Chapter 1: Introduction and Literature Review

1.1 Overview

Past research has shown that moored cylinders have the potential to be effective breakwaters used to protect shorelines and offshore structures from destructive water waves. Recently, there has been an interest in inflatable, cylindrical breakwaters. Some of the advantages of using inflatable breakwaters include the flexibility for either temporary or permanent use, transportability, cost effectiveness, and ease of construction and installation.

Several studies on floating and submerged breakwaters have been conducted, but most of these studies have been linear two-dimensional analyses. The purpose of this thesis is to consider the three-dimensional nonlinear dynamics of a moored, fully submerged cylinder to be used as a breakwater. The structure to be studied in this research is a rigid, solid cylinder that is attached to the sea floor by four symmetrically placed mooring lines. A detailed description, including drawings, of the structure is provided in Chapter 2.

1.2 Literature Review

1.2.1 Floating Breakwaters

As an alternative to fixed structures, floating breakwaters were developed. An early and historical development in this area was the use of the “Bombardon” floating breakwater in World War II. Several of these steel structures in the shape of a Maltese Cross were arranged in two lines along the coast of France to aid the D-Day invasion in 1944. The controversial decision to use this floating breakwater was made after theoretical analyses and hydraulic model testing (Tsinker 1995). The “Bombardon” breakwater served its purpose to dissipate wave energy and provide shelter for invading troops during the critical initial stages of the invasion, until they failed due to an unexpected forty-year storm.

Over the years, many different types of floating breakwaters have been developed and many conclusions have been made. Some of the advantages of floating breakwaters include:

1. Floating breakwaters are an economic alternative to fixed structures for use in deeper waters (depths greater than 20 feet) (McCartney 1985).
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 the only option available (McCartney 1985).
4. Floating breakwaters minimize the interference on water circulation and fish migration (McCartney 1985).
5. If ice formation presents a problem, floating breakwaters can be removed from the site (McCartney 1985).
6. Floating breakwaters are not obtrusive and can be more aesthetically pleasing than fixed structures (McCartney 1985).
7. Floating breakwaters can easily be rearranged in a different layout or transported to another site for maximum efficiency (McCartney 1985).

Some of the disadvantages of floating breakwaters are:

1. Floating breakwaters are ineffective in reducing wave heights for slow waves; 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. Relative to conventional fixed breakwaters, floating breakwaters require a high amount of maintenance (Tsinker 1995).

The list of different types of breakwaters that have been modeled and/or constructed is quite long, but they can divided into four basic groups: box, pontoon, mat, and tethered float. Most box type breakwaters are reinforced concrete rectangular shaped modules. These structures have proved to be effective and have a 50 year design life. The main disadvantages for these structures are that they are considerably more expensive than mat types and require higher maintenance. One restricting design parameter is the L/W (wavelength-to-breakwater width) ratio (McCartney 1985). As this value increases, the wave transmission coefficient, c_t, decreases. The wave transmission coefficient is the ratio between the wave height after the breakwater to the incident wave height.

Pontoon types include several different models, such as the ladder type, catamaran type, and the frame type. Pontoon types are generally less expensive than box types and have similar advantages and disadvantages of the box type. The L/W parameter must be controlled, as it was in the box type (McCartney 1985).

There are three types of tire mat breakwaters that have been used: Wave Maze, Goodyear, and Wave-Guard. The many advantages of the tire mat type breakwaters include low cost, simple construction, portability, low anchor loads, and greater effectiveness than box and pontoon types. However, there are many serious limitations to the mat types, such as lack of buoyancy, 15-20 year design life, practical use for only moderate wave conditions (less than 3 feet high, 3-second periods), and easy accumulation of debris (McCartney 1985).

The last type of floating breakwater is the subject of this thesis, the tethered float. There is not a sufficient amount of prototype experience of these moored breakwaters to merit final conclusions. 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 Moored Structures Used as Breakwaters

There has been much research conducted in the area of moored breakwaters. Although most of the work done in this area has been for floating or partially submerged non-cylindrical structures, it is still beneficial to have a background in this field due to the fundamental relationship with the moored cylinder being considered in this thesis. Two relevant research studies will be discussed in this section.

1.2.2.1 Williams and McDougal Breakwater

Williams and McDougal (1996) conducted a two-dimensional analysis of a long tethered breakwater with a rectangular cross section. The breakwater can either be analyzed as fully submerged or surface piercing (partially submerged). The motion of the structure is described by only surge, heave, and pitch. The rectangle is moored to the sea floor by two linear springs attached at the bottom edges of the object. Fluid-structure interaction is modeled and the equations of motion (EOMs) are linearized. Small amplitude waves of constant period are repeatedly applied to the breakwater. Small-scale experimental tests were conducted to verify the theoretical results.

The main assumption in this research is the two-dimensional idealization of the problem. This can be an invalid assumption when considering the oblique nature of ocean waves. Also, linearized EOMs assume that small motions for the three degrees of freedom (DOFs) will occur.

The results of this research lead to the conclusion that the breakwater is most effective at wave frequencies near the surge natural frequency. Furthermore, the structure's effectiveness was greatest when the diffracted and radiated waves were of the same magnitude, but 180 degrees out of phase. These ideal conditions resulted in a low transmission coefficient of 0.5. The physical tests yielded reasonable agreement with the theoretical results.

1.2.2.2 Yamamoto and Yoshida Breakwater

Yamamoto and Yoshida (1979) conducted large-scale experimental tests to validate theoretical results. In Yamamoto et al. (1980), general equations were developed to model a long two-dimensional breakwater of arbitrary cross section moored to the sea floor at any location. Three DOFs were considered: sway, heave, and roll. Two specific cases were tested in the experiments. One was a three-circle cylinder, which had a cross section of three adjacent circles connected by horizontal lines at the top and bottom. Different mooring configurations were tested, including a cross mooring system. Unlike the cylinder considered in this thesis, the longitudinal axis of the three-circle cylinder was in the same direction as the wave propagation. The other cross section was a rectangle symmetrically moored to the sea floor. The mooring lines were modeled with springs.

Generally, the experimental results yielded good agreements with the theory. The three-circle cylinder was effective when large motions occurred in sway and roll. Zero transmission coefficients occurred at either very low or high frequencies, with moderate results in between. For the rectangular breakwater, the experimental results agreed with the theory at all frequencies except the natural frequencies. However, the lowest transmission coefficients still occurred near the resonant frequencies.

1.2.3 Moored Cylindrical Breakwaters

Several papers have been written on the topic of moored cylindrical breakwaters. Both fully and partially submerged, rigid and flexible cylinders have been researched. Once again, most of the research in this area has involved two-dimensional analyses and some experimental work has been conducted as well. Most of the research covered concluded that the maximum efficiency of cylindrical breakwaters occurs at the “tuning frequency,” or at the natural frequency of the breakwater.

1.2.3.1 Evans’ Cylinder

Evans and Linton (1989) conducted a two-dimensional analysis of a long, fully submerged cylinder that was constricted to small motions in heave and sway. Linear wave theory was used to model the wave forcing and damping. Theoretical results were verified with experimental results. This research concluded that a submerged cylinder can effectively reduce wave heights for a range of different frequencies. In fact, a zero transmission coefficient resulted at the tuning frequency for an infinitely long cylinder. While the assumptions made provided for a theoretically ideal situation, the work does validate the common conclusion that the breakwater is most effective when the forcing frequency equals the natural frequency of the structure.

1.2.3.2 Bristol Cylinder

The purpose of this research by Davis et al. (1981) was not to consider a submerged moored cylinder as a breakwater. Instead, the cylinder was used to transform wave energy to usable energy through the mooring lines. Several concrete cylinders were to be placed in series, normal to the direction of the incident waves. Similar to the breakwaters, the cylinders were most effective in extracting wave energy at the structure's tuning frequency. The conclusion made was that the cylinders were most effective near the wave surface. Experimental results showed fair validation to the theoretical results.

1.2.3.3 Mays' Cylinder

The research conducted by Mays et al. (1999) is the basis for this thesis. The breakwater analyzed is the exact same structure analyzed in the present research. A three-dimensional analysis of the submerged rigid cylinder moored to the sea floor by four massless mooring lines was conducted. The mooring lines were modeled as massless, taut, linear elastic springs. A boundary integral method was used to model the wave forcing and damping matrices. The nonlinear EOMs derived in this research were linearized for the analyses. The purpose of this research was to determine the effectiveness of a single cylinder and two cylinders lined up in series in attenuating the incident wave energy. Because a three-dimensional structure was developed, normal and oblique incident waves were considered. All six DOFs were taken into account: surge, heave, sway, pitch, yaw, and roll. From the boundary integral calculations, the added inertia from the water on the cylinder allowed the six "wet" natural frequencies to be computed.

The results concluded that the cylinder was most effective at its lowest natural frequency, which was a coupled mode of mostly sway with some roll. At this ideal frequency, the transmission coefficient was between 0.4 and 0.6, depending on the wave angle. The breakwater proved to be effective for greater frequencies as well, but this efficiency was lost as the incident wave angle increased. The reason for this is that for oblique angles, the wave energy can tend to pass around one of the sides of the cylinder. For the two-cylinder case, the main conclusion was that the space between the cylinders should be limited to maximize the efficiency, otherwise considerable wave energy can pass between the cylinders.

1.2.4 Mooring Systems

Several methods exist to model mooring lines. As mentioned so far, frequently linear elastic springs are used. Another model sometimes used is a series of springs connected by lumped masses. In the present study, two models are used: taut linear elastic springs and taut compressionless springs.

1.2.4.1 Materials

Skop (1988) conducted a state-of-the-art review of mooring systems. Mechanical properties and characteristics of different material types were listed. A wide variety of available materials were covered, such as conventional steel chain and wire ropes and synthetic fiber ropes. The trend in the offshore industry is to select synthetic materials because they are much lighter than steel and are corrosion resistant. The synthetic materials available for mooring systems are nylon, dacron, polyester, polypropylene, polyethylene, and kevlar. Sometimes a combination of chain and a wire is used. For example, chain links are commonly connected to the anchor (to provide extra weight and abrasion resistance) and the buoy (to provide extra strength and weight for added stability). Other papers dealing with mooring systems include Ansari (1980), Chaplin and Del Vecchio (1992), D’Souza et al. (1993), Dercksen and Hoppe (1994), Bernitsas et al. (1995), and Szelangiewicz (1996).

1.2.4.2 Slack/Taut Behavior

Under extreme loading conditions, some of the initially taut mooring lines may suddenly become slack, causing extreme loads on the cables when they return to a tensile state. This problem represents a nonlinear behavior for true mooring lines. Therefore, modeling mooring lines as regular springs is not sufficient for a nonlinear analysis. Some papers regarding this topic are summarized below.

Goeller and Laura (1971) and Laura and Goeller (1971) considered analytical and experimental studies of a vertically hanging cable system composed of steel and nylon segments. The cable was submersed in water with a payload at the bottom of the cable. Forced oscillations were imposed on the system and “snap loading” conditions occurred in the steel portion of the cable before resonance did. Impact loads, which were up to nine times the static payload, resulted. Such high impact loads can cause catastrophic failure.

Liu (1973) studied snap loads on an analytical mooring system that was composed of lumped masses connected by compressionless springs. The mooring system was loaded by surface waves. Liu defined three different types of tensions in the mooring lines: static tension load, dynamic tension load, and snap load. The static tension load was defined as the initial weight of the cable system. The maximum dynamic tension load was defined as the maximum increase or decrease in tension from the static load. Snap load was defined as the “sudden tensioning of a slack cable system.” This load usually occurred for a very short period of time, but was often orders of magnitude greater than static and dynamic tension loads. Similar models of compressionless springs are utilized in Niedzwecki and Thampi (1991), Huang and Vassalos (1993, 1995), Driscoll and Nahon (1996), and Huang (1999).

Huang and Vassalos (1993) developed a three-dimensional numerical approach for predicting snap loading of marine cables. They modeled the mooring lines with lumped masses connected by compressionless springs. The cables underwent alternating slack/taut behavior. Their theoretical results were confirmed by previous experimental research.

More papers available on the slack/taut behavior of cables and mooring lines are Brekke and Gardner (1987), Milgram et al. (1988), Shin (1991), Driscoll and Iggins (1993), Patel and Park (1993), and Patel and Wilne (1994).

1.2.5 Need For Further Research

Previous research conducted related to this thesis topic has been for two- and thee-dimensional models of cylindrical breakwaters. All of the papers discussed considered only linearized EOMs, therefore ignoring large motions. For a structure of this type, especially under extreme loading conditions, it is necessary to consider the nonlinear EOMs. Another nonlinearity yet to be considered for floating cylindrical breakwaters is the slack/taut behavior of the mooring lines. Most of the prior research used linear elastic springs to model the mooring lines. While this model may prove to be worthy for small loading conditions, it cannot be reliably trusted for large wave loads due to the instant and dramatic change in behavior of the mooring lines. Therefore, it is important to conduct a three-dimensional nonlinear dynamic analysis on this type of breakwater.

1.2.6 Scope of Work

As has been mentioned, the purpose of this research is to conduct a three-dimensional nonlinear dynamic analysis of a rigid cylinder to be used as a breakwater. The formulation of the model used is described in Chapter 2. In that chapter, the nonlinear EOMs are nondimensionalized to simplify calculations and make the results adaptable to different dimensions.

Chapter 3 investigates the “dry” damped and undamped free vibration behavior of the breakwater. The six modes of vibration are described for small motions about equilibrium. The free vibration for large initial displacements is also considered.

In Chapter 4, the forcing analysis is described and results are presented for the taut, linear elastic spring mooring line model. The behavior of the cylinder is presented for various different parameters such as damping and forcing amplitude and frequency. Normal, oblique, and longitudinal wave forces are considered. Poincaré maps are displayed to investigate chaotic behavior, where applicable.

Chapter 5 considers the same analyses conducted in Chapter 4, except for the compressionless spring model to simulate the effects of the slack/taut behavior. The effects of the different parameters on the mooring line tensions are also considered. The thesis is concluded in Chapter 6 with conclusions and recommendations for future work.