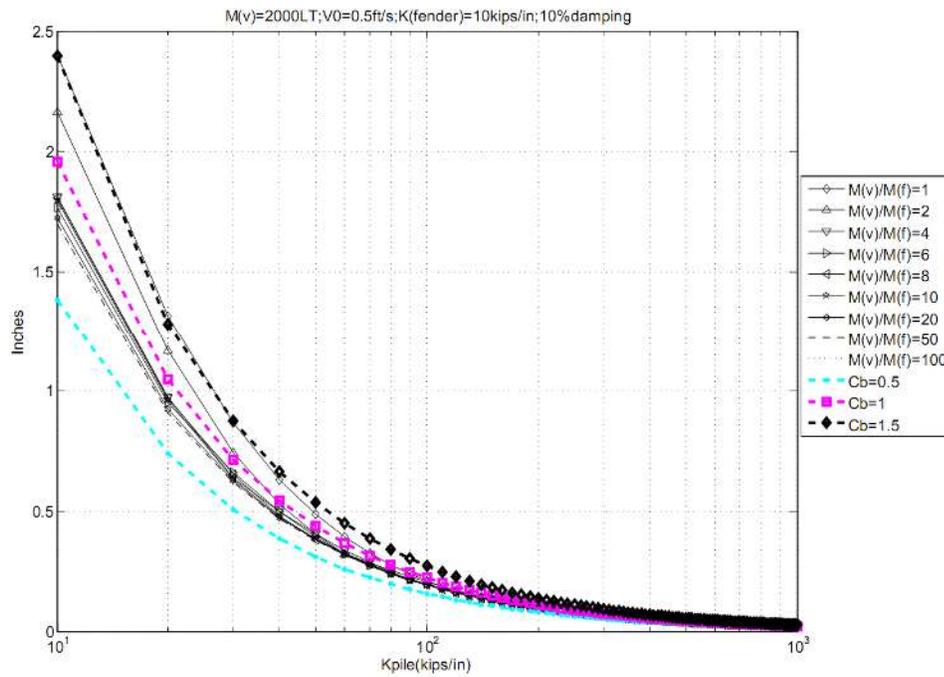


Fig. 3.27 Displacement of the Piling System 1D-c2

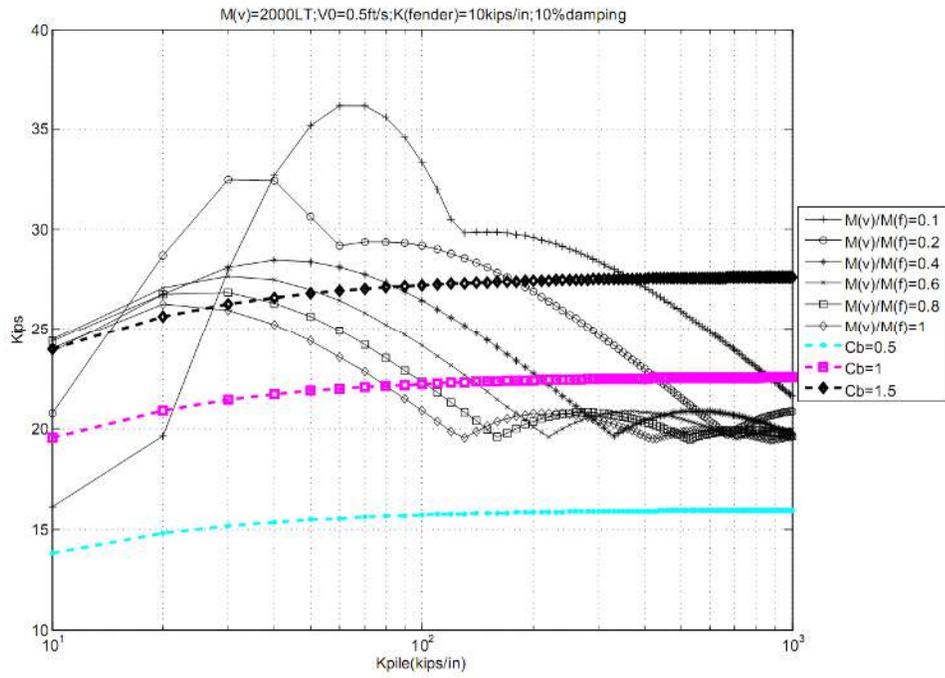


Fig. 3.28 Reaction Force of the Piling System 1D-c1

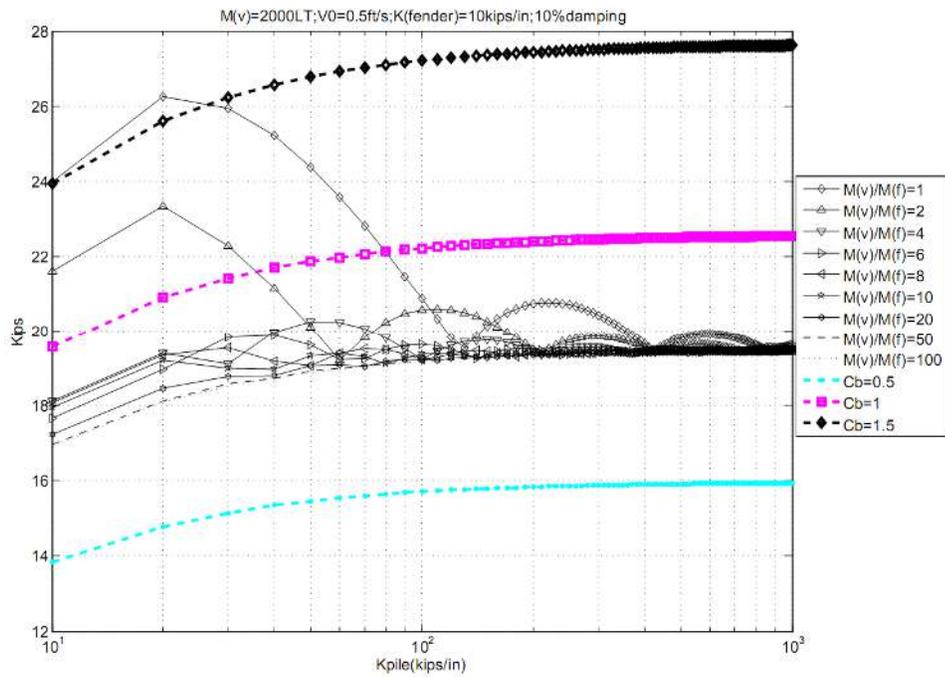


Fig. 3.29 Reaction Force of the Piling System 1D-c2

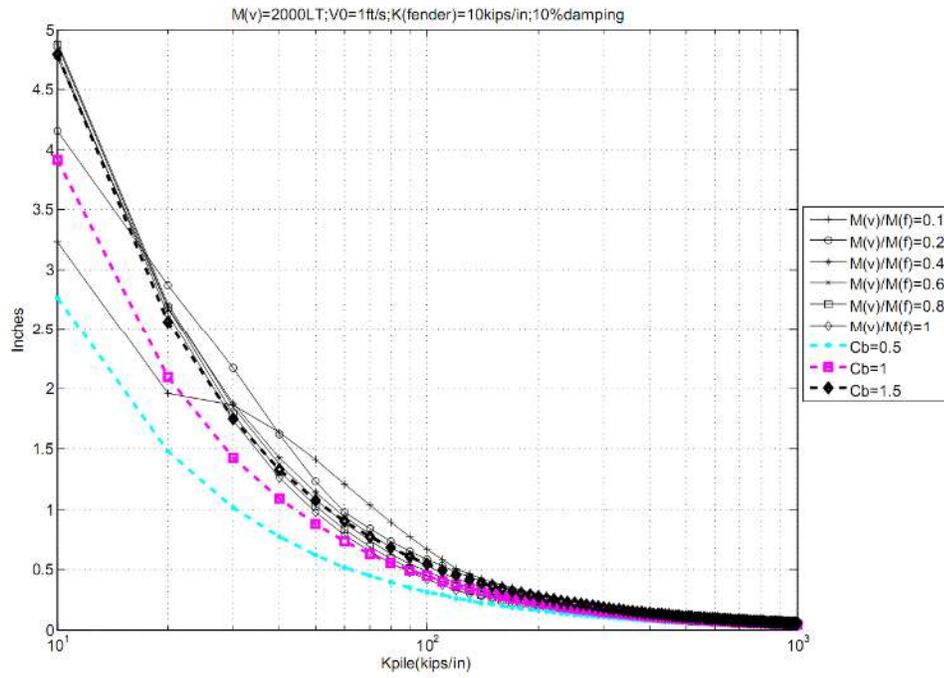


Fig. 3.30 Displacement of the Piling System 1D-d1

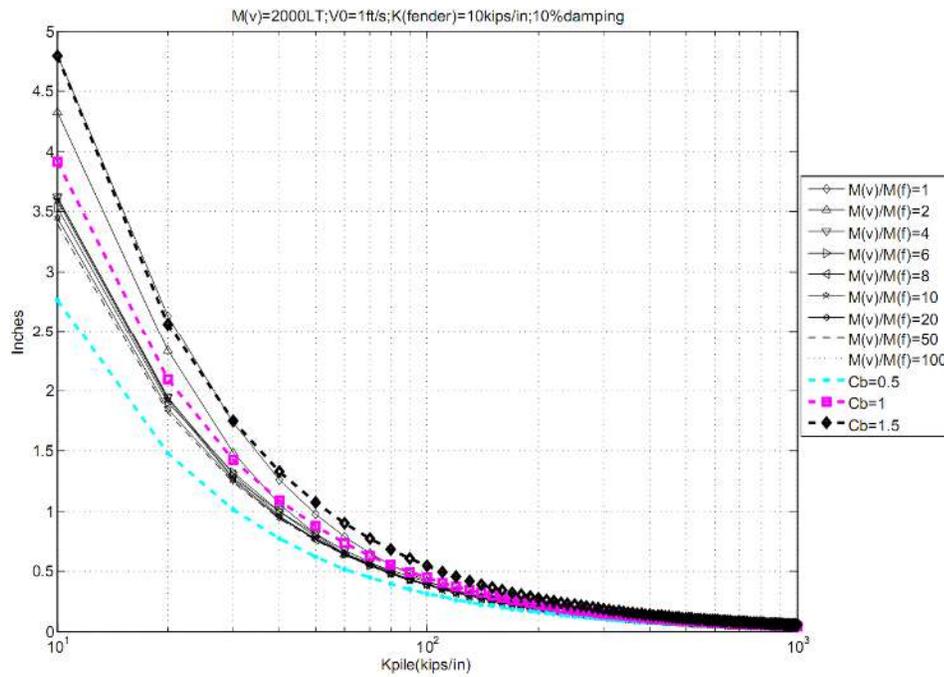


Fig. 3.31 Displacement of the Piling System 1D-d2

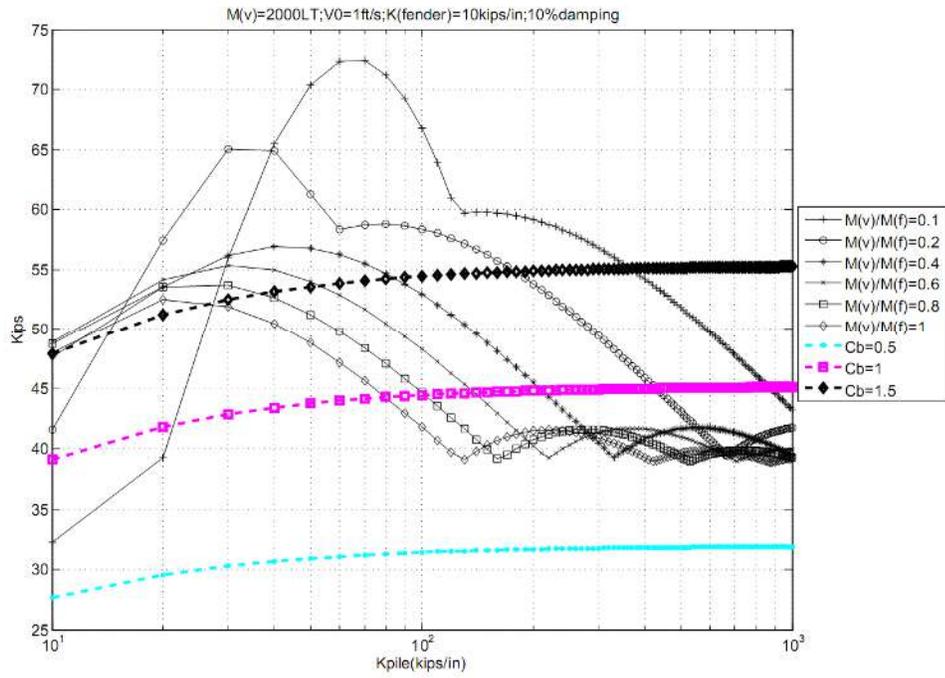


Fig. 3.32 Reaction Force of the Piling System 1D-d1

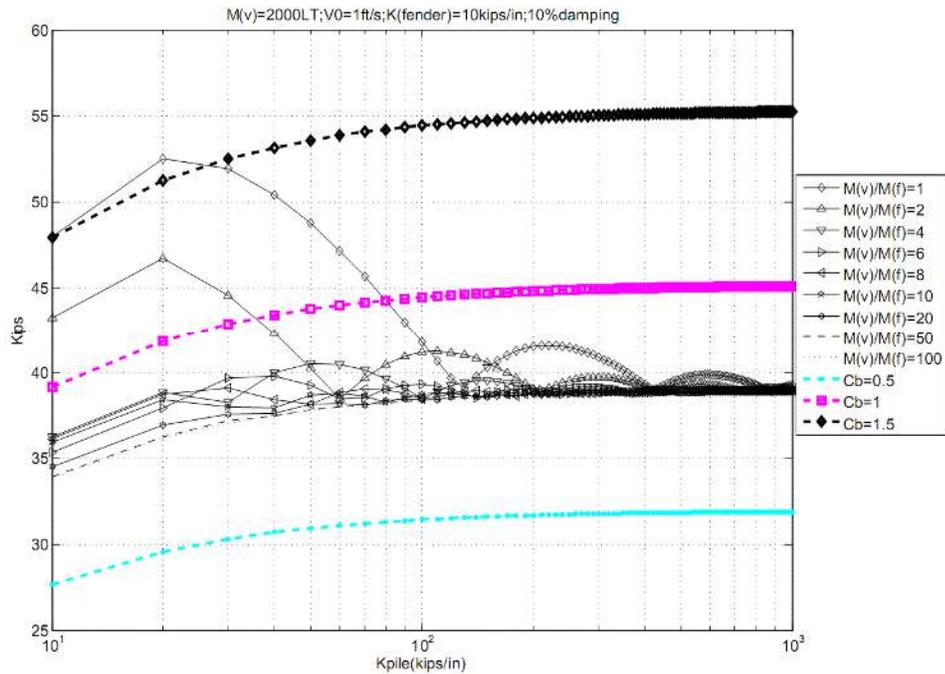


Fig. 3.33 Reaction Force of the Piling System 1D-d2

3.2.2 Two Dimensional Analysis

In this section, the system will be investigated in two dimensions, i.e. the translational responses of the system will be considered in surge and sway directions, and the system will still be treated as a MDF system. Torsional responses will also be investigated later in this section. This will include response in the yaw direction.

The system for two dimensional analysis will have 4 DOFs in the study. This includes one degree of freedom for the approaching vessel in the surge direction, because the fenders only provide support in the surge direction. The float will have three degree of freedom. Two of them are for translational responses, i.e. the surge and sway directions. The last one is for rotational responses, which is the yaw direction. The schematic of the 4 DOFs dynamic system is shown in Fig. 3.34.

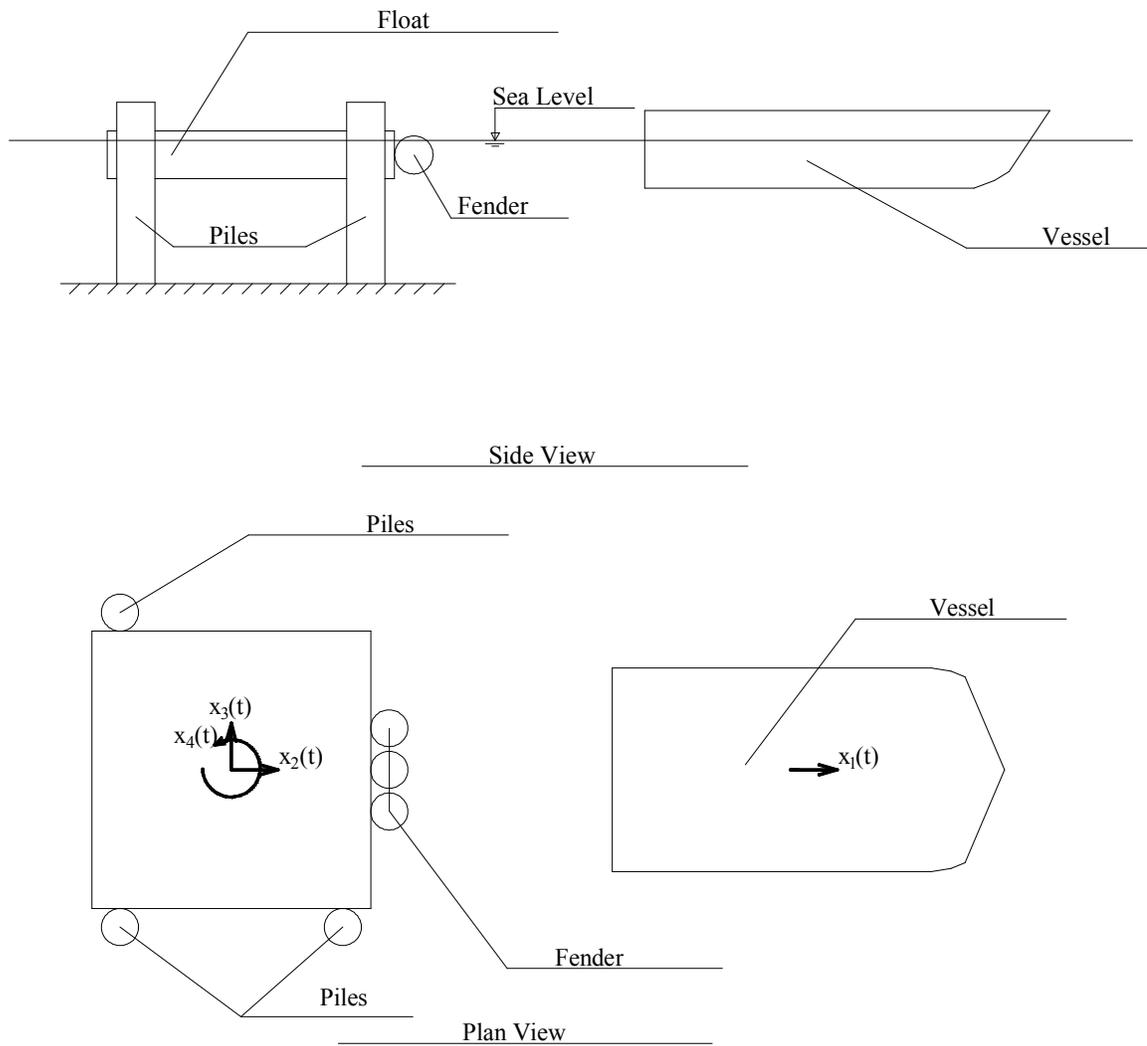


Fig. 3.34 Schematic of 4 DOFs System

The system may have eccentricity due to its inherent configuration, i.e. the *center of mass* (C.M) is not coincident with the *center of rigidity* (C.R). The concepts of both terms are given as following.

Center of Mass (C.M)

C.M is the weighted average location of all the mass in a system. For lumped mass components, C.M is treated as the concentrated mass point, usually for rigid bodies.

Center of Rigidity (C.R)

C.R is the stiffness centroid within a system. When C.R is subjected to lateral loading, the system will experience only translational displacement.

If C.M and C.R of a system are coincident, such as in Fig. 3.35, displacements in different directions are uncoupled, which will result in the simplicity of the dynamic analysis. On the other hand, if eccentricity exists in a system, i.e. C.M and C.R of the system are not coincident, then displacements will be coupled, that is to say, the excitation of one direction will not only cause responses in that direction, but also in other directions. That is quite different from a system that has coincident C.M and C.R. Therefore, it also complicates the dynamic analysis of the system.

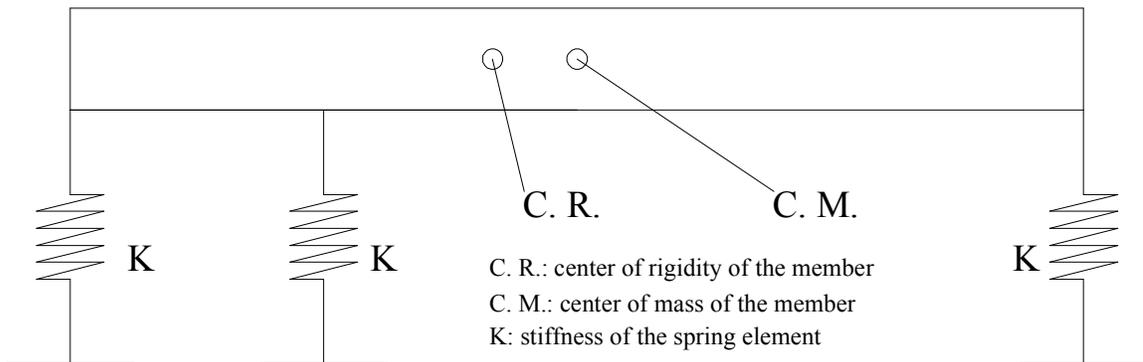


Fig. 3.35 System with Eccentricity

If C.M and C.R of a pile-guided float system are coincident, the system can be treated as a two DOFs system, and the schematic of the system is given in Fig. 3.1. The dynamic model of the two DOFs system for the pile-guided float is shown in Fig. 3.12.

Fig. 3.12 uses lumped mass components to represent the vessel and the float; both of them can translate only in horizontal direction that is the surge direction of the approaching vessel. The instant the vessel impacts the float, the vessel and the float are treated as two lumped mass components for one dynamic system, the dynamic system has two DOFs, and they are for the two lumped mass components in the surge direction of the incoming vessel.

If C.M and C.R of a pile-guided float system are not coincident, eccentricity will occur. The existence of eccentricity could be due to an unsymmetrical configuration of the float or an unsymmetrical arrangement of the piling system. In the study, the pile-guided float is chosen as a square barge. However, unlike the two DOFs system just discussed above, the arrangement of the piling system is unsymmetrical, with three piles fixed at each corner of the float except the one on the upper right. The schematic of the system is given in Fig. 3.36. Due to eccentricity, the dynamic system will have a coupling effect under dynamic responses. Therefore, the system has 4 DOFs, with only one for the vessel in the surge direction since there are no spring elements in other directions. The other three DOFs are all for the float, with one in surge, one in sway, and one in yaw direction; i.e. the float will undergo both translational and torsional displacements.

The schematic of the berthing system in two dimensions is presented in Fig. 3.34. The system has 4 DOFs with one for the vessel in the surge direction, and three for the float: one in the surge direction, one in the sway direction and one in the yaw direction. In the study, the berthing system under investigation will have inherent eccentricity due

model in one dimension, which only has two DOFs. The increased number of DOFs makes it easier to analyze the berthing system by the influence coefficients method.

Stiffness Influence Coefficients

For a linear spring, the force necessary to cause a unit elongation is called the stiffness of the spring. In more complex systems, the relation between the displacement at a point and the forces acting at various other points of the system can be expressed by means of stiffness influence coefficients (Singiresu S. Rao 2004). The stiffness influence coefficient, denoted as k_{ij} , is defined as the force at point i due to a unit displacement at point j when all the points other than the point j are fixed. Using this definition for the spring-mass system shown in Fig. 3.38, the total force at point i , F_i , can be found by summing up the forces due to all displacements x_j ($j = 1, 2, \dots, n$) as:

$$F_i = \sum_{j=1}^n k_{ij} x_j, \quad i = 1, 2, \dots, n \quad (3-53)$$

Equation (3-49) can be stated in matrix form as:

$$\mathbf{F} = [\mathbf{k}]\mathbf{x} \quad (3-54)$$

where \mathbf{x} and \mathbf{F} are the displacement and force vectors, and $[\mathbf{k}]$ is the stiffness matrix given by:

$$[k] = \begin{bmatrix} k_{11} & k_{12} & \cdots & k_{1n} \\ k_{21} & k_{22} & \cdots & k_{2n} \\ \vdots & & & \\ k_{n1} & k_{n2} & \cdots & k_{nn} \end{bmatrix} \quad (3-55)$$

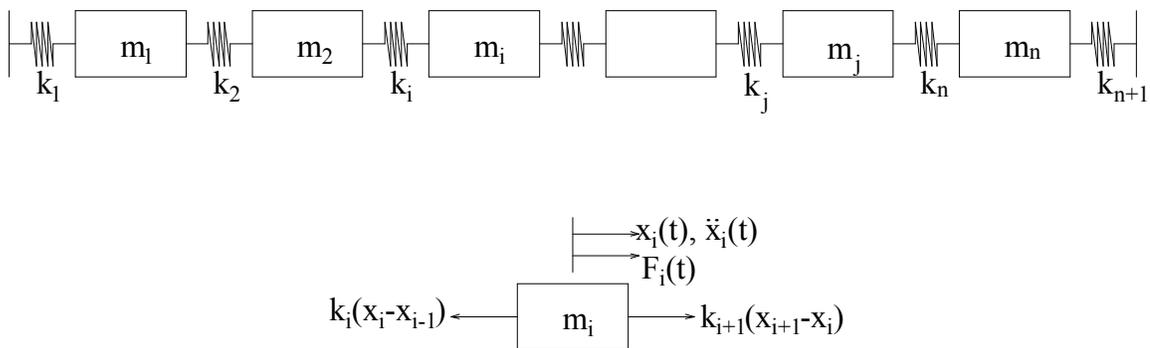


Fig. 3.38 MDF System

The stiffness influence coefficients can be calculated by applying the principles of statics and solid mechanics; stiffness matrix is symmetrical, which means, $k_{ij} = k_{ji}$.

Inertia Influence Coefficients

The elements of the mass matrix, m_{ij} , are known as the inertia influence coefficients. The coefficients can be computed using the impulse-momentum relations. The inertia influence coefficients $m_{1j}, m_{2j}, \dots, m_{nj}$ are defined as the set of impulses applied at points 1, 2, \dots , n, respectively, to produce a unit velocity at point j and zero velocity at every other point (Singiresu S. Rao 2004). Thus, for a MDF system, the total

impulse at point i , F_i , can be found by summing up the impulses causing the velocities \dot{x}_j ($j = 1, 2, \dots, n$) as:

$$F_i = \sum_{j=1}^n m_{ij} \dot{x}_j \quad (3-56)$$

Eq. (3-56) can be stated in matrix form as:

$$\mathbf{F} = [\mathbf{m}] \dot{\mathbf{x}} \quad (3-57)$$

And $[\mathbf{m}]$ is the mass matrix given by:

$$[\mathbf{m}] = \begin{bmatrix} m_{11} & m_{11} & \cdots & m_{11} \\ m_{11} & m_{11} & \cdots & m_{11} \\ \vdots & \vdots & \cdots & \vdots \\ m_{11} & m_{11} & \cdots & m_{11} \end{bmatrix} \quad (3-58)$$

It can be verified easily that the inertia influence coefficients are symmetrical for a linear system, that is, $m_{ij} = m_{ji}$.

Derivation of Stiffness Influence Coefficients

The stiffness influence coefficients, k_{ij} , is the force at point i due to a unit displacement at point j when all the other points are fixed. The force k_{ij} can be found by static equilibrium. Therefore, given the dynamic model of the four degree of freedom system in Fig. 3.36, let x_1 denote the displacement of the vessel in surge direction, x_2 , x_3 denote the displacements of the float in the surge and sway directions, and θ denote the

displacement of the float in the yaw direction. The schematic of the derivation is shown in Fig. 3.39 (a), (b), (c) and (d).

In Fig. 3.39 (a), x_1 is set to be one ($x_1 = 1$) and all the other three displacements are zero ($x_2 = x_3 = \theta$), the forces k_{i1} ($i = 1, 2, 3, 4$) are assumed to maintain the system in this configuration. Therefore, according to the principle of static equilibrium, the total forces and moments acting on the system must cancel each other. The relations can be expressed as follows:

$$\begin{aligned}\sum F_x &= 0; \\ \sum F_y &= 0; \\ \sum M &= 0\end{aligned}\tag{3-59}$$

Therefore, after solving the simultaneous static equilibrium equations, the stiffness influence coefficients can be expressed as:

$$\begin{aligned}k_{11} &= k_{fender}; \\ k_{21} &= -k_{fender}; \\ k_{31} &= 0; \\ k_{41} &= 0\end{aligned}\tag{3-60}$$

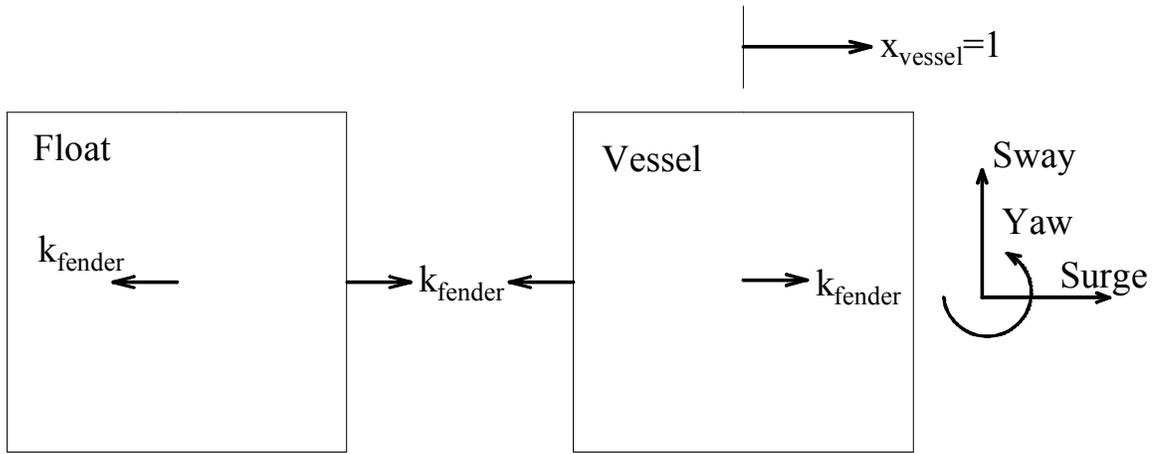
The same procedure is applied to x_2 , x_3 , and θ ; the stiffness influence coefficients are expressed as:

$$\begin{aligned}
k_{12} &= k_{fender}; \\
k_{22} &= k_{fender} + 3k_{pile}; \\
k_{32} &= 0; \\
k_{42} &= -\frac{k_{pile}l}{2}
\end{aligned} \tag{3-61}$$

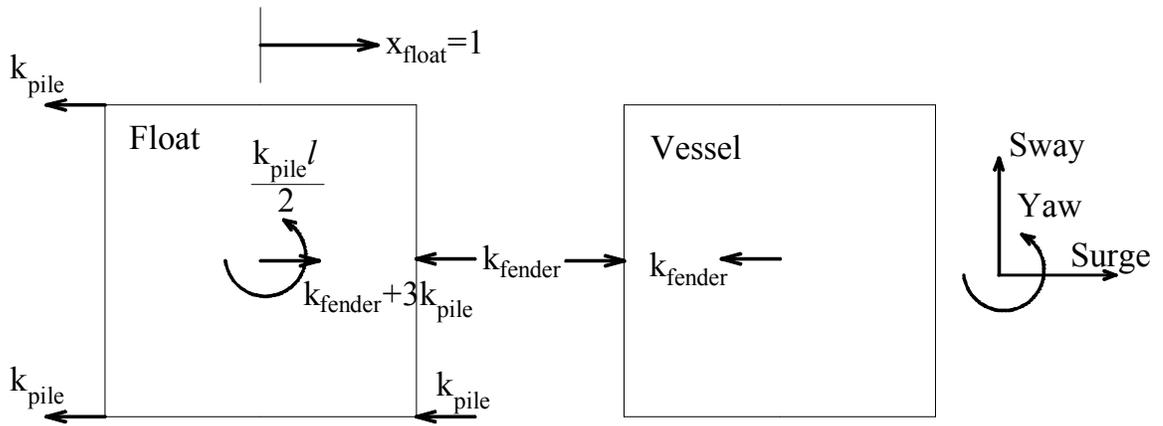
$$\begin{aligned}
k_{13} &= 0; \\
k_{23} &= 0; \\
k_{33} &= 3k_{pile}; \\
k_{43} &= -\frac{k_{pile}l}{2}
\end{aligned} \tag{3-62}$$

$$\begin{aligned}
k_{14} &= 0; \\
k_{24} &= \frac{k_{pile}l}{2}; \\
k_{34} &= -\frac{k_{pile}l}{2}; \\
k_{44} &= \frac{3}{2}k_{pile}l^2
\end{aligned} \tag{3-63}$$

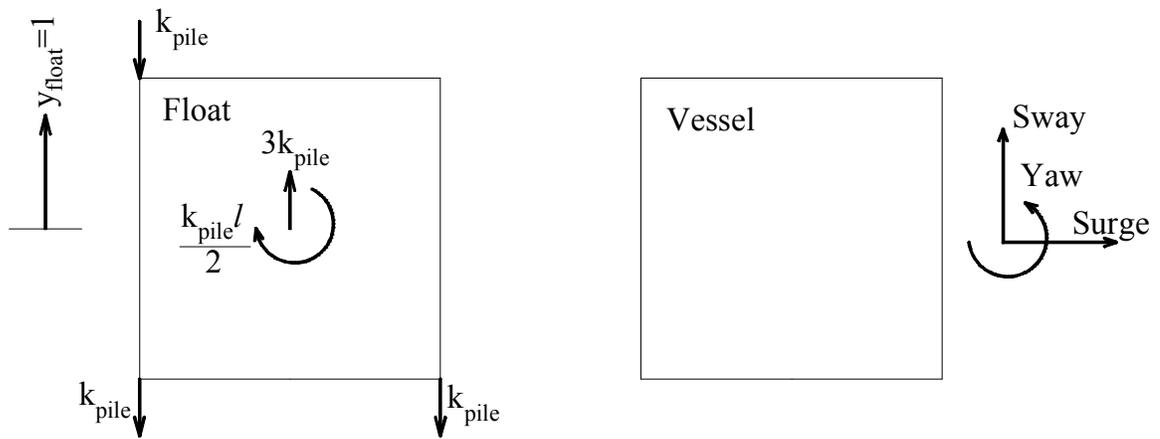
Where k_{fender} is the stiffness of the fender, k_{pile} is the stiffness of the piling system and l is the width of the float.



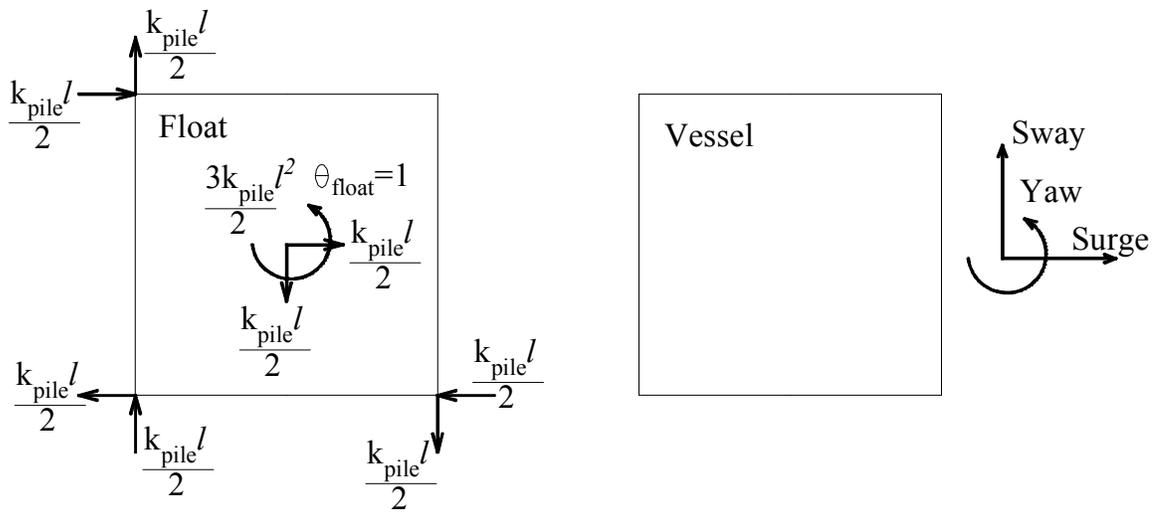
(a)



(b)



(c)



(d)

Fig. 3.39 Derivation of Stiffness Influence Coefficients

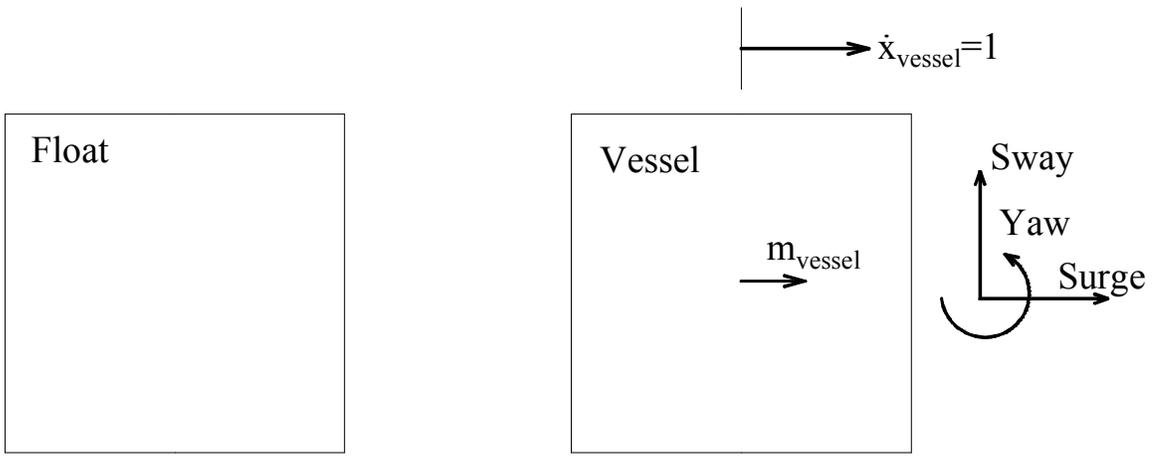
The stiffness influence coefficients can be written in matrix form as:

$$[k] = \begin{bmatrix} k_{fender} & -k_{fender} & 0 & 0 \\ -k_{fender} & k_{fender} + 3k_{pile} & 0 & \frac{k_{pile}l}{2} \\ 0 & 0 & 3k_{pile} & -\frac{k_{pile}l}{2} \\ 0 & \frac{k_{pile}l}{2} & -\frac{k_{pile}l}{2} & \frac{3}{2}k_{pile}l^2 \end{bmatrix} \quad (3-64)$$

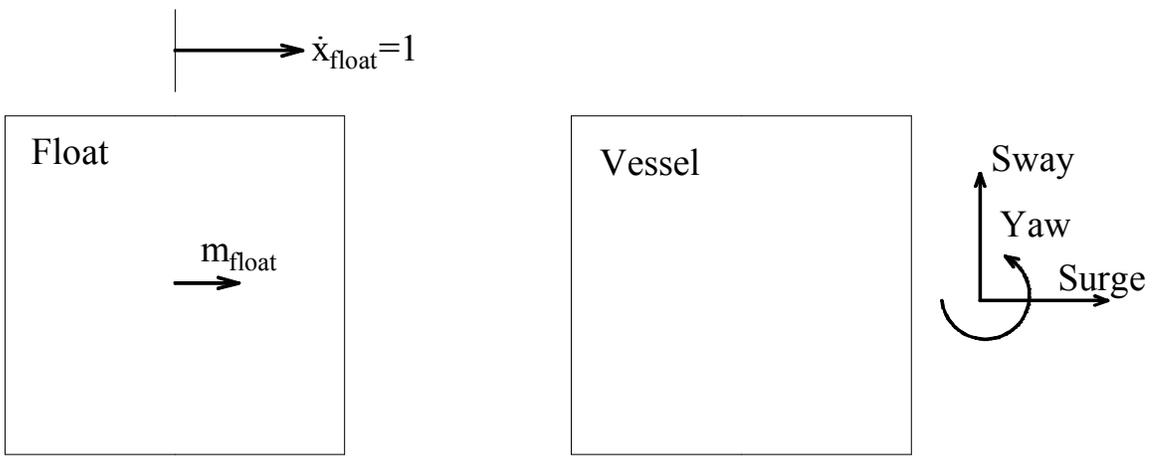
Derivation of Inertia Influence Coefficients

The elements of the mass matrix, m_{ij} , also known as the inertia influence coefficients are defined as the impulse applied at point j that causes an unit velocity at that point while all the other points have zero velocity due to impulses at other points. The derivation of inertia influence coefficients is given in Fig. 3.40 (a), (b), (c) and (d).

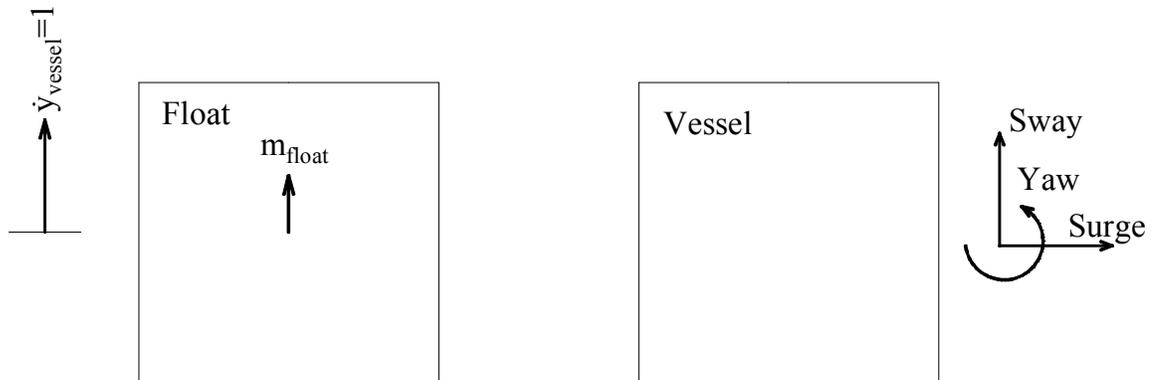
The inertia influence coefficient m_{44} is the moment of inertia of the float with respect to the centroid of the float and, with given mass and width of the float, can be expressed as $\frac{m_{float}(l^2 + l^2)}{2}$.



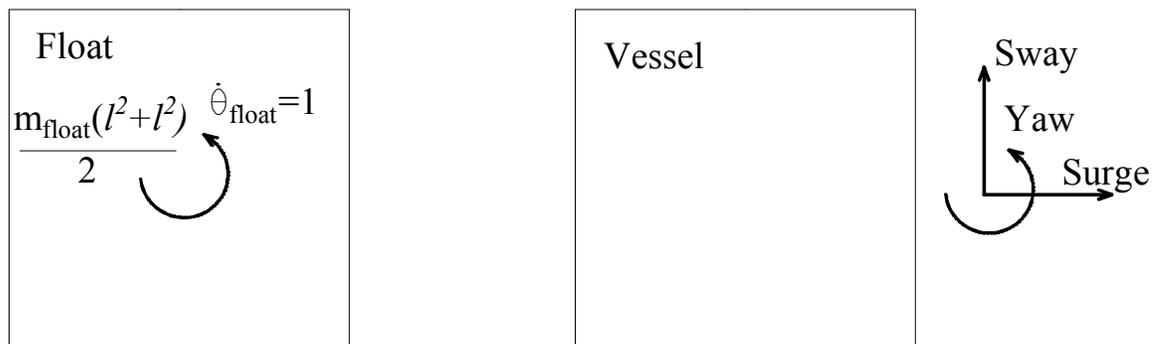
(a)



(b)



(c)



(d)

Fig. 3.40 Derivation of Inertia Influence Coefficients

The inertia influence coefficients can be expressed in matrix form as:

$$[m] = \begin{bmatrix} m_{vessel} & 0 & 0 & 0 \\ 0 & m_{float} & 0 & 0 \\ 0 & 0 & m_{float} & 0 \\ 0 & 0 & 0 & \frac{m_{float}(l^2 + l'^2)}{2} \end{bmatrix} \quad (3-65)$$

Governing Equations of Motion

After deriving the mass and stiffness matrices, the equations of motion for the berthing system without damping can be expressed as:

$$[m]\{\ddot{x}(t)\} + [k]\{x(t)\} = 0 \quad (3-66)$$

in which the mass matrix and stiffness matrix are given in the previous section, respectively. The damping effects can also be incorporated in the equations of motion by proportional damping. The equations of motion with proportional damping can be expressed as:

$$[m][X]\{\ddot{q}(t)\} + [a[m] + b[k]][X]\{\dot{q}(t)\} + [k][X]\{q(t)\} = \{0\} \quad (3-67)$$

The 4 DOFs system will have the same mechanism as the two DOFs system despite the eccentricity that exists between the C.M and C.R. However, since the analysis is in two dimensions, and eccentricity exists in the berthing system, the peak responses will be different in different piles. The schematic of the configuration of the piling system is given in Fig. 3.41. The piles are marked as pile1, pile2 and pile3. The peak responses of each pile will be calculated by using the superposition principle to combine the

responses from the surge, sway and yaw directions of the float. The demonstration is shown in Fig.3.42. The maximum responses among the three piles will be recorded as the peak responses. The maximum peak responses of the piling system will be plotted with different varying parameters, such as masses of the vessel and the float, stiffness of the fender and the piling system.

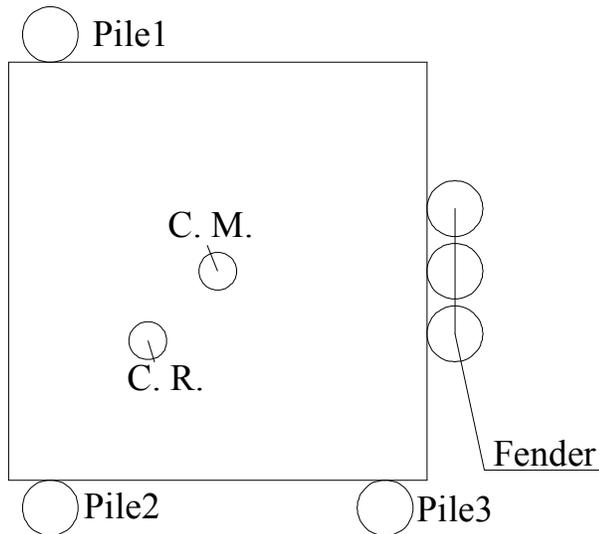


Fig. 3.41 Configuration of the Piling System Fixing the Float

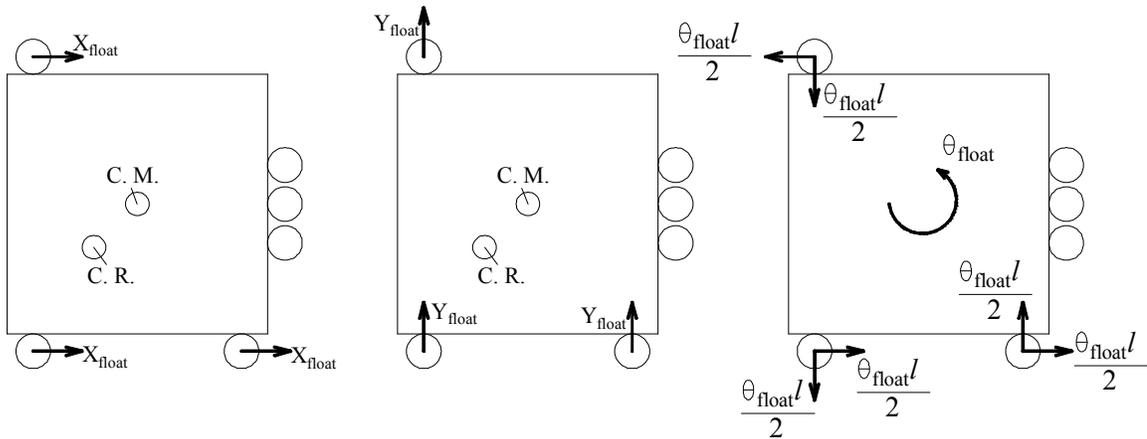


Fig. 3.42 Superposition of the Responses Combining all Directions

x_{float} = displacement of the float in surge direction

y_{float} = displacement of the float in sway direction

θ_{float} = displacement of the float in yaw direction

l = length of the float (same in both directions)

Results for Two Dimensional Analysis

The solutions of the governing equations of motion for the berthing system with proportional damping in two dimensions are obtained by modal analysis as well. In two dimensional analysis, the float is fixed by three different piles with eccentricity, therefore, only the maximum responses among the three piles will be chosen as the peak responses for the berthing system.

The responses of the piling system in two dimensional analysis are numerically calculated given the mass of the vessel and the float, the stiffness of the fender and the stiffness of the piling system fixed on the float. The float is scaled up or down according to the original float, which is chosen as 60ft by 60ft by 10ft with 8ft draft floating on sea water. In the analysis, the ratio of the mass of the vessel to the float is chosen from 0.1 to 100. The mass of the vessel is chosen as a specific value, from 800LT to 10,000LT, for a certain mass ratio. The stiffness of the fender is chosen as 10kips/in, the stiffness of a single pile ranges from 10kips/in to 1000kips/in, therefore the stiffness of the piling system that consists of three piles ranges from 30kips/in to 3000kips/in. In the diagrams given below, the x-axis is chosen as the stiffness of each single pile of the piling system, and the responses on the y-axis are chosen as the maximum responses among all three

piles. The damping ratios are chosen from 2% to 20% of critical damping. As it is for one dimensional analysis, part of the results for two dimensional analysis will be given in the following section. The more detailed results will be given in the reference section.

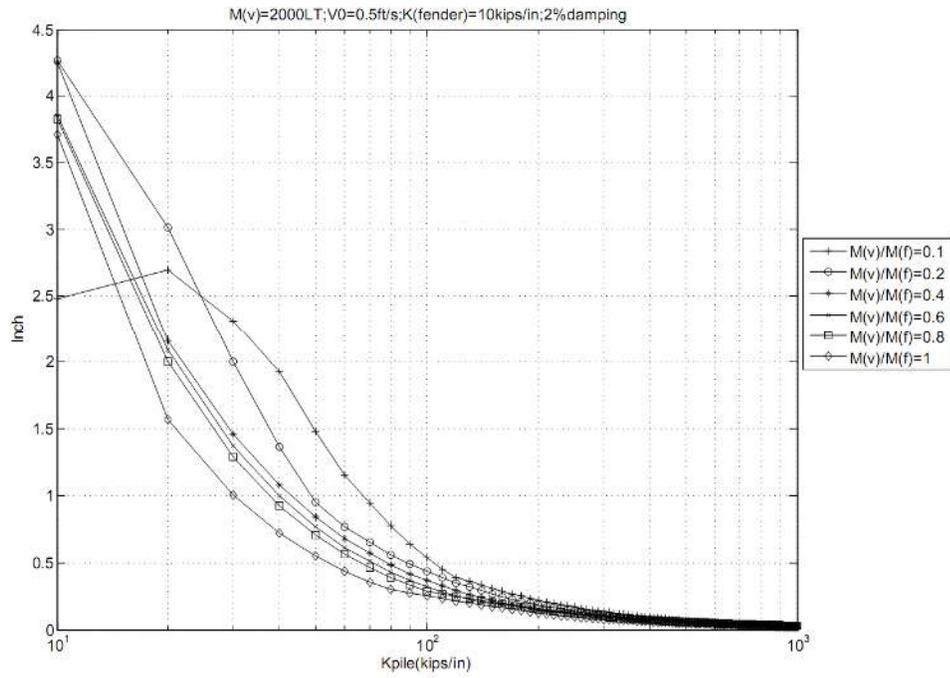


Fig. 3.43 Displacement of the Piling System 2D-a1

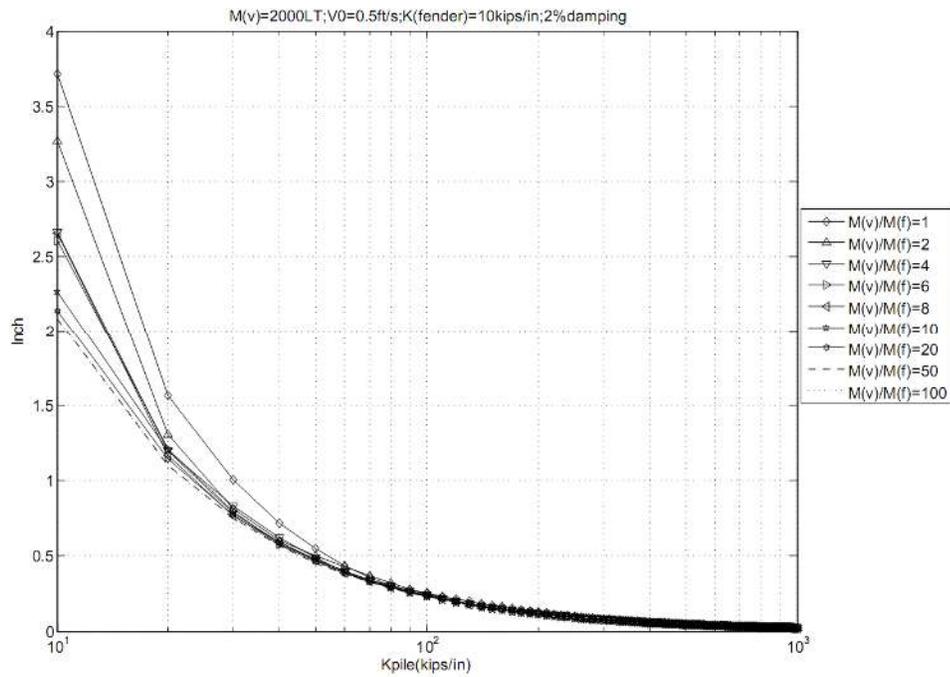


Fig. 3.44 Displacement of the Piling System 2D-a2

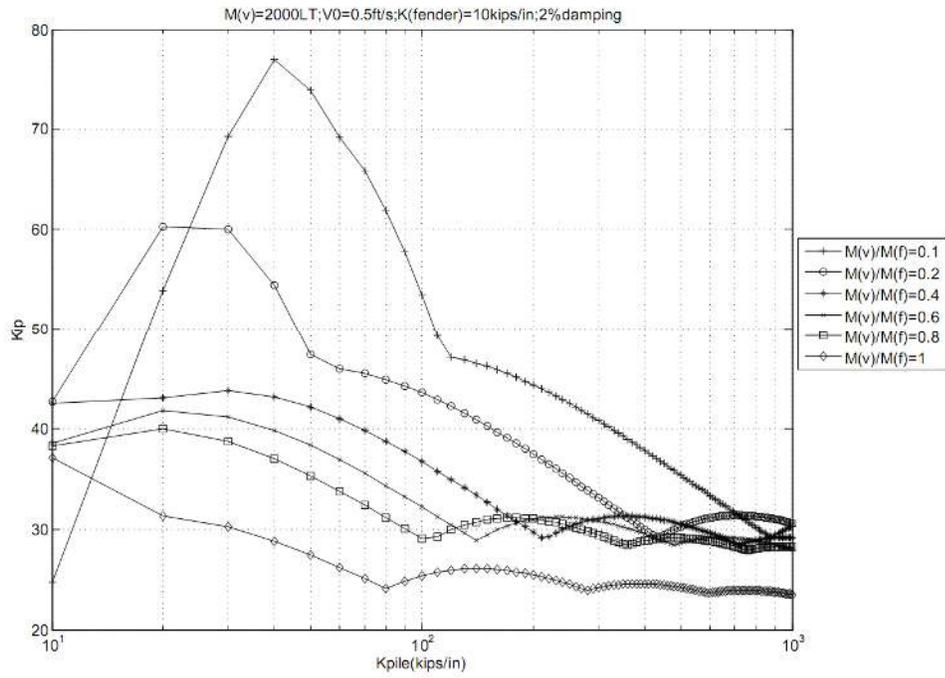


Fig. 3.45 Reaction Force of the Piling System 2D-a1

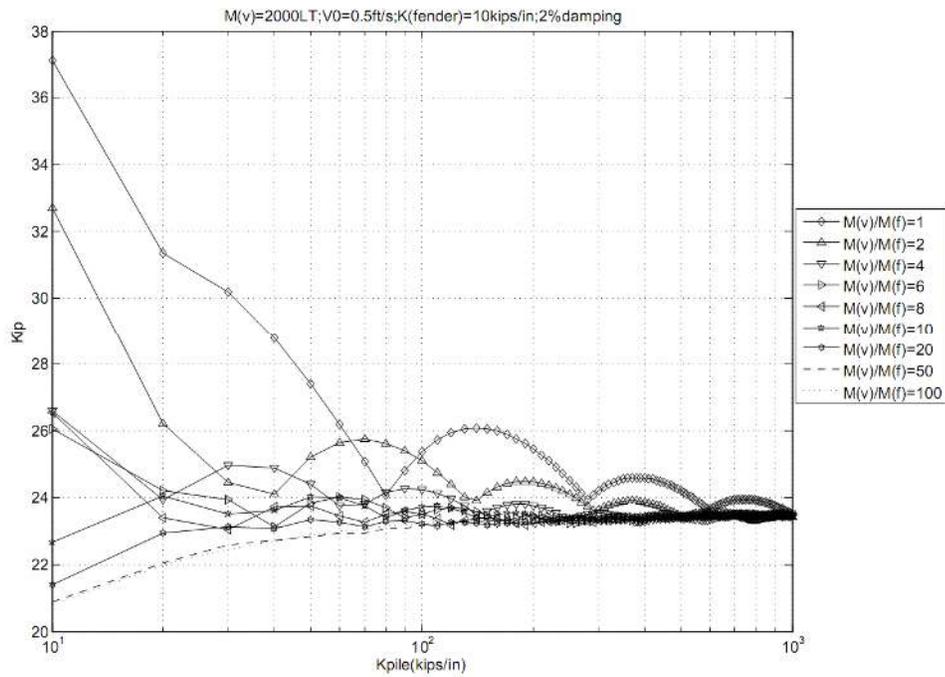


Fig. 3.46 Reaction Force of the Piling System 2D-a2

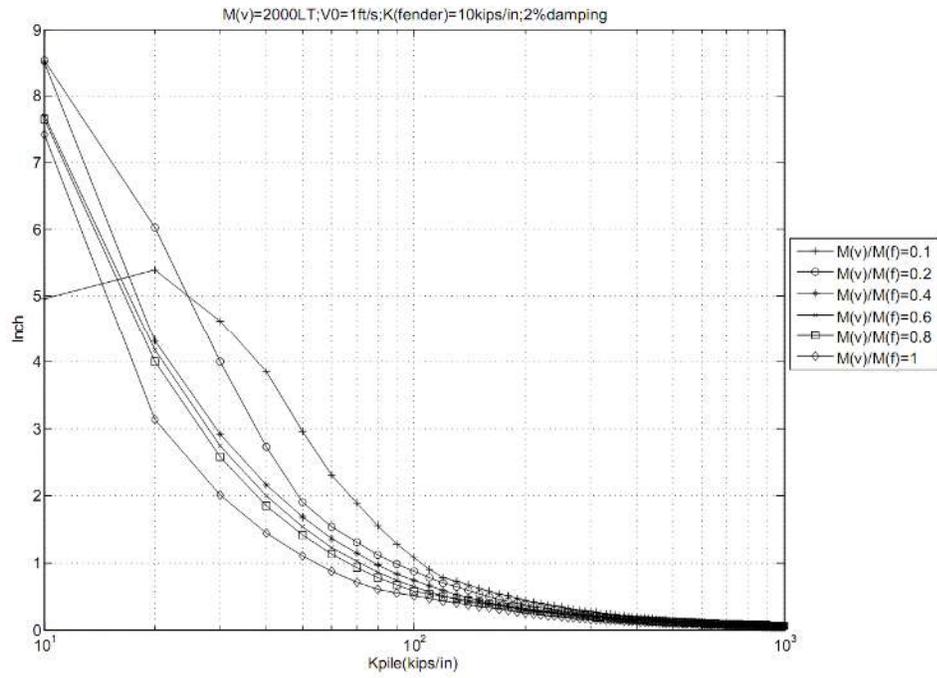


Fig. 3.47 Displacement of the Piling System 2D-b1

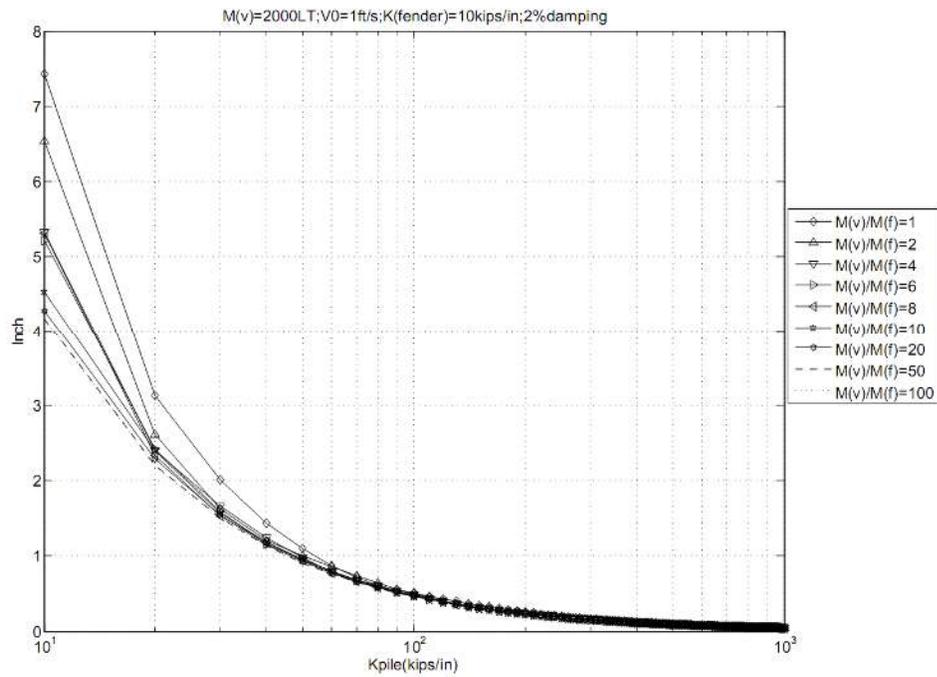


Fig. 3.48 Displacement of the Piling System 2D-b2

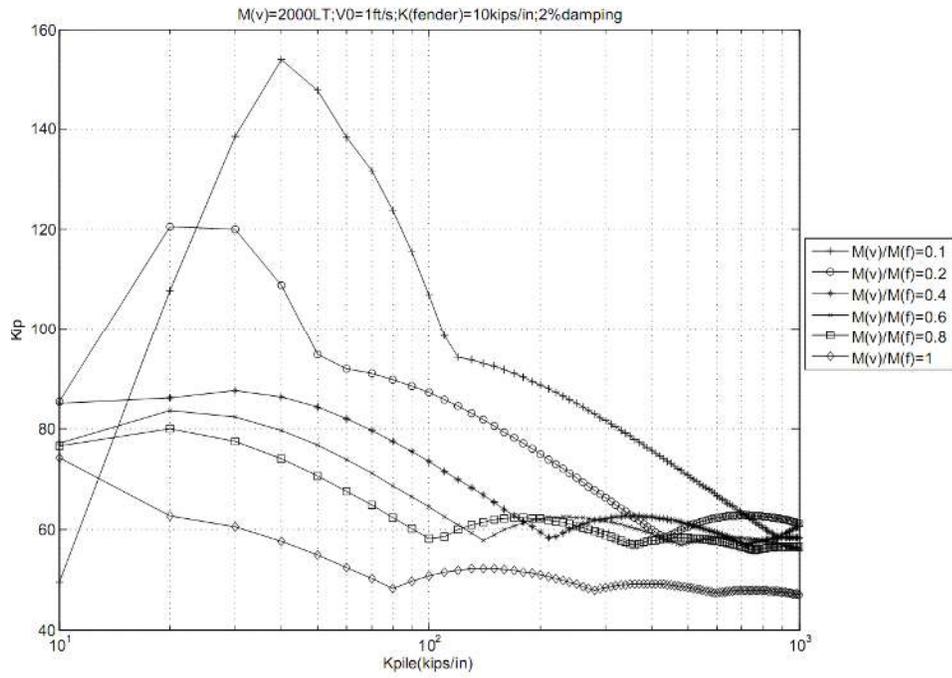


Fig. 3.49 Reaction Force of the Piling System 2D-b1

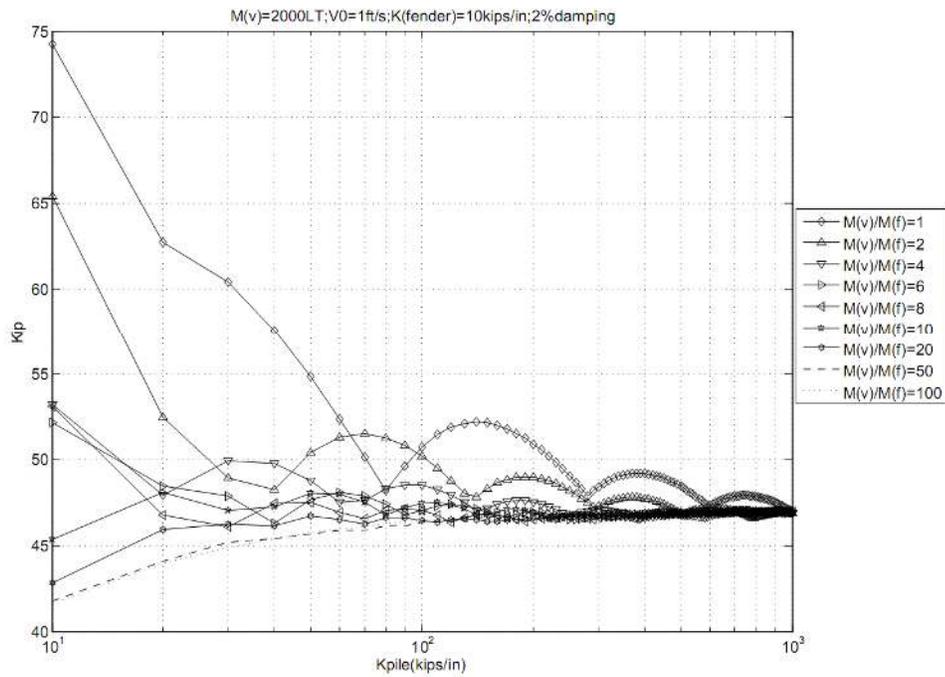


Fig. 3.50 Reaction Force of the Piling System 2D-b2

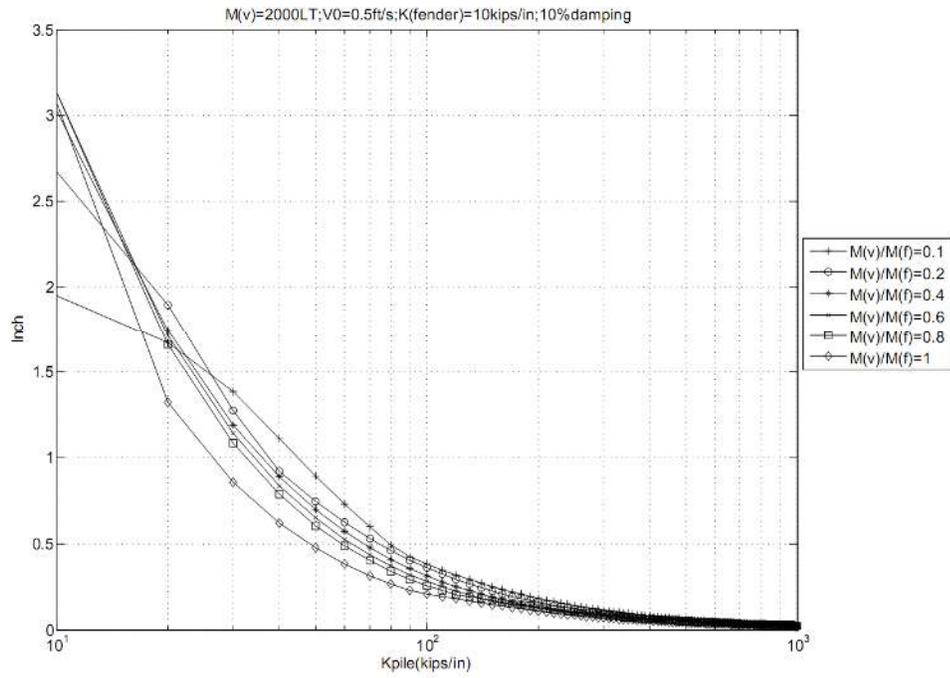


Fig. 3.51 Displacement of the Piling System 2D-c1

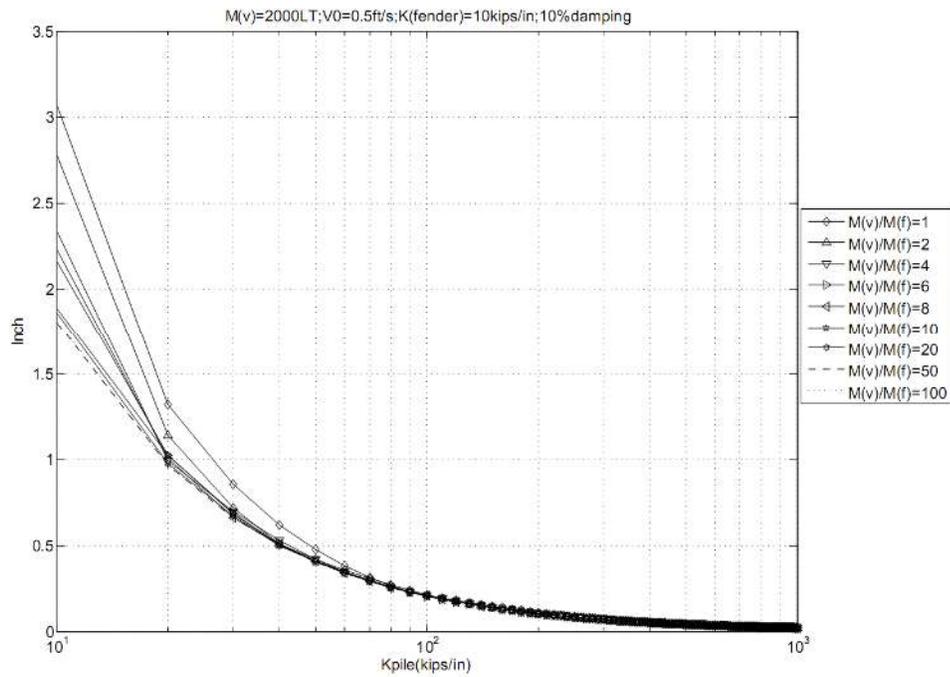


Fig. 3.52 Displacement of the Piling System 2D-c2

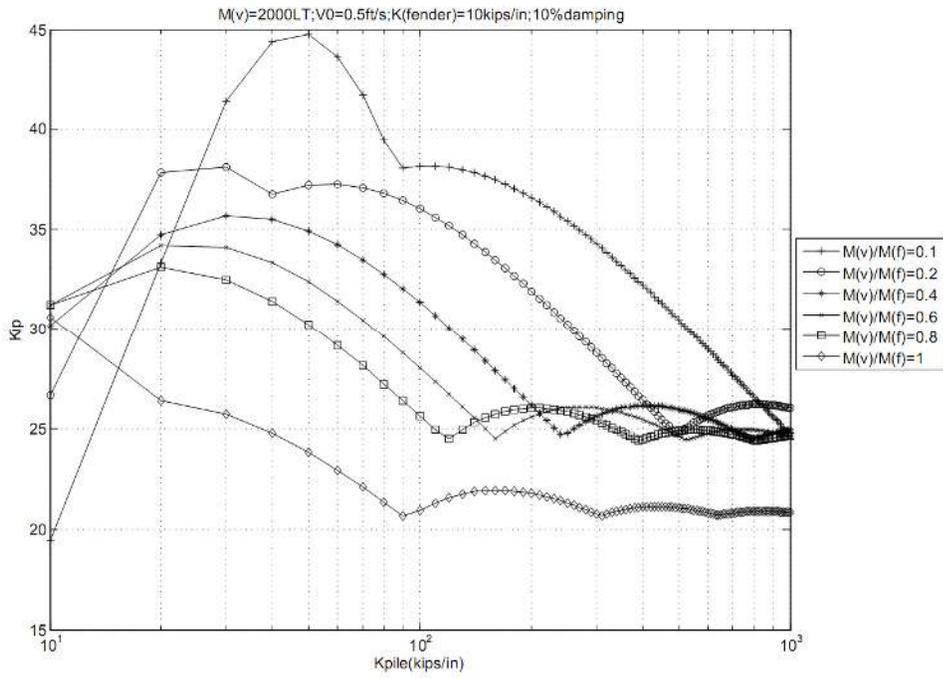


Fig. 3.53 Reaction Force of the Piling System 2D-c1

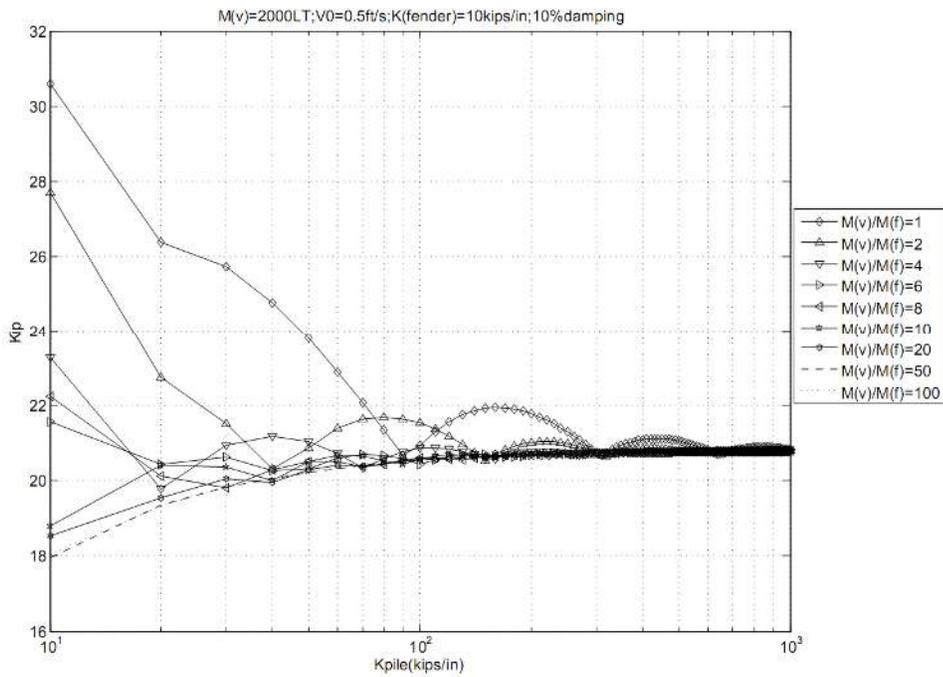


Fig. 3.54 Reaction Force of the Piling System 2D-c2

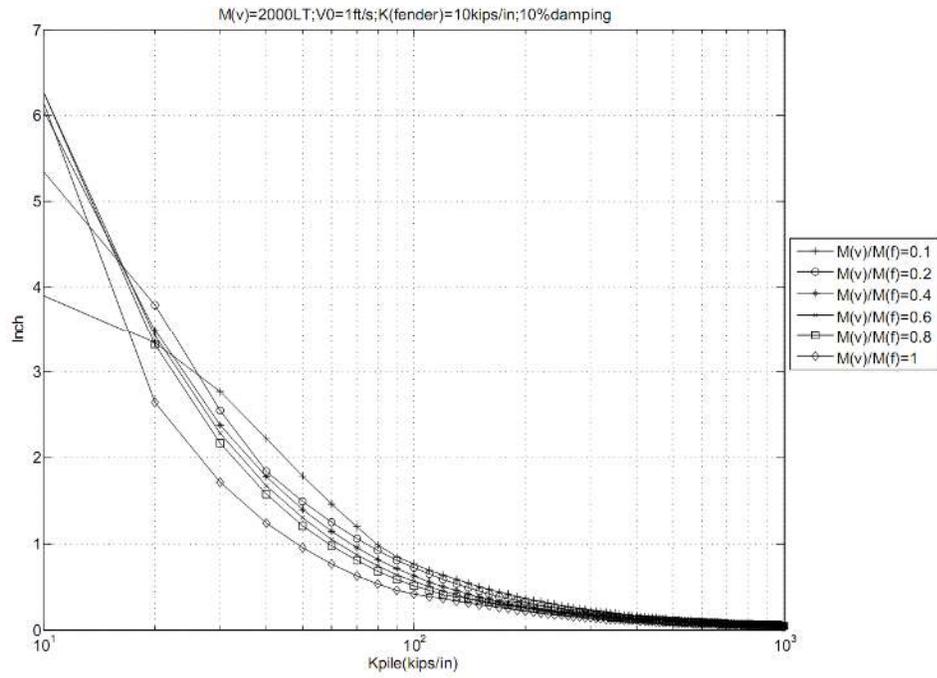


Fig. 3.55 Displacement of the Piling System 2D-c1

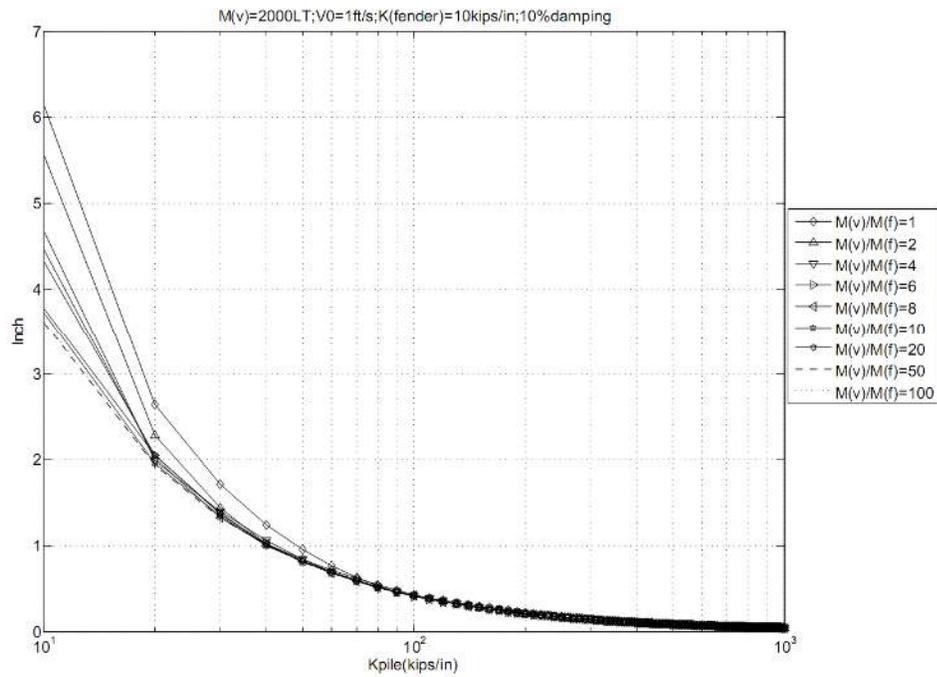


Fig. 3.56 Displacement of the Piling System 2D-c2

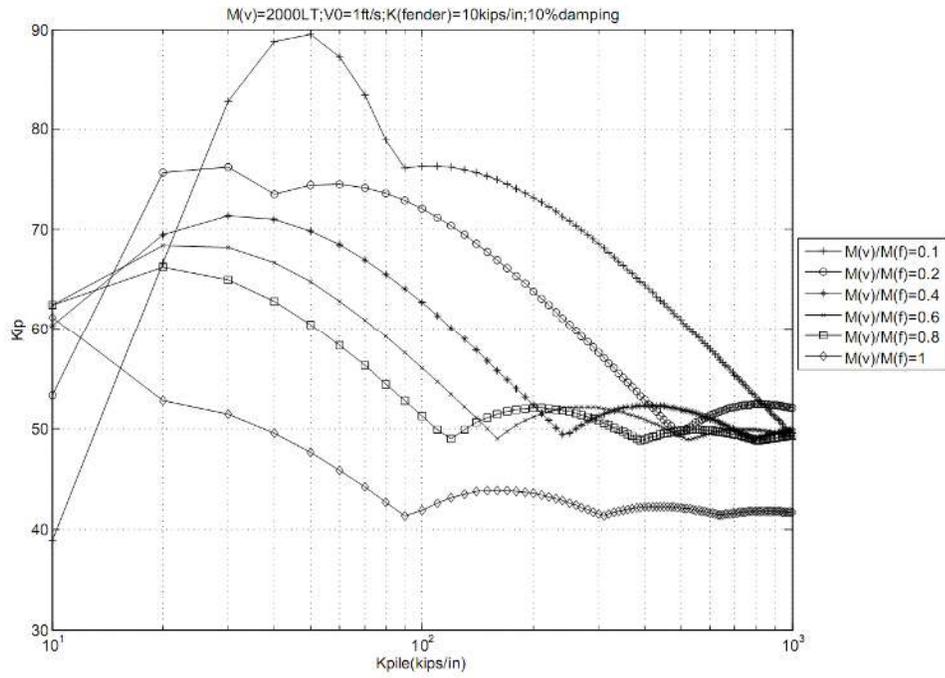


Fig. 3.57 Reaction Force of the Piling System 2D-c1

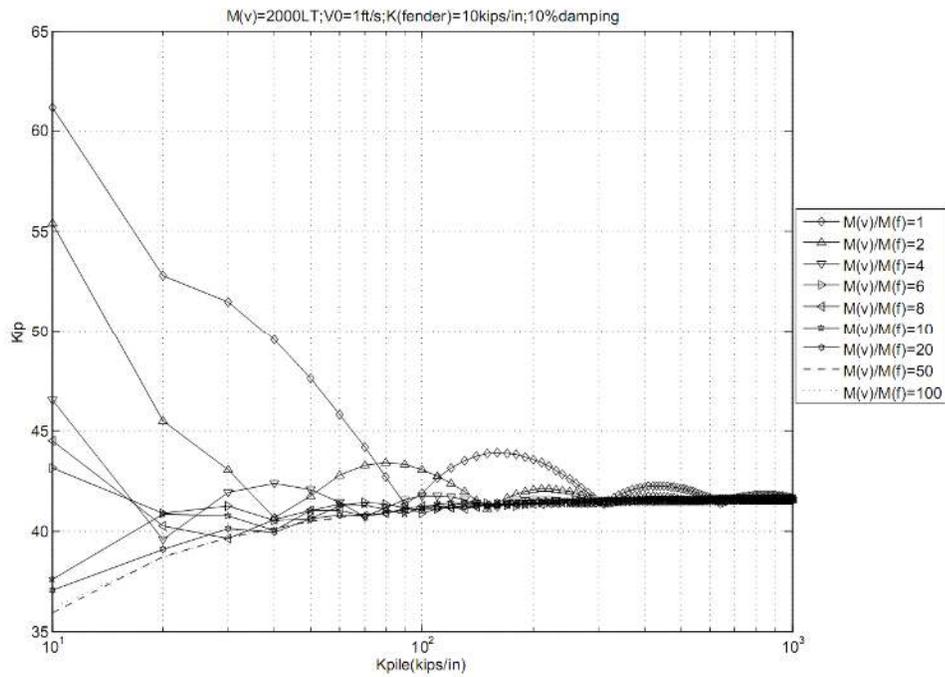


Fig. 3.58 Reaction Force of the Piling System 2D-c2

3.3 Discussion

It can be observed that the responses of the piling system vary significantly given different parameters, such as the mass of the vessel, the approaching velocity of the vessel, and the mass ratio of the vessel to the float, etc. One dimensional analysis shows that the response of the piling system, consisting of displacements and the reaction forces resulting from impact of the approaching vessel, is directly proportional to the velocity of the approaching vessel, given a constant vessel mass and the same damping ratio. The response also becomes larger when the mass of the vessel becomes larger, given a constant approach velocity and the same damping ratio. The same trends were also observed when using the KEM to analyze the response of the piling system, except there is no damping involved in the KEM. Given a constant vessel mass and constant approach velocity, the peak response becomes smaller as the damping ratio becomes larger. There is another interesting characteristic about the response of the piling system that cannot be incorporated by the KEM. The graphs obtained by the DAM present responses resulting from a varying mass ratio of the vessel to the float, whereas the KEM merely treats the float as a massless link between the piling system and the fender. It is clear that for a constant vessel mass, when the mass ratio of the vessel to the float is small, which indicates the float is quite massive compared to the vessel, the responses are larger than if the mass ratio is large, which indicates a relatively massive vessel. It can also be observed when the mass ratio is very large, which indicates that the mass of the float is almost negligible compared with the vessel, the response of the piling system tends to converge to a constant despite decreasing the mass ratio even further with constant damping ratio,

mass of the vessel and approaching velocity. This is due to the nature of a dynamic system, as explained below.

A dynamic system consists of different elements: they are mass elements, spring elements and damping elements. The dynamic system can be considered as a closed system, and the total energy of a closed system is a constant. For the berthing system that is being studied, the total energy before the vessel lands on the float is the kinetic energy of the vessel. After the vessel lands on the float, the whole berthing system starts vibrating, and the energy of the system will still equal the kinetic energy of the vessel before it landed on the float. The elements of the berthing system will all carry part of the energy from the kinetic energy of the vessel at the beginning. However, different elements carry energy in different ways. The mass elements carry kinetic energy as they are moving back and forth, or they can rotate about their C.M if eccentricity exists. The kinetic energy of the mass elements is equal to the sum of half of the mass of the element times the velocity of the mass elements squared and half of the moment of inertia of the element times the angular velocity of the element squared. The expression can be written as follows:

$$E_k = \frac{1}{2}mv^2 + \frac{1}{2}I\omega^2 \quad (3-68)$$

where:

E_k = total kinetic energy of the mass element

m = mass of the mass element

I = moment of inertia of the mass element

v = translational velocity of the mass element

ω = rotational velocity of the mass element

The kinetic energy of the mass elements, which are the vessel and the float in this study, is the sum of the kinetic energy of the vessel and the float. In one dimensional analysis, the kinetic energy is the sum of the translational kinetic energy of the vessel and the float, whereas in two dimensional analysis, the kinetic energy is the sum of the translational kinetic energy of the vessel and the total kinetic energy of the float that consists of the translational and rotational energy due to the existence of the eccentricity. The spring elements will also carry some amount of the energy, but in the form of potential energy as the energy is being stored in the deflected elements. In the study, the potential energy of the spring elements is the strain energy of the fender and the piling system. Besides mass elements and spring elements, the berthing system also has damping elements. The damping elements represent the energy loss during the vibration of the system, and are linearized for simplistic purposes. Unlike mass elements and spring elements, the energy is not being stored in the damping elements; the energy is being dissipated as heat by the damping elements. Therefore, the combined energy of the berthing system consists of the kinetic energy of the mass elements and the potential energy of the spring elements. However, the combined energy of the mass and spring elements is somehow smaller than the kinetic energy of the vessel before it landed on the float at the beginning, due to the

dissipated energy by the damping elements. The kinetic energy of the vessel at the beginning is equal to the sum of the combined energy of the mass and spring elements and the energy dissipated by the damping elements.

The displacements of the piling system are due to the conversion of kinetic energy of the vessel at the beginning to the strain energy being stored in the piling system. It has been observed that the displacements and the reaction forces of the piling system become larger when the mass ratio of the vessel to the float becomes small. It is because the energy distributions are different when the mass ratios are different. If the mass ratio is small, which means the float is massive compared with the vessel; more energy will be converted to the kinetic energy of the float than the vessel due to the large mass of the float. The float is directly connected to the piling system. The moving float will displace the piling system, causing large displacements and consequently large reaction forces of the piling system. On the other hand, if the vessel is massive compared with the float, the vessel is directly connected with the fender, but not the piling system. This results in most of the energy remaining with the vessel. The piling system will not deflect as much because it is not connected with the vessel. Therefore, the more massive the float is compared with the vessel, the larger the responses will be for the piling system.

Another interesting characteristic is with the different stiffness ratios of the piling system to the fender given the constant stiffness of the fender. The peak responses of the piling system can be different even for a constant mass ratio of the vessel to the float. The reason for this is that the spring elements will carry a certain amount of the energy and

the amount of energy being carried highly depends on the stiffness ratio of the spring elements. The spring elements in the study are the fender and the piling system. Only the fender is directly connected to the vessel. On the other hand, both the fender and the piling system are directly connected to the float, meaning the energy distribution among the mass elements and the spring elements is very complicated. Even though the general trend follows that when the float is massive compared with the vessel the responses of the piling system tend to be large, different stiffness ratios between the piling system and the fender can cause responses to vary. It is entirely possible that the responses of the piling system can be smaller when the float is massive than if the float is relatively light, given different stiffness ratios. The trend is demonstrated in all the diagrams given above. The stiffness of the fender is chosen as 10kips/in and the stiffness of a single pile ranges from 10kips/in to 1000kips/in. The responses of the piling system are influenced by all the parameters, which can be summarized into four factors: the kinetic energy of the vessel before it lands on the float, the mass ratio of the vessel to the float, the stiffness ratio of the piling system to the fender and the damping ratio.

The responses with different parameters can also be seen in two dimensional analysis, and the responses follow exactly the same trends for two dimensional analysis as they do for one dimensional analysis. However, it can be observed that the responses of piling system in two dimensional analysis is larger than the corresponding one dimensional analysis, due to the eccentricity between the C.M and C.R of the float when analyzing the berthing system in two dimensions. The eccentricity is dependent on the configuration of the piling system and the geometric configuration of the float. The

configuration of the piling system stays the same as it is shown in Fig. 3.41 despite the change of the float when the mass ratio of the vessel to the float changes. The float will be scaled up or down due to the change of the mass ratio, but the shape of the float remains as a square barge. That means that the larger and more massive the float is, the larger the eccentricity will be. The larger eccentricity will cause a considerable rotational response for the float, causing more energy to transfer on the float. Since the float is directly connected to the piling system. The responses of the piling system are influenced by 5 factors: the kinetic energy of the vessel before it lands on the float, the mass ratio of the vessel to the float, the stiffness of the piling system to the fender, the damping ratio and the eccentricity. Eccentricity is not considered in one dimensional analysis.

Berthing system can be modeled as a vibrational dynamic system with MDF, if the system has no inherent eccentricity. The system can simply be analyzed in one dimension, or otherwise the system can be analyzed in two dimensions if there is eccentricity between the C.M and C.R of the float. The governing equations of motion can be built to capture the motion of the berthing system after the vessel lands on the float. The equation can also be derived either from Newton's second law of motion, which is a better usage for one dimensional analysis since the berthing system has only two DOFs, or the influence coefficients method which is more suitable for two dimensional analysis due to the increased number of DOFs. After the governing equations of motion are derived, the equations can be solved with modal analysis. Modal analysis can also incorporate linearized damping to the berthing system. The solutions of the governing equations of motion are the displacements of the mass elements, which are

the vessel and the float. Only the first half cycle of the responses are kept in record because after the first half cycle, the vessel will bounce back and subsequently separate from the berthing system. The demonstration of the responses is given in Fig. 3.16 and Fig. 3.17. The diagrams show the peak responses, which are the maximum displacement and reaction force for the piling system during the first half cycle.

3.4 Conclusion

The responses of the piling system are plotted for one dimensional and two dimensional analysis given different parameters, including the mass of the vessel, the mass of the float, the approaching velocity, the damping ratio, the stiffness of the fender and the stiffness of the piling system. In two dimensional analysis, eccentricity is also accounted for. The diagrams given in this section present several general trends regarding the response of the piling system. The responses are highly dependent upon different parameters of the berthing system. The parameters can be summarized as: the kinetic energy of the vessel before it lands on the float, the mass ratio of the vessel to the float, the stiffness ratio of the piling system to the fender, and the damping ratio and eccentricity which is for two dimensional analysis only as just mentioned. The larger the kinetic energy of the vessel at the beginning, the larger the responses will be provided other parameters are the same, due to more energy being transferred to the piling system. The larger the damping ratio, the smaller the responses will be provided other parameters are the same, due to less energy being transferred to the piling system because of more energy being dissipated. However, the response due to different combinations of the mass

ratio and stiffness ratio can be quite complicated because different mass ratios and stiffness ratios can redistribute the energy from the approaching vessel. The responses will look unique for different combinations of the mass ratio and stiffness ratio. Though, in general, the more massive the float is, the larger the response of the piling system will be. Furthermore, in two dimensional analysis, the eccentricity effect is considered, and it can be seen that large floats will result in considerable amount of eccentricity, and substantial eccentricity will cause larger response. The response for substantial eccentricities in two dimensional analysis is due to more energy being distributed to the float via rotational displacement.

Chapter 4 Responses of Floats under Wave Loading

4.1 Introduction

Besides dynamic loading coming from the vessel, the float is also subjected to dynamic (time varying) loading from wind generated waves. The float under dynamic wave loading can be viewed as an MDF system under external forcing functions, which represent wave loading. The responses of the MDF system can be captured by the governing equations of motion of the system. The governing equations of motion can be written in matrix form as:

$$[m]\{\ddot{x}(t)\} + [c]\{\dot{x}(t)\} + [k]\{x(t)\} = \{F(t)\} \quad (1-4)$$

These equations were introduced in Chapter 1.

In the study, the berthing float will be treated as an MDF system as stated above, and the responses of the system will be analyzed in two dimensions. That is, the responses in both surge and sway directions will be considered, and in addition to translational responses, rotational response in yaw direction will also be considered. This response was analyzed in the previous chapter for the berthing system under dynamic loading from the vessel. The schematic diagram of the float under wave loading is given in Fig. 4.1. It can be easily observed that the whole configuration is part of the berthing system without impact from the vessel; instead, the berthing system is under dynamic loading from the waves. In the analysis of wave loading, the floating system is chosen such that there is no eccentricity. The configuration of the piling system is given in Fig.

4.2. The dynamic model of the float under wave loading is given in Fig. 4.3. Again, the model is only part of the berthing system without the vessel's impact.

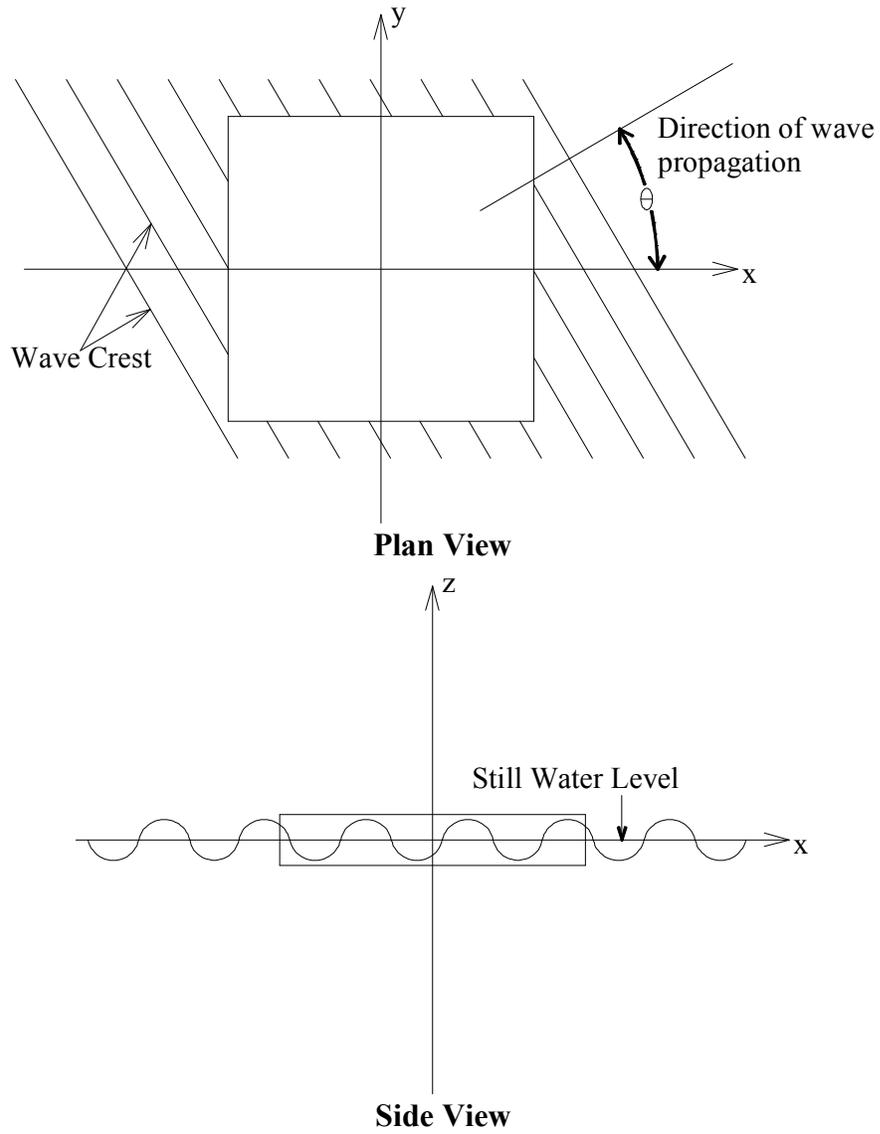


Fig. 4.1 Schematic Diagram of Float under Wave Loading

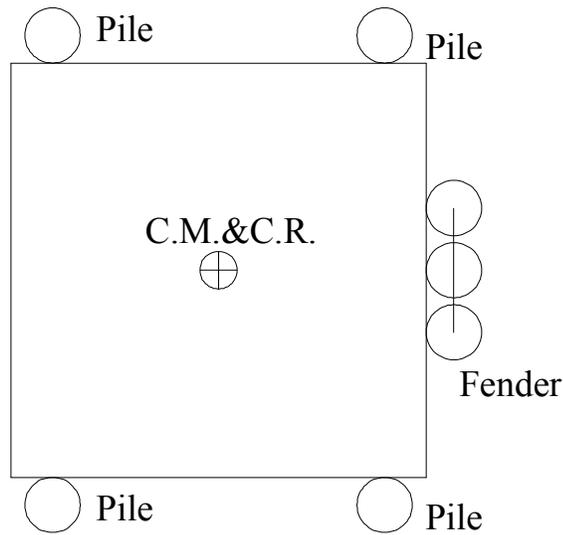


Fig. 4.2 Configuration of the Piling System

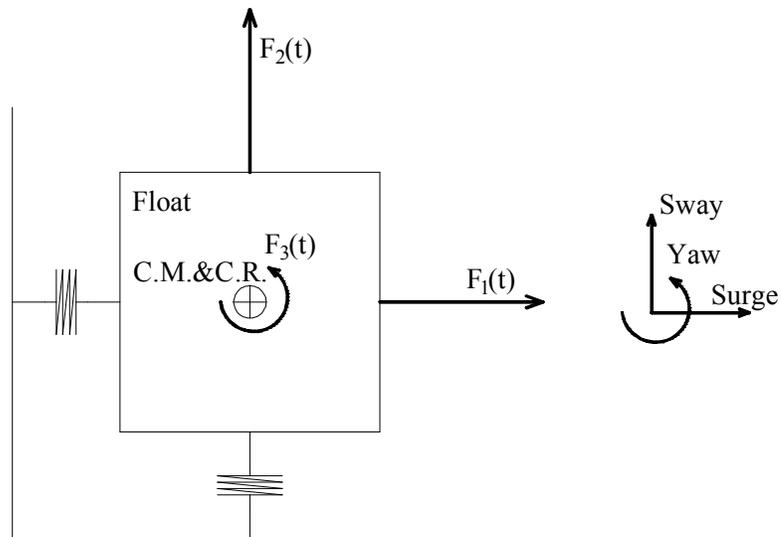


Fig. 4.3 Dynamic Model of Float under Wave Loading

To further simplify the analysis, the floating system is chosen such that no eccentricity exists, and damping will be neglected due to the small displacement of the float. Therefore, the governing equations of motion of the system can be rewritten as:

$$[m] \{\ddot{x}(t)\} + [k] \{x(t)\} = \{F(t)\} \quad (4-1)$$

In Dynamic Analysis of Chapter 3, modal analysis was used to solve governing equations of motion for an MDF system without external forces. Fortunately, only a little change can incorporate the effects of external forces. The governing equations of motion for an MDF system without external forces can be written in another form as:

$$[m][X]\{\ddot{q}(t)\} + [k][X]\{q(t)\} = \{0\} \quad (3-34)$$

Therefore, Eq. (4-1) can be rewritten as:

$$[m][X]\{\ddot{q}(t)\} + [k][X]\{q(t)\} = \{F(t)\} \quad (4-2)$$

Again, premultiplying Eq. (4-2) throughout by $[X]^T$, Eq. (4-3) can be obtained:

$$[X]^T [m][X]\{\ddot{q}(t)\} + [X]^T [k][X]\{q(t)\} = [X]^T \{F(t)\} \quad (4-3)$$

If the mode shapes are normalized, Eq. (4-4) can be rewritten as:

$$[I]\{\ddot{q}(t)\} + [\omega^2]\{q(t)\} = \{Q(t)\} \quad (4-4)$$

where

$$\{Q(t)\} = [X]^T \{F(t)\} \quad (4-5)$$

Eq. (4-4) denotes a set of n uncoupled differential equations of the second order, which describe the undamped motion of n SDF systems under external forces.

The generalized displacements $q_i(t)$ can be found by solving Eq. (4-4), and the responses of the float under wave loading can be found with Eq. (3-31)

$$\{x(t)\} = [X]\{q(t)\} \quad (3-31)$$

Wave Forcing Functions

Naturally occurring waves are very complicated and often difficult to model accurately. Eq. (4-1) is the matrix form of the governing equations of motion for the float under external forces representing the wave loading. $\{F(t)\}$ is the vector form of the external forces. The float will be analyzed in two dimensions: responses in surge, sway and yaw directions of the float. The float has three DOFs, one in each direction considered. Wave forcing functions representing wave loading for surge, sway and yaw directions acting on the float must be determined before the equations of motion can be solved. Fortunately, the wave forcing functions have already been derived for a squared barge structure like the float under investigation (Andrew T. Metzger, Jonathan Hutchinson 2010). Fig. 4.3, 4.4 and 4.5 are diagrams that illustrate the wave profile on the water surface and schematic demonstration of the wave loading acting on the barge.

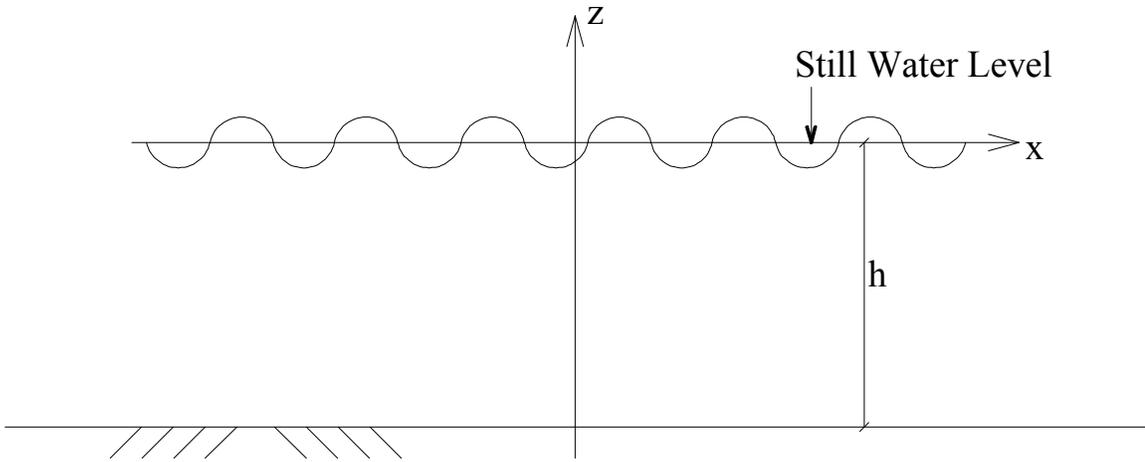
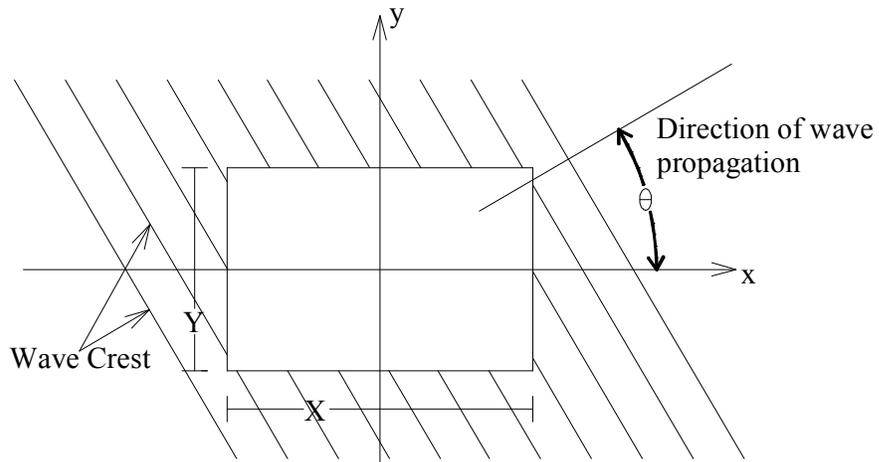
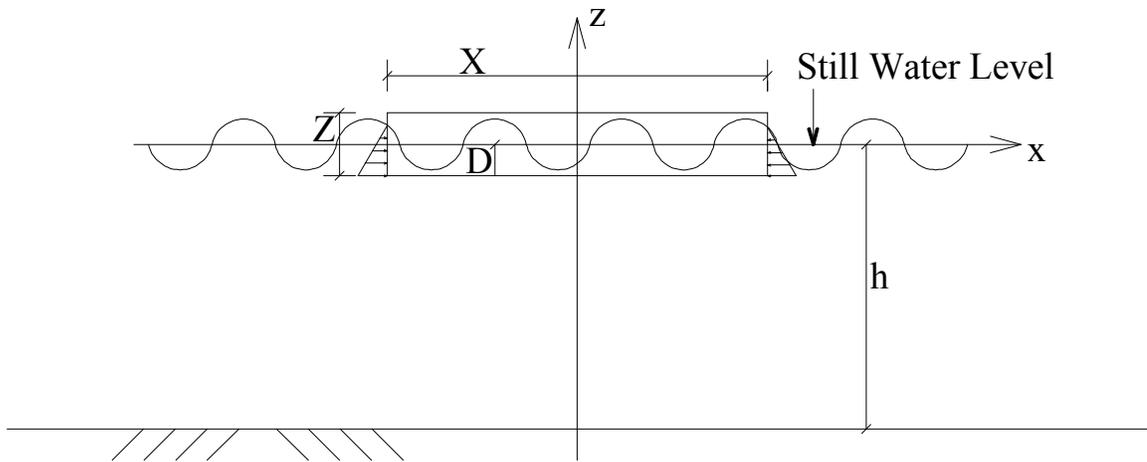


Fig. 4.4 Schematic Diagram of Simple, Harmonic Wave

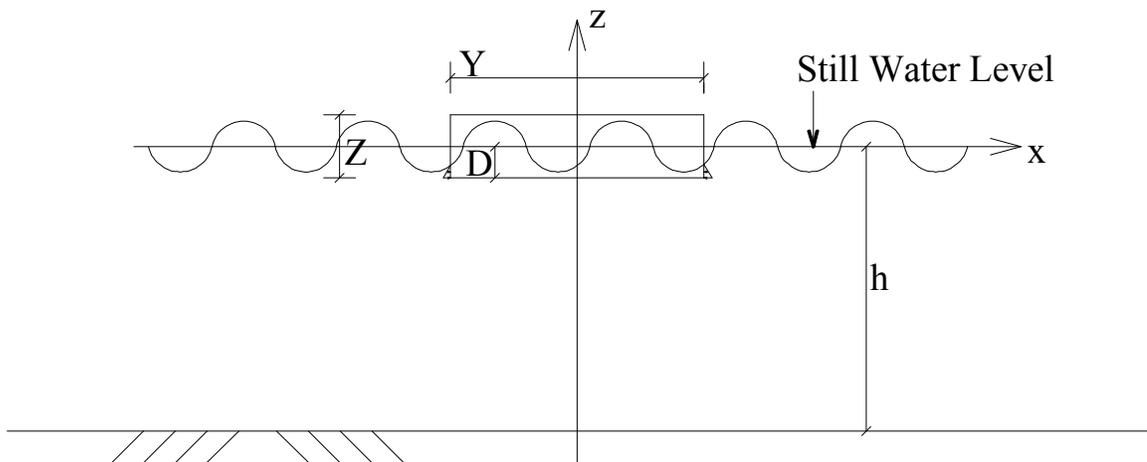


Plan View

Fig. 4.5 Schematic Diagram of a Rectangular Barge under Wave Loading



**Side View
(a) Surge Direction**



**Side View
(b) Sway Direction**

Fig. 4.6 Schematic Diagram of a Rectangular Barge under Wave Loading

The wave forcing functions in surge, sway and yaw directions acting on a rectangular barge are given as follows:

$$F_x(t) = \frac{2\rho gH [\sinh(kh) - \sinh(k(h-D))]}{k^2 \sin\theta \cosh(kh)} \sin\left(k \frac{X}{2} \cos\theta\right) \sin\left(k \frac{Y}{2} \sin\theta\right) \sin(\omega t)$$

(4-6)

$$F_y(t) = \frac{2\rho gH [\sinh(kh) - \sinh(k(h-D))]}{k^2 \cos\theta \cosh(kh)} \sin\left(k \frac{X}{2} \cos\theta\right) \sin\left(k \frac{Y}{2} \sin\theta\right) \sin(\omega t)$$

(4-7)

$$M_w(t) = \frac{\rho gH [\sinh(kh) - \sinh(k(h-D))]}{k \cosh(kh)} \left[\frac{[2\sin\left(\frac{k_x X}{2}\right) - k_x X \cos\left(\frac{k_x X}{2}\right)] \sin\left(\frac{k_y Y}{2}\right)}{k_x^2} + \frac{[k_y Y \cos\left(\frac{k_y Y}{2}\right) - 2\sin\left(\frac{k_y Y}{2}\right)] \sin\left(\frac{k_x X}{2}\right)}{k_y^2} \right] \cos(\omega t)$$

(4-8)

Where:

D = draft of the structure (measured from the SWL)

g = acceleration due to gravity, taken to be 9.80665 m/s^2 (32.1440 ft/s^2)

h = water depth

H = wave height

k = wave number

$$k_x = k \cos\theta$$

$$k_y = k \sin\theta$$

t = time variable

T = wave period

\bar{X} = distance in the x direction from the origin of the orthogonal system to the C. R

\bar{Y} = distance in the y direction from the origin of the orthogonal system to the C. R

\bar{Z} = distance in the z direction from the origin of the orthogonal system to the C. R

X = “x” dimension of structure

Y = “y” dimension of structure

Z = “z” dimension of structure

θ = direction of wave propagation with respect the x-axis

λ = wavelength

ρ = density of water

ω = angular frequency of a wave

C. R = center of rigidity

Therefore, the resultant wave forcing functions can be expressed in matrix form as:

$$\{F(t)\} = \begin{Bmatrix} F_x(t) \\ F_y(t) \\ M_w(t) \end{Bmatrix} \quad (4-9)$$

With external forcing functions prepared, it remains to derive the stiffness influence coefficients and inertia influence coefficients that make up the stiffness and mass matrices.

Derivation of Stiffness Influence Coefficients

The stiffness influence coefficients, k_{ij} , are to be derived in the same manner as for the berthing system in Chapter 3, except that the vessel is no longer in the dynamic model.

The stiffness influence coefficients, k_{ij} , are found with the principle of static equilibrium. In Fig. 4.6 (a), x_1 is set to be one ($x_1 = 1$) and the other two displacements are zero ($x_2 = \theta = 0$), the forces k_{i1} ($i = 1, 2, 3$) are intended to maintain the system in this configuration. Therefore, according to the principle of static equilibrium, the total forces and moments acting on the system must cancel one another. The relations can be expressed as follows:

$$\begin{aligned}
\sum F_x &= 0; \\
\sum F_y &= 0; \\
\sum M &= 0
\end{aligned}
\tag{4-10}$$

Therefore, after solving the simultaneous static equilibrium equations, the stiffness influence coefficients can be expressed as:

$$\begin{aligned}
k_{11} &= 4k_{pile}; \\
k_{21} &= 0; \\
k_{31} &= 0;
\end{aligned}
\tag{4-11}$$

The same procedure is applied to x_2 and θ , wherein the stiffness influence coefficients are expressed as:

$$\begin{aligned}
k_{12} &= 0; \\
k_{22} &= 4k_{pile}; \\
k_{32} &= 0;
\end{aligned}
\tag{4-12}$$

$$\begin{aligned}
k_{13} &= 0; \\
k_{23} &= 0; \\
k_{33} &= 2l^2k_{pile};
\end{aligned}
\tag{4-13}$$

where k_{pile} is the stiffness of the piling system, l is the width of the float.

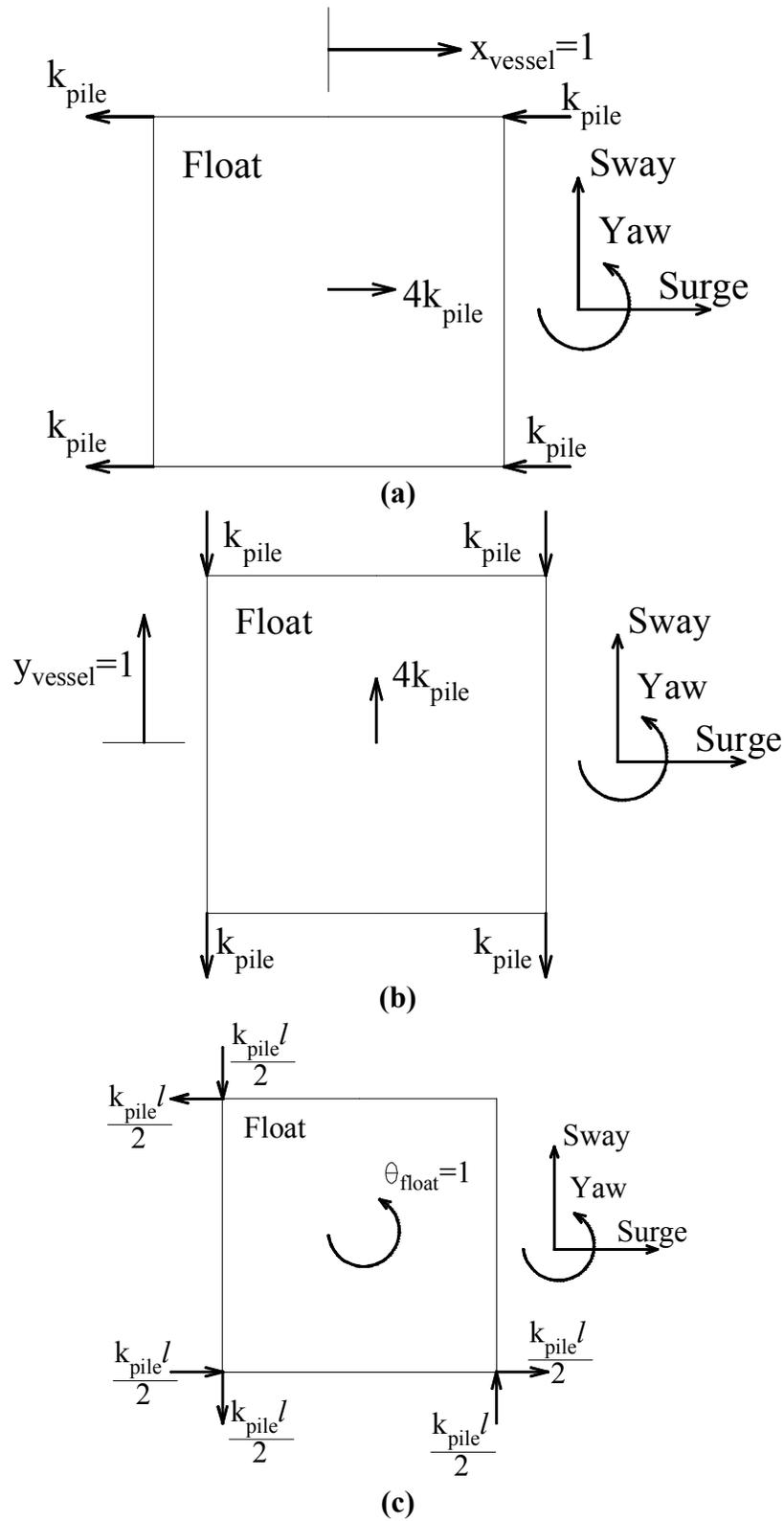


Fig. 4.7 Derivation of Stiffness Influence Coefficients (b)

The stiffness influence coefficients can be written in matrix form as:

$$[k] = \begin{bmatrix} 4k_{pile} & 0 & 0 \\ 0 & 4k_{pile} & 0 \\ 0 & 0 & 2l^2k_{pile} \end{bmatrix} \quad (4-14)$$

Derivation of Inertia Influence Coefficients

The elements of the mass matrix, m_{ij} , also known as the inertia influence coefficients are defined as the impulse applied at point j , which causes unit velocity at that point while all the other points have zero velocity due to impulses at other points.

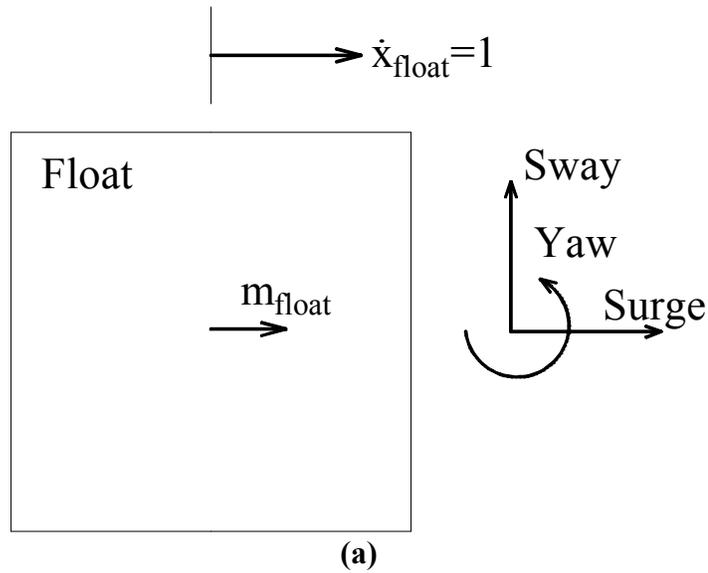
The derivation of inertia influence coefficients is given in Fig. 4.8 (a), (b), and (c). The inertia influence coefficients are expressed as:

$$\begin{aligned} m_{11} &= m_{float}; \\ m_{21} &= 0; \\ m_{31} &= 0; \end{aligned} \quad (4-15)$$

$$\begin{aligned} m_{12} &= 0; \\ m_{22} &= m_{float}; \\ m_{32} &= 0; \end{aligned} \quad (4-16)$$

$$\begin{aligned}
 m_{13} &= 0; \\
 m_{23} &= 0; \\
 m_{33} &= \frac{m_{float}(l^2 + l^2)}{2};
 \end{aligned}
 \tag{4-17}$$

The inertia influence coefficient m_{33} is the moment of inertia of the float with respect to the centroid of the float, and the expression is the same as the one shown before in Chapter 3.



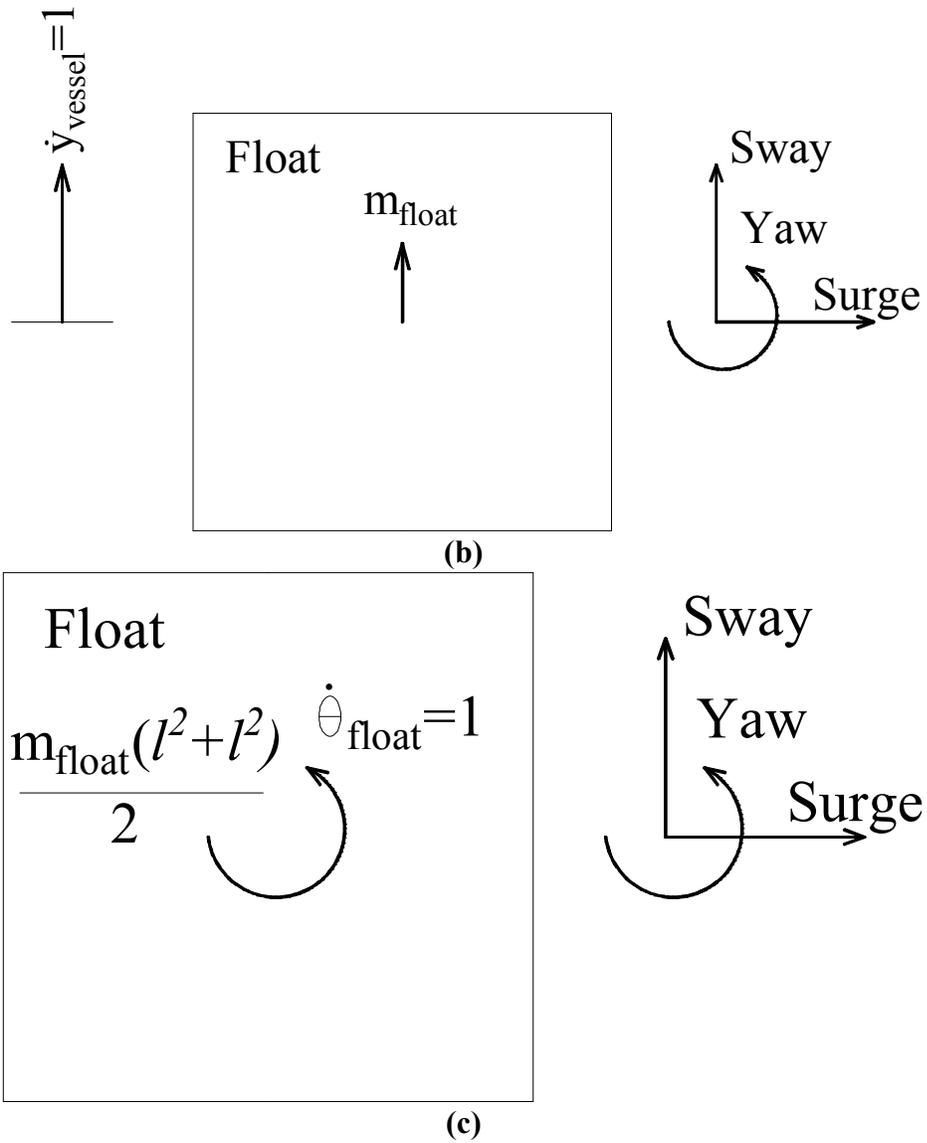


Fig. 4.8 Derivation of Inertia Influence Coefficients (b)

The inertia influence coefficients can be expressed in matrix form as:

$$[m] = \begin{bmatrix} m_{float} & 0 & 0 \\ 0 & m_{float} & 0 \\ 0 & 0 & \frac{m_{float}(l^2 + l^2)}{2} \end{bmatrix} \quad (4-18)$$

Governing Equations of Motion

After deriving the mass and stiffness matrices, the equations of motion for the berthing system without damping can be expressed as:

$$[m]\{\ddot{x}(t)\} + [k]\{x(t)\} = \{F(t)\} \quad (4-19)$$

in which the mass matrix and stiffness matrix are given in the previous section. The damping effects are neglected due to the small displacement of the float. The equations can be solved with modal analysis. The procedures are the same as were shown in Chapter 3, except that the berthing system is under external forces from the wave loading and the wave forcing functions, which have been derived previously in the chapter. The solutions of the governing differential equations represent the displacement of the float under wave motion. The results are given in the following results section.

4.2 Results

The results of the floating system under wave forcing functions are given in Fig. 4.15 and Fig. 4.16. The angle of the direction of the wave with respect to the surge direction of the float θ is chosen as zero in the analysis. Due to the characteristic of the wave forcing functions, the responses of the floating system are proportional to the magnitude of the wave height. In addition, the forces generated by the waves in sway and yaw directions both disappear when θ is zero. In the analysis, the mass of the float is chosen as 820.3 long tons, and the dimension of the float is 60ft by 60ft by 10ft with 8ft draft. In Fig. 4.15 and Fig. 4.16, the y-axis is chosen as the ratio of the maximum responses of the translational displacement of the piling system to the wave height and the x-axis is chosen as the ratio of the natural period of the wave forcing function T_w to the natural period of the floating system in the surge direction T_n . In Fig. 5.15, the ratio of T_w/T_n is from 0 to 3, and the ratio is from 3 to 10. T_w is chosen as 2s, 4s, 6s, 8s, 10s, 12s, 14s and 50s. The piling system consists of 4 identical piles acting as spring elements of the floating system and the maximum responses are chosen as the maximum displacements among the 4 piles under wave forcing functions. The natural period of the floating system in the surge direction can be calculated as $\sqrt{\frac{K_{pile}}{m_{float}}}$. The configuration of the floating system is given in Fig. 4.1. The results are given as follows:

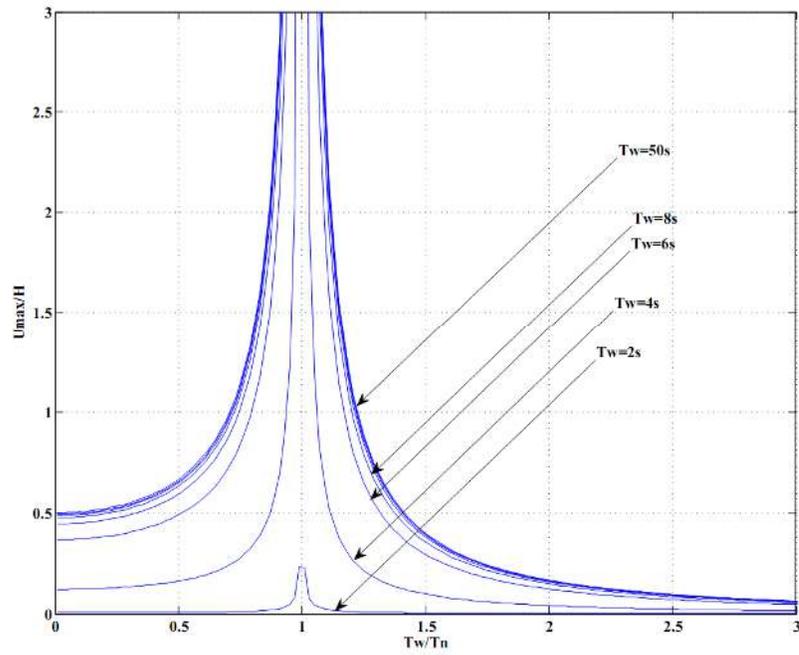


Fig. 4.9 Responses of the Floating System under Wave Forcing Function (a)

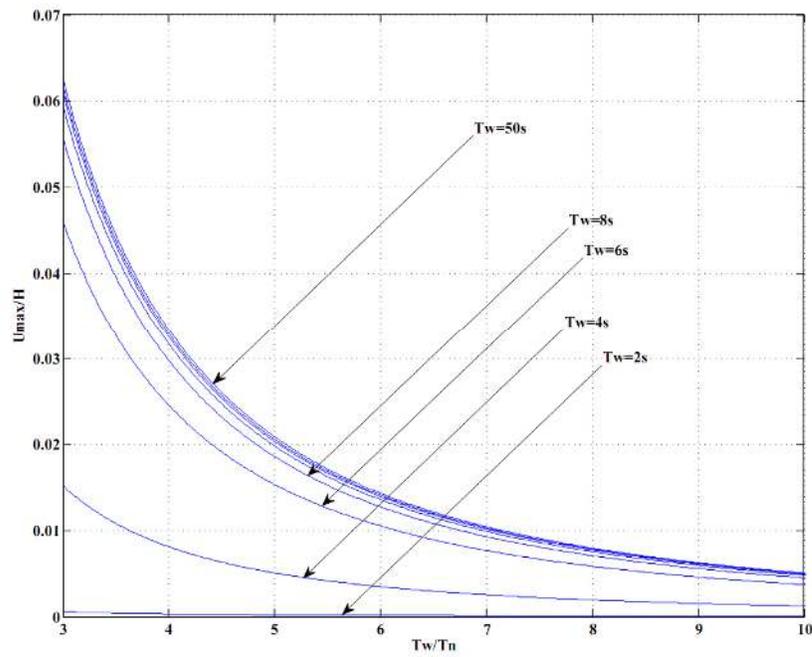


Fig. 4.10 Responses of the Floating System under Wave Forcing Function (b)

In addition to θ being zero, where the results were just presented, the angle could vary from 0 to 90 degrees (for angles greater than 90 degree angles, the analysis can always be conducted by switching the original surge and sway direction of the float). In the analysis, θ is chosen as 0, 10, 20, 30 and 45 degrees. The maximum responses of the piling system are still considered as the largest responses among the 4 identical piles. However, when θ is no longer zero, the wave forcing functions in sway and yaw directions are not zero either. Therefore the responses of the piles will be superimposed from the responses resulting from the movement of the floating system under wave loading in all three directions: surge, sway and yaw. The result is given in Fig. 4.17 to Fig. 4.21. In the diagrams presented below, the y-axis is chosen as the maximum responses of 4 piles; the x-axis is chosen as the ratio of T_w to T_n ; T_w is chosen as 5s in all the diagrams. The diagrams are given below:

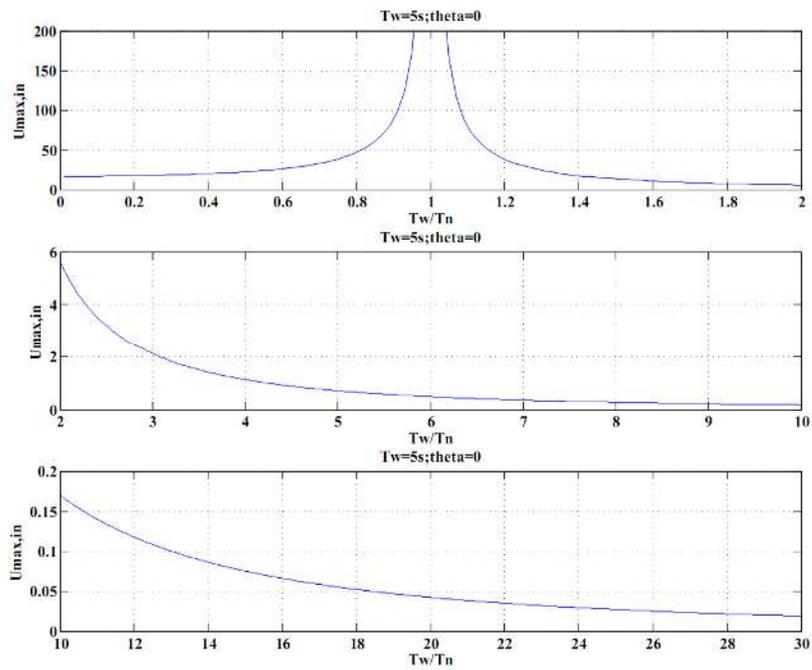


Fig. 4.11 Responses of the Floating System under Wave Forcing Functions (a)

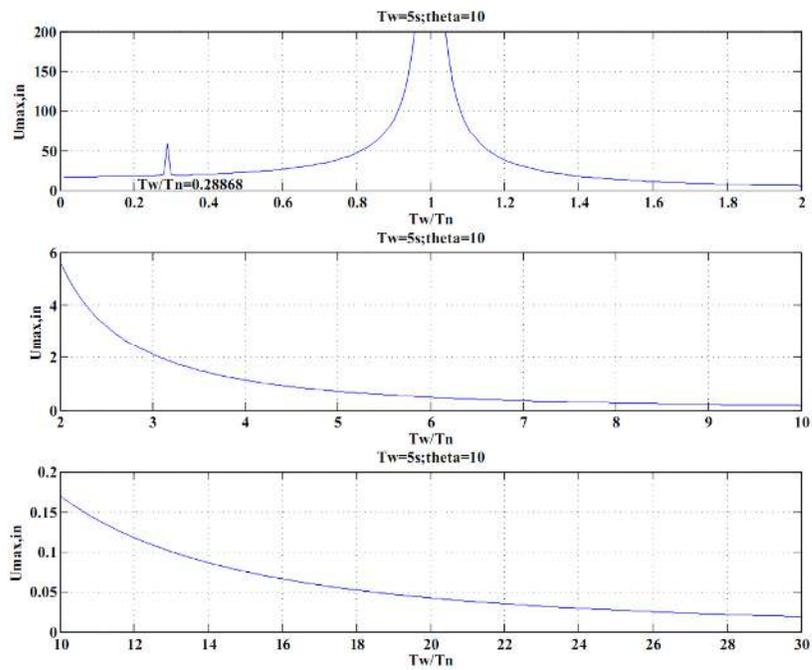


Fig. 4.12 Responses of the Floating System under Wave Forcing Functions (b)

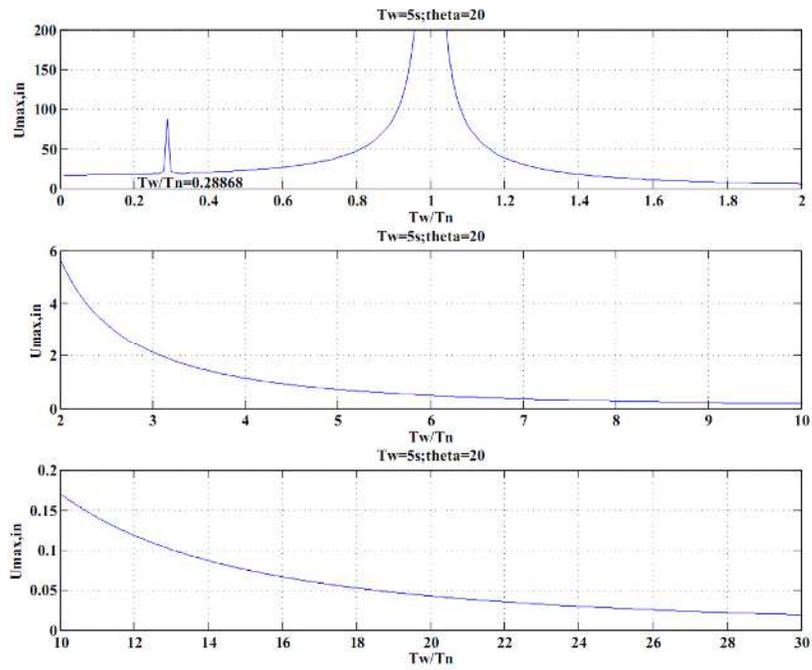


Fig. 4.13 Responses of the Floating System under Wave Forcing Functions (c)

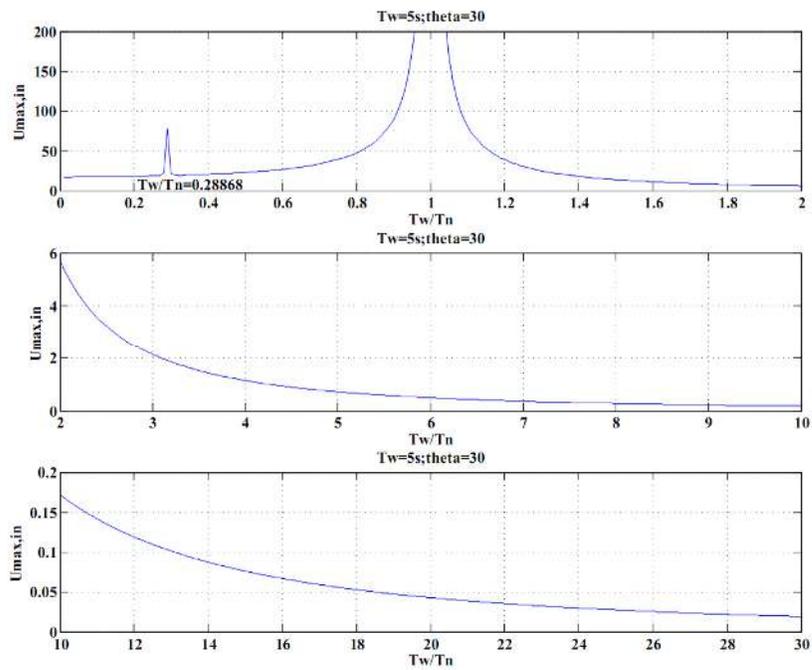


Fig. 4.14 Responses of the Floating System under Wave Forcing Functions (d)

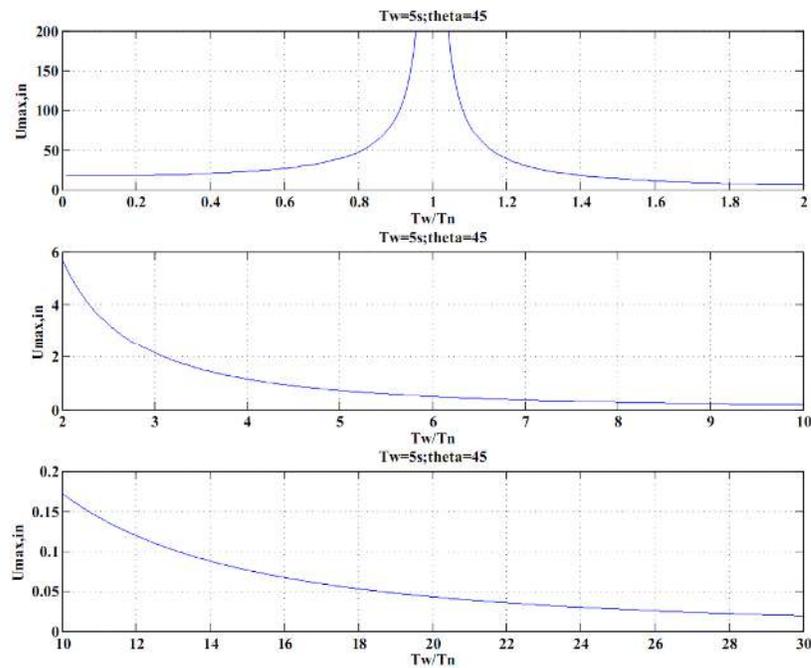


Fig. 4.15 Responses of the Floating System under Wave Forcing Functions (e)

4.3 Discussion

The responses of the floating system were presented in the last section, and several characteristics of the responses of the floating system under wave forcing functions can be observed. Assuming a deep water situation and given the dimension of the floating system from Fig. 4.15 and Fig. 4.16, the maximum responses of the piling system are proportional to the amplitude of the wave and the responses also increase as T_w increases. However, the responses increase very slowly after T_w has reached a certain point, which is $8s$ in the analysis. In addition, the analysis has shown that the responses increase dramatically when the ratio of T_w to T_n approaches unity. This physical phenomenon is known as resonance: when the period of the external force is equal or

very close to the natural period of the dynamic system. Consequently the responses of the system are extremely large or even infinite. The further the ratio of T_w to T_n deviates from 1, the smaller responses the floating system will have under wave forcing function.

From Fig. 4.17 to Fig. 4.21, for the same float and water depth but different θ , the maximum responses of the floating system are plotted with varying ratio of T_w to T_n . It can be observed that the maximum responses of the floating system are very close to each other when θ varies, and the responses follow the same trend as when θ is zero. The further the system deviates from resonance, the smaller the responses are. However, when θ equals 10, 20 or 30 degrees, there is a small peak response at some point when the ratio of T_w to T_n is between 0 and 1. The small peak response is due to the wave forcing function being not 0 in the yaw direction when θ is not 0 or 45 degrees. It should be noted that the configuration of the piling system in the study is symmetrical in both the surge and sway directions. Therefore the natural periods are the same in both directions, and thus the responses reach very large values only when the ratio of T_w to T_n is close to 1. If the floating system has different natural periods in all three directions, the maximum responses of the system will have three peaks at three different locations of T_w/T_n , where resonance happens.

The responses of the floating system are analyzed when neglecting the damping effects from the structure or the water. However, there will always be damping inherent in the system. Subsequently, the responses will be smaller due to the energy loss from

damping, and the resonance will still happen, though at slightly different locations of T_w / T_n .

4.4 Conclusion

It can be concluded that for a given floating system and deep water condition, the maximum responses of the piling system will increase as the period of the wave increases. However, the rate of the increase is becoming smaller as the period increases. Eventually the responses will be near constancy, even when the period of the wave is very long (and very long period waves are rare in nature). If the period of the wave is close or equal to any natural period of the floating system, in any direction, resonance will occur. The wave forcing functions only have values in the surge direction when θ is equal to 0 or 45 degrees. Therefore, the system can be monitored more easily and have smaller responses if located with respect to the direction of the wave.

There will be inherent damping effects in the system, which are neglected in the analysis. The responses will be smaller and the resonance will take place at slightly different period ratios.

Chapter 5 Conclusions and Recommendations

5.1 Overview

Pile-guided floats represent promising alternatives to the traditional, stationary berthing system, as the pile-guided floats do not require constant monitoring and can consequently reduce costs. It is crucial to predict the design loads of the guide piles that are fixed on the floats. The floats will be subjected to time-varying loading from wind generated waves and vessel impacts.

In this study, the responses of the berthing system under dynamic loading have been analyzed. Previous works from other authors regarding floating structures have been reviewed. However, little design information is available and empirical data is often highly site specific. The responses of the floating system under the impact of the vessel are analyzed by two different methods: the KEM and the DAM. The KEM is a quasi-static analysis and uses the principle of conservation of energy. DAM is based on dynamic models that represent the key features of the dynamic system, thus deriving the governing differential equations that describe the motion of the system. The responses of the berthing system can be obtained by solving the governing differential equations. The procedures to obtain responses of the berthing system are given in detail in the study and the results from the two methods obtained are interpreted and compared.

In addition to dynamic loading from the vessel, wave loading can generate responses from the berthing system. The responses of the system under wave loading are analyzed only by the DAM, and the results are interpreted.

5.2 Summary

The following list is a summary of conclusions of the study.

For the responses of the berthing system under vessel impact analyzed by the KEM:

- The response of the berthing system is directly proportional to the kinetic energy of the approaching vessel.
- The responses of the spring elements heavily depend upon the stiffness of the elements. Softer elements will lead to smaller reaction forces but larger displacements.
- The stiffness ratio of the spring elements (the fender and the piling system) determines the distribution of the kinetic energy from the vessel. If the stiffness of one element is large compared with the other, the displacement of the more rigid element will tend to be small and the reaction forces will be large but ultimately reach a constant if the element is very rigid. However, the kinetic energy absorbed by the more rigid element is smaller compared to the softer element.
- The mass of the float and the damping effects from the structures are neglected in the KEM.

For the responses of the berthing system under vessel impact analyzed by the DAM:

- The characteristics of the responses share the same first three trends as in the KEM.
- The DAM incorporates the damping effects and the mass of the float.

- Higher damping ratios may considerably reduce the responses of the berthing system.
- The mass ratio of the vessel to the float and the stiffness ratio of the fender to the piling system have significant effects on the responses of the system under vessel impact.
- The general trend is for the float to be massive compared to the vessel. The responses tend to be larger than if the float is light.
- The right combination of the mass ratio and the stiffness ratio can significantly complicate the responses of the piling system provided the kinetic energy of the vessel and damping ratios are constants for each combination.
- If the mass of the float is negligible, the responses of the system almost converge with the responses obtained from KEM, given a small damping ratio. A high damping ratio will reduce the response.
- If the piling system is very rigid compared to the fender, the responses of the piling system will tend to converge with the results obtained from the KEM regardless of the mass of the float.
- Comparing the results obtained from two methods, it can be concluded that the responses of the piling system by the DAM can be greater than the responses by the KEM for the same berthing condition, even if the berthing coefficient is chosen as 1.5 which is the maximum value in design practice. The difference is magnified when the float is massive, the damping is small or negligible, or eccentricity exists.

For the responses of the floating system under wave loading analyzed by the DAM:

- The responses of the piling system will increase as the period of the wave increases. However, the rate of increase will approach zero if the period of the wave is very long (and very long period waves are rare in nature).
- If the period of the wave is very close to the natural period of the floating system in any direction, resonance will occur; the responses of the piling system will grow significantly. Therefore, resonance should be avoided as much as possible.
- If the incoming angle of the wave is 0 or 45 degrees with respect to the surge direction of the floating system, the wave loading only has effects in the surge direction. Therefore, the floating system should be placed accordingly, to avoid coupled effects.

5.3 Further Study

This study uses the KEM and the DAM to analyze the responses of the berthing system under dynamic loading from vessels and wind generated waves. The analysis is purely theoretical. Therefore, field experiments should be conducted to validate the results obtained. The results should also be compared with the results obtained from other analytical methods, such as the Finite Element Method (FEM). In addition, more field data should be collected in order to obtain the corresponding information relating to the analysis. The following should be gathered for more accurate analysis: damping ratios, the information about the waves (such as wave height, period of the wave, and water depth), the properties of all the elements of the berthing system, such as the mass of the vessel and the float as well as the stiffness of the fender and the piling system, along with its specific configuration).

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