

## Chapter 7

### Summary, Conclusions, and Recommendations

#### 7.1 Summary and Conclusions

An investigation into the snap loading of cables used in the mooring system of a breakwater was carried out in this thesis. Four problems were investigated, which had the breakwater modeled in two manners undergoing two forms of forcing. Each problem consisted of several cases, which were created by varying parameters and initial conditions for those cases. The first problem investigated had the breakwater modeled as a point mass which would undergo free vibration. The second problem was with the breakwater still modeled as a point mass, but it was subjected to elliptical forcing, which is a mathematical model to simulate natural wave forcing. The third problem investigated involved free motions like the first problem, but the point-mass breakwater was given dimensions and became a rigid-body breakwater with free motions. The fourth and final problem investigated was 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 are added. These angular variables modify the breakwater's response at impact; however, the solution procedure stays the same. To get a feel for the typical responses a breakwater exhibits before a more mathematically complicated rigid-body model was investigated, a point-mass breakwater was analyzed first, which is a simpler model to handle mathematically. The rigid-body breakwater undergoing forced wave-like motions is thought to be the most realistic of the problems investigated.

A solution was developed and employed on the problems using FORTRAN. Using either an analytical or numerical solution proved acceptable for analyzing the problems. The

results of the analyses were examined in many graphical forms and interpreted in several ways. Microsoft Excel was used to plot and evaluate the data collected.

Several assumptions were utilized to perform the analysis of these highly nonlinear problems. First, the problems were analyzed in a planar fashion and the breakwater was modeled in cross-section. The breakwater was modeled in an upside-down configuration, with the breakwater hanging by two support cables. The mooring lines were assumed to be inextensible and their weight, inertia, bending resistance, and axial resistance in compression were all neglected. The only dissipation of energy in this investigation occurred at a boundary impact (i.e., when a cable reaches its natural length) where a coefficient of restitution was used. No other damping was considered in this investigation, including fluid damping and internal resistance of the cables. Added-mass effects of the fluid also were neglected. The wave forcing is mathematically modeled as a perfectly elliptical force in the vertical plane, acting as a simple harmonic function of time. In reality waves are not regular motions; they are a combination of several varying waves. The rigid-body breakwaters were either modeled as thin-walled circular structures or solid square or rectangular types.

Certain conditions were analyzed as standard conditions, and the parameters and initial conditions of the cases analyzed were varied off of this starting point. The standard conditions were chosen to induce some desired responses but were mostly arbitrary with some judgement involved. The researcher used this judgement to try to predict the actual nature of a breakwater under real conditions. There are many variables involved in this analysis. It would be impossible and not worthwhile to investigate the infinite number of cases generated from the high number of variables; thus, the cases that were analyzed represent a small portion of a larger set of variables. Therefore, all of the analyses performed during this investigation were done so with a given set of parameters and conditions corresponding to the best guess for the situation being investigated.

From the varying of the parameters and initial conditions and the interpretation of the results of the analyses carried out, several conclusions may be drawn. First, the length of the mooring line (i.e., the nondimensional radius,  $r$ ) determines how deep the breakwater is moored relative to the distance between the mooring anchorages. During this investigation, changes in this value did not seem to produce any large changes in characteristic behavior. The only effect upon the behavior of the breakwater was that with a greater radius the area of the region of possible motion is larger and there is less of a point at the bottom of the region. With this larger area and flatter bottom, the breakwater may move about the region longer before settling to the bottom. But this may also lead to the point-mass breakwater going above the top of the region or the rigid body rotating excessively.

It has been seen through this investigation that the value of the coefficient of restitution,  $e$ , has a severe impact on the snap loading (i.e., normal velocity before impact) and the extent of motions of the breakwater. As the coefficient of restitution is decreased from unity, more energy is dissipated at the time of impact and the motions of the breakwater are suppressed. It is suggested that cables with a low value of  $e$  be used to help attenuate wave motions most effectively.

Another manner in which the snap loading or normal velocity before impact is decreased is from the effect that the size and shape have on the motion of the breakwater. It was noticed that the size and shape have a definite effect on how well a breakwater will dissipate wave energy. It was found that a point-mass breakwater dissipates less energy than a rigid-body breakwater because a rigid body utilizes its rotational resistance (i.e., the mass moment of inertia) to indirectly dissipate some of the translational energy. This is accomplished because in the point-mass investigations the breakwater is infinitesimally small and thus has no rotational ability or resistance. All of the energy of a point mass goes into translational energy and the normal velocity before impact develops from the translational velocities of the breakwater at impact. However, a rigid body has rotational

ability and thus a rotational velocity as well as a rotational inertia. Some of the energy that would go into translation is converted into rotational energy and is resisted by the moment of inertia. Thus, when a breakwater strikes a boundary, it does so with less energy because the rotations are decreasing the translational energy.

Another effect of the size of the breakwater is on the shape and size of the region in which the breakwater may move about. When the breakwater is modeled as a point mass, the area of possible motion has definite boundaries. However, when the breakwater is modeled as a rigid body, the boundaries become more like regions than definite arcs because of the rotations involved in the rigid-body investigations. Also, as the size of the breakwater increases, the flatter the bottom of the region becomes because of how the breakwater is configured with the connecting ends of the cables spreading apart as the size of the breakwater increases.

The problems investigated are initial-value problems; thus the initial position of the breakwater has an obvious effect upon the motions. During the point-mass breakwater investigations, when the breakwater was analyzed under free motions, it was started initially from a height near the top of the region. This was done to give the breakwater more energy so that it would move about the region more before settling to the bottom. This settling would happen because no energy was being introduced into the system, and thus gravity controlled the motion. During the other analyses, the breakwater was given an initial position near the equilibrium state. This was done because it is felt that this is a better representation of how the breakwater would truly behave in reality. The breakwater is subjected to a gravitational force, used to model the net buoyant force in an actual floating breakwater, which would tend to pull the breakwater downwards, near the equilibrium state. The inability to accurately predict the motions of the breakwater at a certain time during the life of the breakwater make the starting position and time totally arbitrary for a given analysis. In other words, there is no way of knowing precisely how a breakwater will behave at any point in its life because of the unknown past history and

the highly nonlinear nature of its motions. Further, the many variables involved in its modeling will also contribute to an inaccurate prediction, thus it might be said that the starting position may be anywhere in the region and the starting time of zero may be thought of as a time during the breakwater's life. The decision to start the point-mass breakwater under free vibration case at a higher position was just to allow the investigators to get a sense of the range of motions and responses during an initial analysis; this height was later refined. Though the predicting of an exact starting point is impossible, an intuitive conclusion may be drawn from the fact that the breakwater will stay near the bottom of the region in reality. This is why when the other, more accurate problems were investigated, the breakwater was given an initial position near the equilibrium state.

An interesting phenomenon was noticed while performing the forced motion analyses; this is the concept of the critical force. The critical force has been defined in two manners during this investigation. The first definition arose from the point-mass breakwater case. Here, the critical force is defined as the forcing amplitude which would cause the breakwater to hit the upper boundary ( $y=h$ ), which indicates that the forcing was so large that it controlled the motions of the breakwater and caused it to hit the sea floor. The second critical force came about from the rigid-body breakwater analysis. Here, the critical forcing was defined as the force that causes the breakwater to rotate more than  $\pm\pi/2$ . This limit is reached before the  $y=h$  limit in this problem and is significant in the sense that if the breakwater rotates past this value, the mooring lines may become entangled, which is undesirable. Further, in this situation the analysis discussed in this thesis is invalid. It was seen that the critical force solutions as a function of the coefficient of restitution or the forcing frequency are not monotonic in nature; they contain some local maxima and minima. The breakwater will be most effective in attenuating waves when the forcing amplitude is below the critical force for a given set of conditions. All of the forcing parameters are important to the response of the breakwaters. As stated above, the critical force is an important consideration in an

analysis and is dependent upon the parameters used in the analysis. Thus, a slight variation in these parameters may cause a point-mass breakwater to hit the upper boundary or cause the rigid-body breakwater to rotate excessively. A breakwater should be designed to prevent these excessive motions.

The special situations where either sliding or rocking or both occur during the motions of a breakwater were considered. These special motions were found to occur in several combinations and may arise during any analysis if the conditions are right. These motions were more likely to occur in the rigid-body investigations because of the rigid body's rotational ability. Both sliding and rocking occurred when the normal velocity before impact was very low. With sliding, in addition to a low normal velocity before impact, if the wave forcing was pushing a breakwater into a boundary (i.e., one cable is taut) then the breakwater may begin to slide on the boundary. This motion would last until the wave forcing changed direction and pulled the breakwater off of the boundary or the other cable became taut and the breakwater started to rock. With rocking, in addition to a low normal velocity before impact, if the breakwater was near the bottom of the region and both cables became taut, the breakwater may begin to rock. This motion would cease when the forcing would cause either one or both of the cables to become slack. Thus, the breakwater may begin to slide or go into slack motions after rocking. Rocking was found to occur at low values of forcing amplitude, but is possible during any analysis if the conditions are right. In fact, both of these special motions were found to occur at almost any set of parameters and conditions if the conditions are right to induce the motions. Thus, an analysis that includes slack motions, sliding motions, and rocking motions is necessary because it is hard to predict when one or both of the special situations may occur.

The life of a mooring line is affected by the number of times it experiences a transition from a slack condition to a taut condition (i.e., impacting a boundary), and by the magnitude of the normal velocity (i.e., snap load). Numerical results of these important

points may be seen in the previously discussed norms for the different problems investigated. Therefore the type of analysis presented here, using a simple impact model of snap loading, may be useful in assessing fatigue of mooring lines for various types of moored structures, as well as for other applications of cables, e.g., suspension and cable-stay bridges, cable-suspended roof systems, toelines, tethers, and guy wires.

In conclusion, the rigid-body breakwater, which undergoes wave forcing, was believed to be the more realistic model used during this investigation, because of the significant effects that rotations have on the breakwater's response. A rigid-body model of a moored breakwater was thought to have the ability to transform translational energy into rotational energy and thus reduce snap loading at higher values of forcing amplitude because of the rotations involved. The rigid-body model was found to be more sensitive to its definition of critical force than the point-mass model. However, because the shape, the ability to rotate, and the definition of critical force all differed between the two models, a direct comparison of results can not be made. Further, it was found that energy was dissipated most effectively by use of mooring lines with a low coefficient of restitution.

## **7.2 Recommendations**

There are several refinements and extensions that may be made to the models used in this investigation. It is recommended that these refinements be made and the research in this thesis be continued so that a more accurate model may be used to investigate the snap loading of cables used in moored breakwaters. Below are some of the suggested refinements to the models.

Most importantly, a more accurate analysis may be conducted to include parameters that were either neglected in assumptions or simplified to make the analysis conducted in this thesis easier. First, an analysis may be performed which would include the fluid inertia

and damping forces induced by the breakwater and its mooring lines moving through the fluid.

Next, the “impact” or sudden tensioning of a slack cable used in this thesis may be modeled as a non-instantaneous action. In other words, a mooring line may be modeled as an extensible cable. This could be accomplished by treating the cable as a very stiff spring which would take time to deform instead of instantaneously rebounding. Further, the inertia, internal energy dissipation abilities, weight, bending resistance, and axial resistance of the cables may be included in the mooring line model.

The breakwater may be modeled right side up instead of the simplification used in this thesis of upside-down. Further, the configuration may be made unsymmetrical where the spacing is not identical and is varied. This would cause the cable lengths to be varied as well.

The breakwater may be modeled in its true three-dimensional form. This would include cables on both sides of both ends of the cylindrical or 3-D rectangular breakwater. Also a cable may be attached to the ends of the breakwater for added lateral stability. All of the motion responses of these cables may be analyzed in three dimensions.

The wave forcing may be modeled more accurately to what it truly is in nature. This means that the wave forcing is dependent upon position. Actual wave motions decrease with depth. The model used in this thesis has the wave forcing the same at any position. Further, waves may not be harmonic, as they were assumed to be in this investigation. A wave model that best depicts the natural nonharmonic motions of waves should be used.

A non-rigid inflatable breakwater model may be investigated. An inflatable breakwater would have the ability to deform as well as move around under wave forcing. This deformation would be just another manner in which energy may be dissipated from

waves. Investigations may show that a deformable inflatable breakwater is better at dissipating wave energy than a rigid-body breakwater.

Lastly, either a scale or a full-scale model of a moored breakwater may be constructed to experimentally, rather than analytically, investigate the responses of a breakwater. The experimental results from the physical models may be compared with the results from this study and other studies conducted in the future.