Chapter 1

Introduction and Literature Review

1.1 Introduction

Breakwaters are structures used to attenuate or eliminate waves. They help prevent damage to shorelines, harbors, and other natural or man-made marine structures. There are two types of breakwaters; one is a fixed barrier structure and the other is a moored floating type. Several different forms of floating breakwaters have been investigated and used for various applications in the past. Now inflatable floating breakwaters are being investigated for potential use and are the focus of this research. However, the primary motivation of this research is to investigate a simple model of snap loading that occurs in the cable mooring system of a breakwater and investigate fatigue of the cables due to snap loading.

The purpose of this research is to investigate the mooring system of a floating breakwater which moves about a region, causing its mooring cables to transition between slack and taut conditions. The breakwater will be modeled as a point mass and a rigid body, both of which will be subjected to free and forced motions. The analysis will be performed in two dimensions and the snap loading in the mooring system will be monitored.

1.2 Literature Review

1.2.1 Floating Breakwaters

Little attention was paid to the use of floating or transportable breakwaters until the necessity arose of landing men and materials during the Normandy invasion of World

War II. Two types of breakwaters were used during this event. The first were fixed breakwaters that were barges floated from Great Britain positioned just off shore and sunk. The second were actual floating breakwaters of cruciform cross section (Hales 1981). These "Bombardon" floating breakwaters were steel structures arranged in two lines along the Normandy coast. The controversial decision to use this floating breakwater was made after theoretical analyses and hydraulic model testing were conducted by Great Britain (Tsinker 1995). These breakwaters both served their purpose to dissipate the waves of the English Channel and provide shelter for invading troops and their materials during the crucial invasion. The "Bombardon" breakwaters were successful during the invasion, but they later failed during a storm which created stresses eight times larger than those for which they were designed.

Use of floating breakwaters declined over the following years until the 1950's, when the U.S. Navy saw the potential of these structures to protect small craft and marine structures from open-ocean waves (Hales 1981). As people started moving towards the coasts during the 1960's, the need to protect boats and structures increased. Later, studies were performed on the use of breakwaters to protect beaches, harbors, pleasure craft, and other important natural and man-made marine structures from the effects of waves. Some of these studies are Carver et al. (1987), Gaythwaite (1987), and Mays (1997, 1999).

Thus, over the years, many different types of floating breakwaters have been developed and many conclusions have been made as to their effectiveness. Some of the advantages of floating breakwaters include the following:

1. Floating breakwaters are less expensive than fixed structures in deeper water (depths greater than 10 feet) (Hales 1981).
2. Floating breakwaters can effectively attenuate moderate wave heights (less than about 6.5 feet) (Tsinker 1995).

3. Poor soil conditions may make floating breakwaters more feasible to use than heavy rubble fixed breakwaters (McCartney 1985).
4. Floating breakwaters produce minimal interference on water circulation, sediment transport, and fish migration (Kelly 1999).
5. Floating breakwaters can be easily moved and rearranged in different layouts or transported to another site (Hales 1981).
6. If ice formation presents a problem, floating breakwaters can be removed from the site (McCartney 1985).
7. Floating breakwaters are not as obtrusive as fixed breakwaters and can be more aesthetically pleasing (McCartney 1985).

Some of the disadvantages of floating breakwaters are the following:

1. Floating breakwaters are less effective in reducing wave heights for slow waves than fixed structures are; a practical upper limit for the design wave period is in the range of 4 to 6 seconds (equal to a minimum frequency of 1.0 rad/s to 1.6 rad/s) (Tsinker 1995).
2. Floating breakwaters are susceptible to structural failure during catastrophic storms (Tsinker 1995).
3. If the structure fails and is detached from its moorings, the breakwater may become a hazard (Kelly 1999).
4. Relative to common fixed breakwaters, floating breakwaters require a high amount of maintenance (Tsinker 1995).

Advantages and disadvantages of the use of inflatable breakwaters came up during a discussion with Mr. Howard Kelly of the Naval Facilities Engineering Command in Norfolk, Virginia in July of 1999. Mr. Kelly stated that some potential advantages to using inflatable structures as breakwaters include the following:

1. As opposed to a rigid breakwater, which absorbs wave energy by its mass and mooring system, inflatable breakwaters may absorb energy through the structure’s deformations as well.

2. When the breakwater is not required, it may be deflated and stored efficiently.
3. The breakwater may be inflated onshore or on a ship.
4. Moorings could be left in place and structures floated to the site when needed.

Some disadvantages may include the following:

1. Inflating and towing would require higher labor costs than structures which are left in place.
2. The structure has the possibility of becoming punctured.

There are an extensive number of different types of floating breakwaters in existence today. The types of floating breakwaters may be seen as combinations of variations of materials, breakwater shape, its mooring system (including configuration), and its function. These variables generate a large list of possible floating breakwaters; however, they can be divided into four basic groups: box, pontoon, mat, and tethered float (McCartney 1985).

Most box-type breakwaters are reinforced concrete, rectangular-shaped modules that may be flexibly or rigidly connected to other modules to make a larger breakwater. Box breakwaters may also be constructed of steel or even barges. These structures have proved to be effective and have several uses, including recreational and temporary boat moorage. The main disadvantages for these structures are that they are considerably more expensive than mat types and require higher maintenance. One parameter that restricts the design of these structures is the L/W (wavelength-to-breakwater width) ratio. McCartney (1985) shows that as this value increases, the wave transmission coefficient decreases. The wave transmission coefficient is the ratio between the wave height after striking the breakwater and the incident wave height. For design purposes, the wave transmission coefficient should be as low as possible for the given case; this indicates that the wave heights are being decreased.

Pontoon types include several different models, such as the ladder type, catamaran type, sloping-float (inclined pontoon), and a frame type. This group of breakwaters has been investigated extensively by experimentalists and theorists. These prismatic structures are ideal for other uses such as floating walkways, storage, boat moorings, and fishing piers (Hales 1981). Pontoon types are generally less expensive than box types and have similar advantages and disadvantages to the box type. Attention must be paid to the L/W parameter, to control deformation, as it was in the box type (McCartney 1985).

An interesting way of dealing with the ever-increasing number of old tires is to bind a group of them together to create a floating breakwater. There are three basic designs for tire mat breakwaters; these are known as Wave Maze, Goodyear, and Wave-Guard (Hales 1981). The many advantages and disadvantages were discussed by DeYoung (1978) and McCartney (1985). Some advantages of the tire mat breakwater include low cost, simple design and construction, portability, low anchor loads, and greater effectiveness than box and pontoon types. Disadvantages include lack of buoyancy, 15-20 year design life, they do not effectively damp long wave lengths, they cannot be moored year round because of icing effects, and they can break apart if not constructed adequately and then they would create floating debris.

The last type of floating breakwater is the subject of this thesis, the tethered (moored) floating breakwater. Unlike the other types of breakwaters, which use their mass to attenuate waves, the tethered floating breakwater uses its mooring system to dissipate wave energy. This is accomplished by restricting the motions of the breakwater by use of a mooring system. Waves move the breakwater around until the mooring system restricts its motion; then wave energy is transferred to the anchors and ultimately the sea floor, dissipating the wave height. Work involving this type of breakwater has been performed by Mays (1997, 1999) and Archilla (1999); however, this type of breakwater is still under investigation and there is not a significant amount of information on these moored breakwaters to make any conclusive remarks. Thus, the remainder of this literature review will cover the theoretical and limited experimental research completed on these types of breakwaters, along with a review of applicable mooring systems and slack/taut behavior of cables.

1.2.2 Mooring Systems

Several reviews of mooring systems have been conducted. There are several types of systems used to moor a breakwater to the sea floor. Some of these are piling, mass anchors and line, and stake piles and line (McCartney 1985). The choice of a mooring system depends on the type of breakwater to be used and the site conditions where it is to be placed. This investigation will be concerned with the lines used in a mooring system and not the anchors. McCartney (1985) discusses further about the configuration of mooring lines and types of materials used.

1.2.2.1 Materials

There are several types of materials, mooring line setups, and configurations that have been discussed in the literature. McCartney (1985) and Skop (1988) both discuss the material and mechanical properties and characteristics of different material types used for mooring lines. A wide variety of available materials were covered, such as synthetic line, chain, and wire ropes or cables. Sensibly, the mooring system must possess a high resistance to corrosion and wear due to the harsh environment in which it is exposed. The offshore industry is starting to use synthetic materials in mooring systems because they are corrosion resistant and are lighter than the steel materials commonly used. Several types of synthetic materials are available for mooring systems; these materials include nylon, dacron, polyester, polypropylene, polyethylene, and kevlar. Ansari (1980) discusses how sometimes a mooring system may be segmented in a multicomponent setup with a combination of materials used in one single line. For example, steel chain is commonly connected to the anchor (to provide extra weight and abrasion resistance) and the floating body (to provide extra strength and weight for added stability), with a different material in between for economic, mechanical, and property reasons. Other papers dealing with mooring systems include Gaythwaite (1987), Chaplin and Del Vecchio (1992), D'Souza et al. (1993), Dercksen and Hoppe (1994), Bernitsas et al. (1996), and Szelangiewicz (1996). Whatever the material used, the mooring system must be designed adequately to resist the mooring forces induced by the absorbed wave energy.

1.2.2.2 Cables

This investigation will consider a non-segmented homogeneous mooring line. String, rope, wire, chain links, and cables are all members of a family known as tension members. A tension member has the interesting property of being able to resist tensile forces but poorly resists flexure and compression. A cable is typically known and referred to as a steel member either in strand or wire rope form used to transfer tensile forces. Cables, in one form or another, have been used for centuries as structural components. Many ancient civilizations, like the Chinese and Incas, constructed suspension bridges to span rivers and gorges. Handmade forms of cables date back to Babylonian and Roman times. Not until 1834 did a German, A. Albert, first produce wire rope mechanically. The methods he used to produce this early cable are still used today (Scalzi et al. 1969). Applications of cables in structures include suspension bridges, marine anchoring systems (e.g., buoy anchors), wind-resisting systems in buildings (e.g., lateral X bracing), construction applications (e.g., cranes), towing and securing of objects (e.g., tugboats and mooring), and even in space as tethering components. Cables are everywhere and it is hard not to see a use for them as structural components.

The major disadvantage of cables is that they lack rigidity in bending and compression and are useful only when a member in a structure is designed to carry tension or when a component must have little resistance to bending. This property makes cables ideal for use in mooring systems. Leonard (1988) states some of the advantages of cable members for use as structural components:

1. They are lightweight and collapsible, and therefore easy to transport and erect.
2. They can be prefabricated in a factory, have low installation costs, and are potentially relocatable.
3. Loads can be efficiently carried by direct stress without bending.
4. They are load-adaptive in that the members change geometry to better accommodate changes in load patterns and magnitudes.

Also, cables can be quite pleasing aesthetically when left exposed to the public eye. An excellent example of this is the Brooklyn Bridge in New York City with its diagonal cable stays. With these considerations in mind, an engineer can easily take advantage of the properties of cables in order to design a safe and economic structure.

1.2.2.3 Analysis of Cables

In order for engineers to design an adequate cable component, they must analyze it for static and dynamic loads. As seen in texts such as those by Irvine (1981) and Leonard (1988), there has been much research and analysis on cable configurations under static conditions. These texts give standard equations for various geometric configurations of cables under different loading conditions. Using geometric and trigonometric principles and basic laws of statics, one can analyze a cable structure under static loads fairly easily.

The primary focus of recent research has been the response of cables under dynamic loading conditions. The two chief dynamic responses of cables include free movement and vibration. Free movement is the behavior of a cable as it moves freely in space. Irvine (1981) discusses the vibration analysis of cables. Time-varying forces such as wind, wave action, and earthquake loading may cause these vibrations. Bathe (1982) states that if time-varying forces shake a structure at less than one-third of the lowest natural frequency of vibration for the structure, the response is essentially static in nature and dynamic motions and stresses can be considered to be negligible. At higher frequencies the inertial forces on the structural components are mobilized and dynamic motions become important. For extremely high frequencies, greater than four times the highest natural frequency of vibration for the structure, there is insufficient time for the structure to respond to the load before the direction of load reverses, and therefore the dynamic motions may be small.

Leonard (1988) states that in tension structures, the stiffness is relatively small compared to other structural components, but their mass may be large because of attached components or cladding. Since natural frequencies are proportional to the square root of the stiffness-to-mass ratio, the natural frequencies of tension structures can be expected to be smaller than for most other structural types. Dynamic responses to time-varying loads are more significant for tension structures in that dynamic stresses superposed on loading may lead to failure of members as a result of overstressing or fatigue. Leonard (1988) continues to say that stiffness is proportional to cable tension, that is, if a tensile component is overstressed by an applied load, the natural frequency will drop, because frequency is proportional to stiffness, making the component more susceptible to dynamic load responses.

Hence, since cables have little stiffness, thus producing low natural frequencies, and due to the fact that natural frequency and load are related, dynamic analysis of tension structures is vital. Dynamic analysis should be considered on a case-by-case basis, since some structures are more susceptible to dynamic load conditions (like suspension bridges) than others (like a wind-resistant component of a building). As a result, from these basic facts, much research has been done in the area of dynamic effects on cable components and cable systems involved in structures.

The major types of dynamic response phenomena associated with flexible systems are forced vibrations, self-induced vibrations (self-excitation), and flutter. Forced vibrations of flexible components and systems come from such time-varying external loads as wind, waves, or earthquakes. Structures have the ability to damp these oscillations out over time. When a structure goes through some displacement or deformation and then returns to its original configuration, the internal forces that return it are known as self-induced internal forces or self-excitation. Flutter is a vibration associated with a fluid moving across a flexible member (e.g., wind and water) and may cause failure of the structure (Scalzi et al. 1969).

These effects occur frequently in marine anchoring systems, since wave action tends to toss objects around easily, causing the mooring cables to transition between slack and taut conditions repeatedly. Therefore, mooring cable dynamics is another topic in which much research has been performed. The need for adequate marine anchoring systems for many offshore and subsea engineering projects is obvious. Researchers like Liu (1973), Lo (1982), Brekke and Gardner (1988), Niedzwecki and Thampi (1991), and Huang and Vassalos (1993, 1995, 1996) investigated many different topics involved in the area of marine cable anchorage, suggesting design criteria and methods of analysis. The development of analytical methods for nonlinear marine cable analysis has met with much difficulty since researchers were unable to solve the highly nonlinear governing equations involved in finite deformation analysis, and the stress-strain relationships for inelastic materials were not well established. But perhaps the most important reason is that the interest is such analysis was not stimulated until the widespread use of cables as structural elements occurred. Students of mechanics and applied mathematics have known small-deflection, isotropic, linearly elastic solutions for cables for many years. However, the applicability of linear solutions is limited because nonlinear effects are generally predominant in anchoring systems (Lo 1982).

1.2.3 Snap Loading

“Snap loading” and “snatch loading” are terms used to describe a dynamic response which arises when a cable goes through a transition from a slack condition to a taut condition suddenly (i.e., over a small interval of time). “Taut” in the sense of this thesis means that the cable has been stretched out and has reached its natural length. Similar but slightly different definitions will be discussed later. This phenomenon of becoming taut suddenly is like an impact and may be very violent. Because snap loading may be several orders of magnitude greater than static or simple dynamic loading, where the tension member stays taut in both cases, cables usually exhibit a jerk, accompanied by impulsive forces. This phenomenon may be attributed to the high tensile capacity but low compressive and flexural resistance of cables. Snap loading is very significant to the life of a cable, because cables are susceptible to fatigue when subjected to cyclic loading. This phenomenon has applications to other cable structures, such as suspension and cable-stay bridges, cable-suspended roof systems, and moored marine structures, all of which undergo dynamic loading. This thesis will investigate snap loading in the cables of a floating breakwater mooring system.

In Juan Archilla's Master's thesis (1999), for example, mooring lines were modeled as compressionless springs. When a line was slack (i.e., the distance between its ends was smaller than its natural length), it was assumed that the line had no effect on the breakwater. When a line was taut, it acted like a linear spring. During motions in which a line became alternately slack and taut, large tension loads (snap loads) occurred in the line during the taut phases. Here a simpler model is considered. Instead of being extensible, the lines are assumed to be inextensible. When a line becomes taut, it is assumed to instantaneously rebound and become slack again. This can be related to the motion of a bouncing ball. The objective of this thesis is to examine the behavior of mooring lines using this simple model.

Several researchers performed investigations into the phenomenon of snap loading. Snap loading is defined by the researchers as sudden re-tensioning of a slack cable, producing a spike in the tension of the member. However, not everyone described the same conditions under which this phenomenon arose. Some papers regarding this topic are summarized below. Goeller and Laura (1971) and Laura and Goeller (1971) considered experimental and analytical studies of a vertically hanging segmented cable system. The top portion is composed of steel and the bottom segment is composed of nylon. The cable was analyzed as a structure used to deliver or recover a payload from the sea floor. Forced oscillations were imposed on the system, and it was found that “snap loading” conditions occurred in the steel portion of the cable before resonance was achieved. “Snap loading” in this sense was defined as occurring when one section or both became slack and then taut all of a sudden. Impact loads from the cable becoming taut suddenly were found to be up to nine times the static payload. Such high impact loads or “snap loads” can cause catastrophic failure.

Huang and Vassalos (1993, 1995, 1996) performed a significant amount of research in determining methods for solving the highly complex dynamics of cables when used in anchoring systems. They derived mathematical models for the geometric motions of the marine cables and the forces that cables experience. Their models include allowances for the following:

1. Three-dimensional motion.
2. Large displacements. No linearization is made based on a small-amplitude motion assumption.
3. Inclusion of forces due to the weight of the cable, buoyancy, drag, and inertia of the fluid.
4. Non-uniform cables. Their approach has the capacity to include any subsystems, such as hanging weights on the cable.
5. Bi-linear axial stiffness of the cable operating in alternating taut-slack conditions.

Their models are a powerful means of solving for the dynamic responses of cables, like forces and motions. Their theoretical results were confirmed by previous experimental research. In the analyses described, they define snap loading as occurring when a portion of a cable, modeled as lumped masses connected by massless springs, becomes slack and then taut suddenly while the rest stays taut.

Liu (1973) looked at how surface waves affected the cables in mooring systems as well as when packages are being lowered to the sea floor. Liu defined three different types of tension loads on the mooring lines: static tension load, dynamic tension load, and snap load. The static tension load was simply the initial weight of the cable system. The dynamic tension load was defined as the maximum increase or decrease in tension from the static load. Snap load was defined, in this case, as the sudden tensioning of a slack cable system after a state of zero tension and is a special type of dynamic loading. It was found that this load usually occurred for very short periods of time, but was often orders of magnitude greater than static and dynamic tension loads, and would significantly impact the design of the mooring system.

The work of other authors in this area includes Suhara et al. (1981), who performed a similar analysis to Huang and Vassalos, but investigated the dynamic behavior and tension force of oscillating mooring chains. They describe snap loading as when the chain slacks and becomes taut in a short interval of time. Niedzwecki and Thampi (1991) expanded on the investigations into the dynamic response of cables when packages were being delivered to the seabed, defining snap loading as a severe impact upon re-tensioning which is several orders of magnitude larger than normal static and dynamic loads. More papers available on the slack/taut behavior of cables and mooring lines are Brekke and Gardner (1988), Milgram et al. (1988), Shin (1991), Driscoll and Iggins (1993, 1996), Patel et al. (1994), and Patel and Park (1995).

All of these investigations show that the dynamic analysis of cables is important and that the effects of snap loading should play a significant role in the design of a mooring system in marine situations. Although these authors looked at different applications of cables, they all investigated the dynamic response of these cables to external and internal effects. Their results give good insight into cable dynamics, as they propose methods for analysis and design of cable systems in marine applications especially relevant to the mooring system of a breakwater.

1.3 Need for Further Research

Most previous research studies, as seen in the previous discussion, dealt with slack/taut conditions in cables where “taut” was defined as “positive tension,” and some have talked of “snap loads” when a cable exhibits a transition form zero to positive tension in a small interval of time. Souza de Cursi (1992) defines another concept of “taut:” when a cable reaches its “natural length.” Therefore, when the distance between the ends is less than its “natural length,” the cable is thought to be slack, and conversely, when the distance between its ends is equal to its “natural length,” then it is considered to be taut. When a cable goes from a slack to a taut condition suddenly, a jerk is felt in the cable, which is analogous to an impact with some loss of energy. This situation is defined as snap loading and produces a spike in the tension of the member. This loading is considered as being felt throughout the cable and is not localized as others might suggest. Whatever the situation, when the tension peaks suddenly, this has a significant effect on the life of a cable and should be of interest. This concept has not been investigated in detail in the literature; thus, this definition of “taut” in association with the term “snap loading” will be investigated in detail in this thesis.

1.4 Scope of Research

This thesis will investigate a simple model of snap loading that occurs in the cable mooring system of a breakwater and investigate fatigue of the cables due to snap loading. Four problems were investigated. Each consisted of several cases, which were created by varying parameters and initial conditions for those cases. The basic formulation of these problems is discussed in Chapter 2. The motions of the breakwater will be studied in a two-dimensional vertical plane.

The first problem investigated is discussed in Chapter 3. This problem had the breakwater modeled as a point mass which would undergo free vibration. Free motions are where the only forces acting on the breakwater are buoyancy and gravity.

The second problem investigated is discussed in Chapter 4. This problem still had the breakwater modeled as a point mass, but it was subjected to sinusoidal horizontal and vertical forcing which when combined form an ellipse. This elliptical forcing is a mathematical model of natural wave forcing.

The third problem investigated is discussed in Chapter 5. This problem investigated free motions like the first problem, but now the point-mass breakwater is given dimensions and becomes a rigid-body breakwater with free motions.

The fourth problem and final problem investigated is discussed in Chapter 6. This problem investigated a rigid body undergoing forced wave motions. The third and fourth problems are very similar to the first and second except that angular positions and velocities of the breakwater are added. These angular variables modify the breakwater's response when a cable becomes taut; however, the solution procedure stays the same.