

# **Bending Fatigue Analysis of Sea Floor Observatory Moorings**

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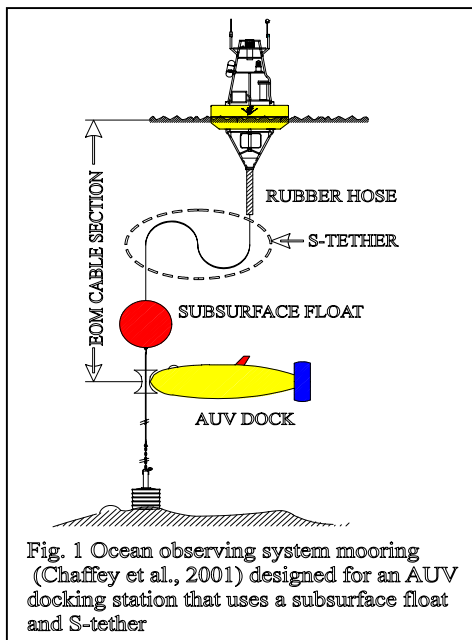
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## **ABSTRACT**

The purpose of this paper is to provide design criteria for seafloor observatory moorings for which the principle mooring line element is an electro-mechanical (EM) cable. A single point mooring system that consists of a disc surface buoy, an S-tether, a subsurface buoy, and an anchor is considered for this analysis. The waves are assumed random and modeled using the Pierson-Moskowitz spectrum. When such mooring systems are analyzed, the maximum tension at the surface buoy, subsurface buoy, and the anchor are often used to evaluate a particular mooring design. However, the copper wires of an EM cable often fail where it is connected to the subsurface buoy due to bending fatigue. In this study, bending fatigue damage is used to arrive at an optimal design and to estimate the operational life.

Surface moorings that use electro-mechanical (EM) cables are being proposed as platforms for making long-term, time-series measurements of the ocean and ocean floors for oceanographic, climatic, and meteorological investigations (Detrick *et al.*, 2000; Chaffey *et al.*, 2001; NAS/NRC, 2000). EM cables are designed to carry power from the surface buoy to instruments that are attached to the cable or placed on the seafloor. Data from the instruments travel up the cable to the surface buoy where they are transmitted ashore via satellite. Such an arrangement allows for the collection of large amounts of data at high sampling rates, which is difficult to accomplish with present-day, self-recording instruments or acoustically linked observatories. An EM cable is essential for subsurface activities that require either a high data transfer rate or high power consumption. In addition, the new moorings allow for the data to be examined and analyzed almost immediately.

In this paper, we will analyze a single point mooring system with a subsurface buoy and an S-tether as shown in Figure 1. The S-tether is a long section of the EM cable, a portion of which is made positively buoyant (by attaching floats) and a portion of which is made negatively buoyant (by using steel-armored EM cable or attaching weights to EM cable). In a traditional mooring, a reduction in dynamic tension (due to wave action) is achieved through a large scope (the ratio of the mooring length to the ocean depth). Wave action then picks up or lays down a



section of the mooring line from the bottom rather than contributing to dynamic tension. The S-tether provides the same geometric compliance via an S-shape that contracts or expands according to the wave action. Unlike the traditional mooring with large scope, the S-tether limits the interaction with the bottom and opportunities for cable abrasion. In addition, the S-tether provides a high degree of isolation between the sea surface, where most of the dynamic loads are applied, and the portion of the cable below the S-tether.

The design challenge of these moorings is in dealing with the EM cables. The copper conductors

and optical fibers cannot stretch or bend as much as traditional mooring materials. In order to maintain the integrity of these elements, the strength member of the cable (either steel or synthetic Vectran) is quite stiff. Experience has shown that the EM elements typically fail at the connection between the cable and the buoy, and special measures must be taken to minimize stress at this connection. WHOI engineers have devised rubber connections, called snubbers, and helical paths for the conductors and optical fibers in the upper 10 to 30 meters of the mooring (Paul *et al.*, 1999). These steps have improved system performance, but failures of copper conductors and optical fibers still occur at the connection. Moored buoy systems are used in remote areas where these failures can be quite costly. Therefore, a full understanding of the failure mechanism of the EM buoy system is necessary to improve reliability and have a predictive ability.

Until now, the design of the S-tether has involved a certain degree of guesswork. Each effort usually starts from scratch with little idea of what effect changing the different parameters has on the overall mooring dynamics. For example, how deep should the subsurface float be placed and how buoyant should it be? What is the effect of not using a subsurface float? How long should the S-tether be? What percentage of the S-tether should be positively buoyant and what percentage should be negatively buoyant? How buoyant should the buoyant section of the S-tether be and how heavy should the weighted section of the S-tether be?

In previous studies (Detrick *et al.*, 2000; Paul *et al.*, 1999; Han and Grosenbaugh, 2003), only axial tension was considered in evaluating particular mooring designs. The parameters of a certain mooring system design were optimized in terms of the maximum tension (defined as the sum of the mean and four times the STD) at the anchor and the snubber, where one-time

excessive loads may be detrimental. This approach, however, does not take into account the most common failure scenario, the bending fatigue at terminations, nor does it provide us with a mean to estimate the operational life of the mooring. The reason why only the maximum tensions were considered is because the fatigue failure of a cable is a difficult problem, and it has only recently been treated theoretically for deterministic loads.

When cables fail at terminations or connections, bending fatigue is a primary cause. For a given rod, the maximum bending stress depends on the radius of curvature. In the case of a strand (with a king wire in the center and the layers of wires wound around it), it is tempting to calculate the stresses in the individual wires assuming that they do not interact with each other (*eg.* no friction). However, experimental data show that the strand almost always fails near the neutral axis of the cable, where the relative motion between the outer two layers is the largest. This reveals that the friction must play an important role in the bending fatigue of cables. In fact, the failure is due to the stress caused by the interlayer fretting or sawing actions between the two layers. For a cable under constant tension and alternating curvature (between  $-\kappa$  and  $+\kappa$ ), Raouf (1988, 1990, 1992) showed that a single *S-N* curve can be drawn in terms of the *contact stress-slip parameter* for cables with various dimensions and construction methods. The contact stress-slip parameter depends on the construction method (lay angles, wire radii, helix angle, and etc), mean axial strain, and the alternating curvature.

In this study, we attempt to apply Raouf's results to evaluate the fatigue damage in the cable of the sea floor observatory mooring system (just above the subsurface buoy) subjected to current, wind, and random waves. The bending fatigue damages per unit cycle for different designs are compared to arrive at an optimal design. We first obtain the responses of the moored buoy systems using WHOI Cable, a general-purpose code that was developed at Woods Hole Oceanographic Institution for calculating the statics and dynamics of moored and towed oceanographic systems (Gobat and Grosenbaugh, 2000). The finite difference time domain simulation is built around a mathematical model of cable dynamics (Tjavaras, 1996). We assume that the vertical displacement of the surface buoy follows the random wave elevation, which is modeled by the Pierson-Moskowitz spectrum.

Secondly, Raouf's contact stress-slip parameter is obtained as a function of time for a given response. The distribution of the peaks of the contact stress-slip parameter is expressed using the Rice distribution. The fatigue damage is then calculated using the *S-N* curve proposed by Raouf.

Lastly, the fatigue damage for different mooring designs are compared, and the operational life is estimated. The results are then compared to the ones obtained using the

maximum tension at the anchor and the snubber (Han and Grosenbaugh, 2003).

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