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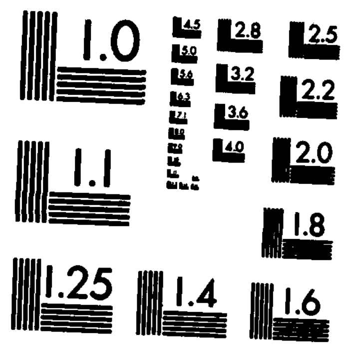

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STATIC AND DYNAMIC ANALYSIS OF A DEEP-WATER SUBSURFACE MOOR'NG FOR NEAR-SURFACE CURRENT MEASUREMENTS

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Abstract

The performance of a single-point subsurface mooring for near-surface curre measurements in the Gulf of Mexico is examined. Using state-of-the-art computer programs for static and dynamic analysis of single-point moorings, the response a proposed design to forcing caused by ocean currents, waves, and deployment is predicted. These predictions are, in turn, compared with the performance criter specified to evaluate the proposed design. It is found that the proposed design is reasonably rigid and, with high probability, will survive the environmental co ditions assumed. Selected computer solutions are shown and discussed.

Introduction

The Naval Ocean Research and Development Activity is planning an oceanograp experiment to gather data on the high frequency, high wave number fluctuations occurring in the near-surface internal waves of the central Gulf of Mexico. As illustrated in Figure 1, the experiment will use three types of instrument platforms: A ship for taking environmental data; a NOAA data buoy for taking meteorological and surface wave data; and a single-point subsurface mooring for takir ocean current and mooring dynamics data. The single-point subsurface mooring, which was selected over other classes of moorings because of cost, reliability, a deployment considerations, is the primary instrument platform. It will contain 2 current meters — 17 located in the near-surface (upper 300 m of water) and the remainder spread over a significant portion of the water depth. It will be anchored near the data buoy in about 3300 m of water, and will take data for approximately seven weeks.

During the initial planning phase of the experiment, a preliminary design of the subsurface mooring was proposed. This design is shown schematically in Figure 2, and is intended to satisfy the need for a reasonably rigid measurement pla form. As a next step in the design process, the performance of the proposed desi was predicted by using several computer programs developed for static and dynamic mooring analyses. This is an important step since it allows the designer a comparison of the probable performance with that which is desired. Also, such analy ses are useful in optimizing the design from the possibilities available.

This paper covers the problems analyzed during the initial planning phase of the experiment. Presentations include prediction of the mooring response to forc ing caused by ocean currents, waves, and system deployment. Because the forcing considered can be classified as either time-independent or time-dependent, the paper is divided appropriately into two broad analytical categories. The first

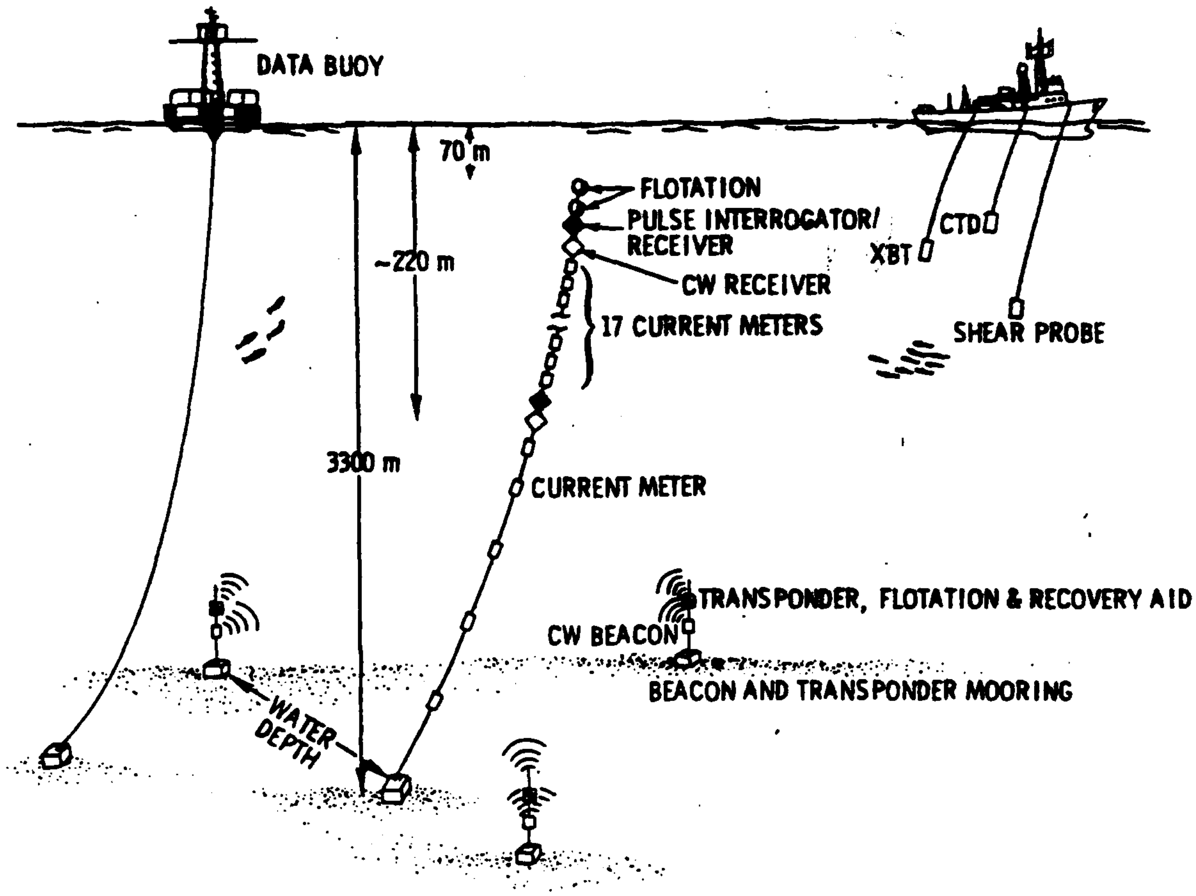

Figure 1. Schematic illustration of the experiment. As presently planned, the subsurface mooring shown in the center will be deployed in mid-December 1979. To evaluate and possibly correct the motion-contaminated current meter records, it will contain: acoustic receivers for motion measurement, and instruments for measuring such parameters as depth, temperature, tension, acceleration and inclination.

category considers the static analyses, and the second the dynamic analyses. The computer programs used to solve these analysis problems are briefly described at the beginning of each section. These computer programs are based on state-of-the-art mathematical models of cable moored systems[1] and, in addition to environmental forcing, require certain physical and hydrodynamic data for the mooring components as inputs. Reliable data for the components of the subject mooring were garnered from manufacturers data and from Reference 2.

Static Analyses

The computer programs used to solve the problems in this section are thoroughly described in References 3 and 4. They can model currents that vary in both magnitude and direction with depth. In solving the problems below, the following important features were considered: mooring line elasticity, normal and tangential hydrodynamic loading on mooring lines, forces due to gravity, in-line lengths of instruments and tackle, and drag forces on instruments.

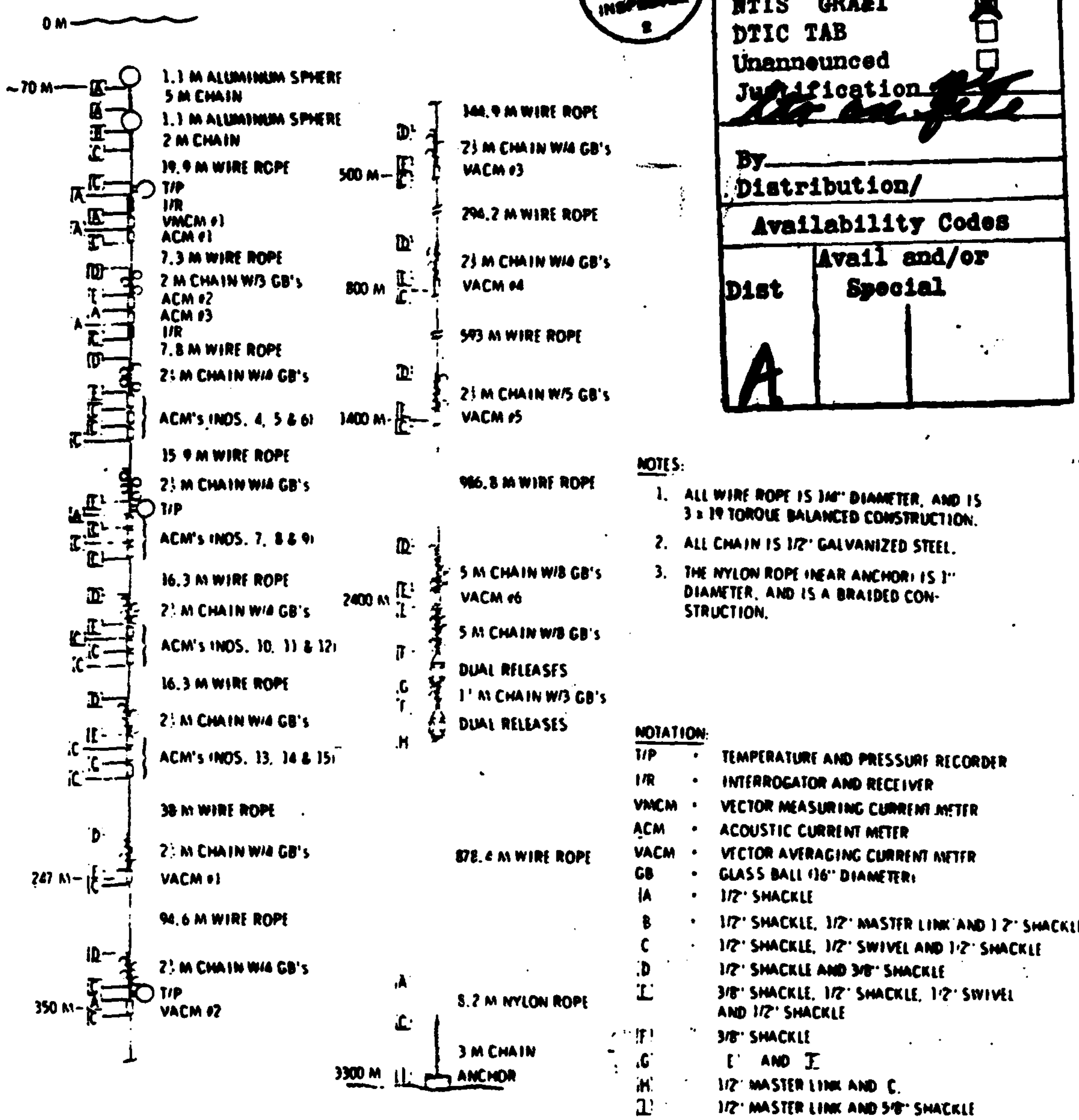

Figure 2. Preliminary design of the single-point subsurface mooring. The instruments denoted above by T/P and I/R are a tentative choice.

Design Check

The proposed design, as originally synthesized, was based on simple static, hand-calculations to size the mooring lines and tackle for adequate strength. These calculations did not include such important considerations as cable stretch, in-line lengths of instruments and tackle, back-up recovery tensions[5], and descent tensions resulting from system deployment. Hence, the problem here was to analyze the original design with the static computer programs mentioned previously, and to modify it, as necessary, to meet the following performance criteria in the absence of any currents:

a. A minimum system safety factor of 2.5 while moored and 2.0 during deployment.

b. A minimum back-up recovery tension of 440 N at any point above th upper set of acoustic releases. In the event that the mooring should break at point above the acoustic releases, this will provide sufficient buoyancy to re the mooring parts remaining.

c. The depths desired for the current meters and top buoy.

To meet these performance criteria, the original design was modified by sh ening the lengths of rope and by adding five more glass balls above the upper of acoustic releases. Figure 2 presents the proposed design with these modifi tions. It also shows the unstressed lengths of cable required to achieve the ponent depths desired. The minimum system safety factors found in the analysi were 2.7 while moored and 2.1 during deployment. This latter safety factor is based on a steel, dead-weight anchor weighing 13.34 kN in water. Also, it was found that the system has a descent rate of 90 cm/s, and that the minimum back recovery tension is 534 N.

Response to Steady-State Current Profiles

Two planar current profiles, which will be referred to in subsequent disc sions as the typical and maximum expected profiles, were used in this problem. Each of these has constant currents that act in a horizontal direction and var with depth. The typical profile (whose current varies exponentially and cosin soidally with depth) is shown in Figure 3, and the maximum expected profile (wh current varies exponentially with depth) in Figure 4. Using ocean current dat garnered from physical oceanographers, both profiles were constructed to provi worst case conditions at the site of the experiment.

The configuration of the mooring when subjected to the typical current pr file is shown in Figure 3. Although inclined, it is quite straight with tilt angles (defined with respect to the vertical) varying from about 7 to 10 degre This indicates that mooring will be reasonably rigid under normal current conditions. When subjected to the stronger maximum expected current profile, the mooring configuration changes to the one shown in Figure 4. In particular, the excursions of the top buoy change from 510 m to 640 m horizontally and from 42 to 65 m vertically. Figure 4 shows that the top two buoys remain well above th maximum allowable depth limit.

In each of the above mooring configurations, the tension distribution was found to be about the same as that of the no current mooring configuration. He the system safety factor remains essentially unchanged for the current profiles The largest horizontal component of tension at the anchor was found to be 2560 and occurs (as expected) when the mooring is subjected to the maximum expected current profile. Thus, to keep the mooring on station for the duration of the experiment, it is necessary to use an anchor that can resist this horizontal pu It can be shown that a dead-weight anchor weighing 16 kN in water has sufficien holding power[5]. Another approach, however, is to use a dead-weight anchor weig ing 13.34 kN in water in conjunction with a Danforth anchor weighing about 150 Because of its lighter weight, this latter approach is recommended.

To examine the effect of increased buoyancy and cable drag on mooring response, two cases with the typical current profile as forcing were considered. the first case, the top buoy on the mooring was replaced by one having enough buoyancy to produce a system safety factor of 2, which is a lower limit. Relat to the response of the unmodified mooring, this change resulted in an 11% decre in horizontal excursions and about a 25% decrease in system safety factor. On

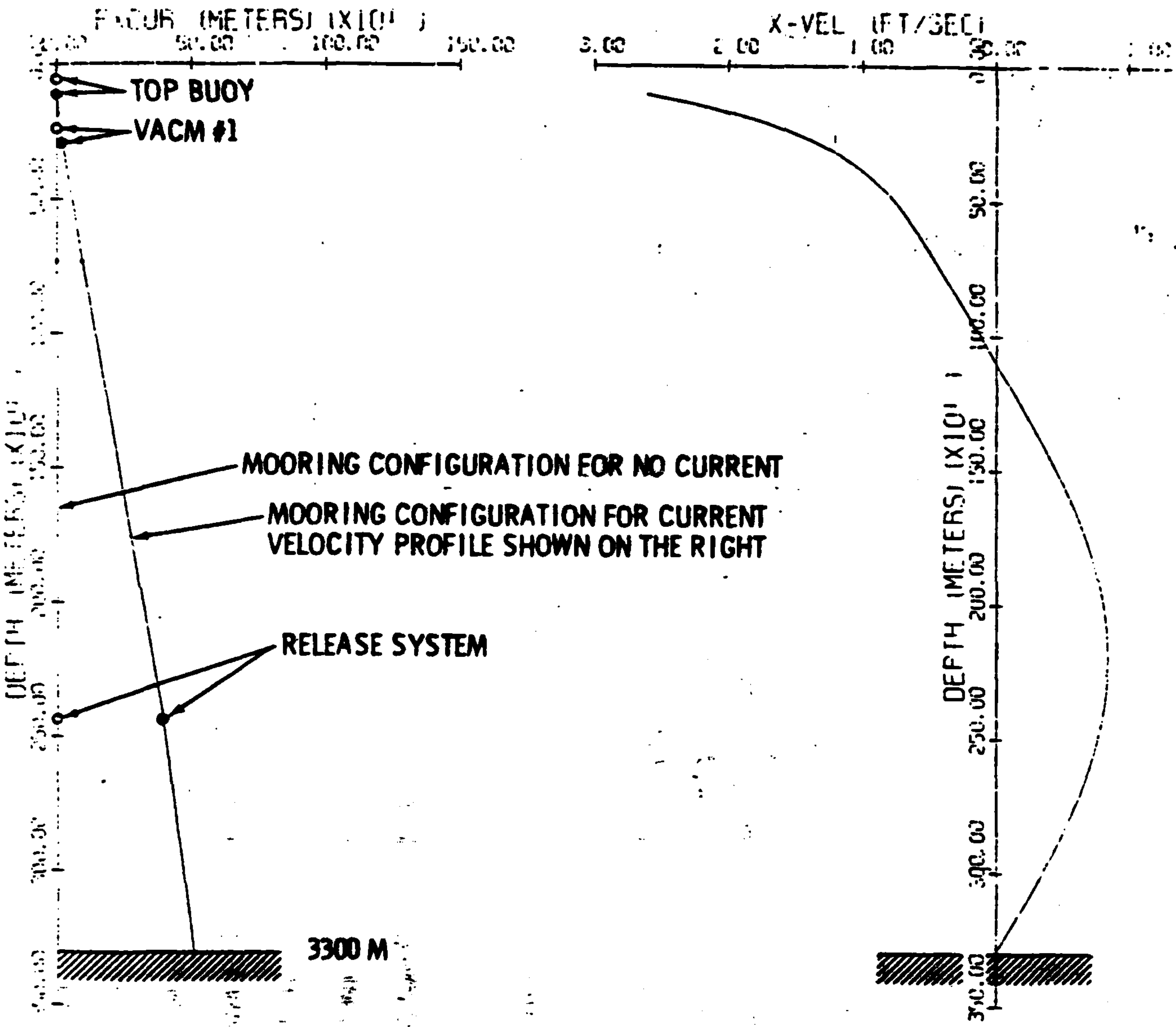

Figure 3. The mooring configuration (left) when subjected to the typical current profile (right). Note that the circles shown correspond to the no current configuration.

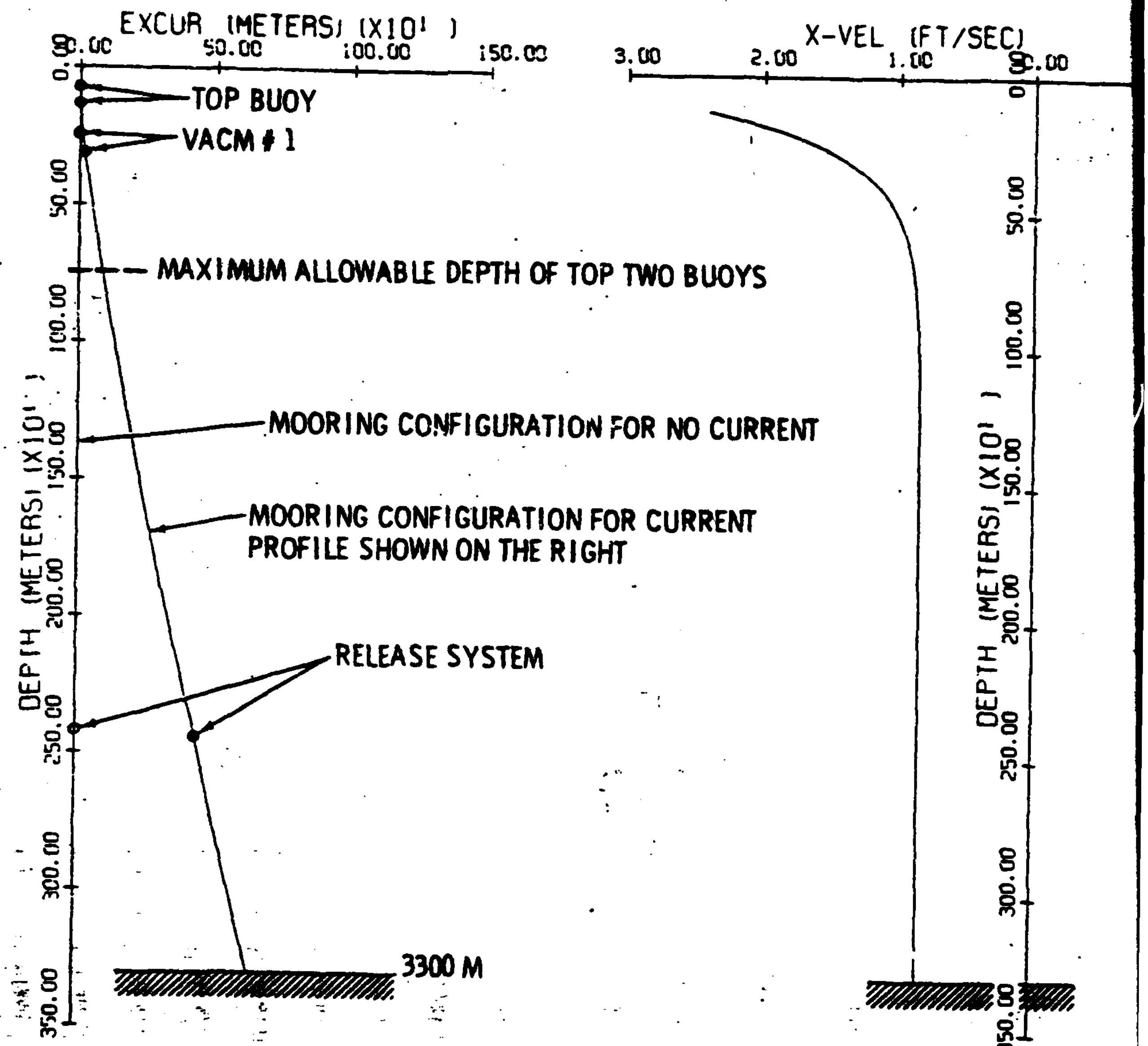

Figure 4. The mooring configuration (left) when subjected to the maximum expected current profile (right). Note that the circles shown correspond to the no current configuration.

weighing these results, it appears that the addition of buoyancy is not an attra tive design consideration. For the second case, normal drag coefficients for th mooring ropes were increased from their nominal values of 1.4 to 1.8. This chan intended to account for some degree of cable strumming, resulted in a slight increase in horizontal excursions (about 3%) and essentially no change in the mooring tensions.

Response to a Uniformly Rotating Current Profile

Because ocean currents are not steady but continuously change direction and speed, a mooring will continuously seek a new equilibrium configuration. This co tinual readjustment is termed mooring motion, and its magnitude can determine th usefulness of the mooring for current measurements. For slowly changing current it is reasonable to assume that the mooring displacements will keep up with thes currents. Hence, at any instant in time, the mooring will remain in static equilibrium with the current.

In the Gulf of Mexico, inertial and tidal currents change slowly; and, becaus of their large vertical scales, are believed to be the primary cause of low frequency mooring motion. To examine current meter errors, these currents were modeled in this problem by the typical current profile rotating at a constant rat of 2π radians in 12 h. The case of a uniformly rotating current profile is instructive since the mooring motion is most pronounced under these circumstances. Also, it simplifies the computation of current meter errors because the mooring will respond with pure rotational motion.

The horizontal motion of the mooring's current meters, found by applying a static analysis to the uniformly rotating current profile, is plotted in Figure 5 Since the motion is circular, the absolute speed of any current meter, V_m, is given by

$$V_m = \omega R$$

where ω is the constant rate of rotation and R is the horizontal excursion of the current meter. And, since V_m is perpendicular to the current, V, the relative speed measured by the current meter, V_R, is found as

$$V_R = (V^2 + V_m^2)^{1/2} = (V^2 + (\omega R)^2)^{1/2}$$

Table 1 presents some errors for selected current meters on the mooring. These errors were calculated from the following formulas:

$$E_m = (V_R - V)/V$$

and

$$E_p = \tan^{-1}(V_m/V)$$

where E_m is the speed error and E_p is the phase error. As can be seen, the speed of the uppermost meter through the water is 7.4 cm/s. Although the lower meters have less speed, some of them have significantly larger errors compared to the upper meters. This occurs, as shown in Table 1, when the meter speed approaches tha of the current.

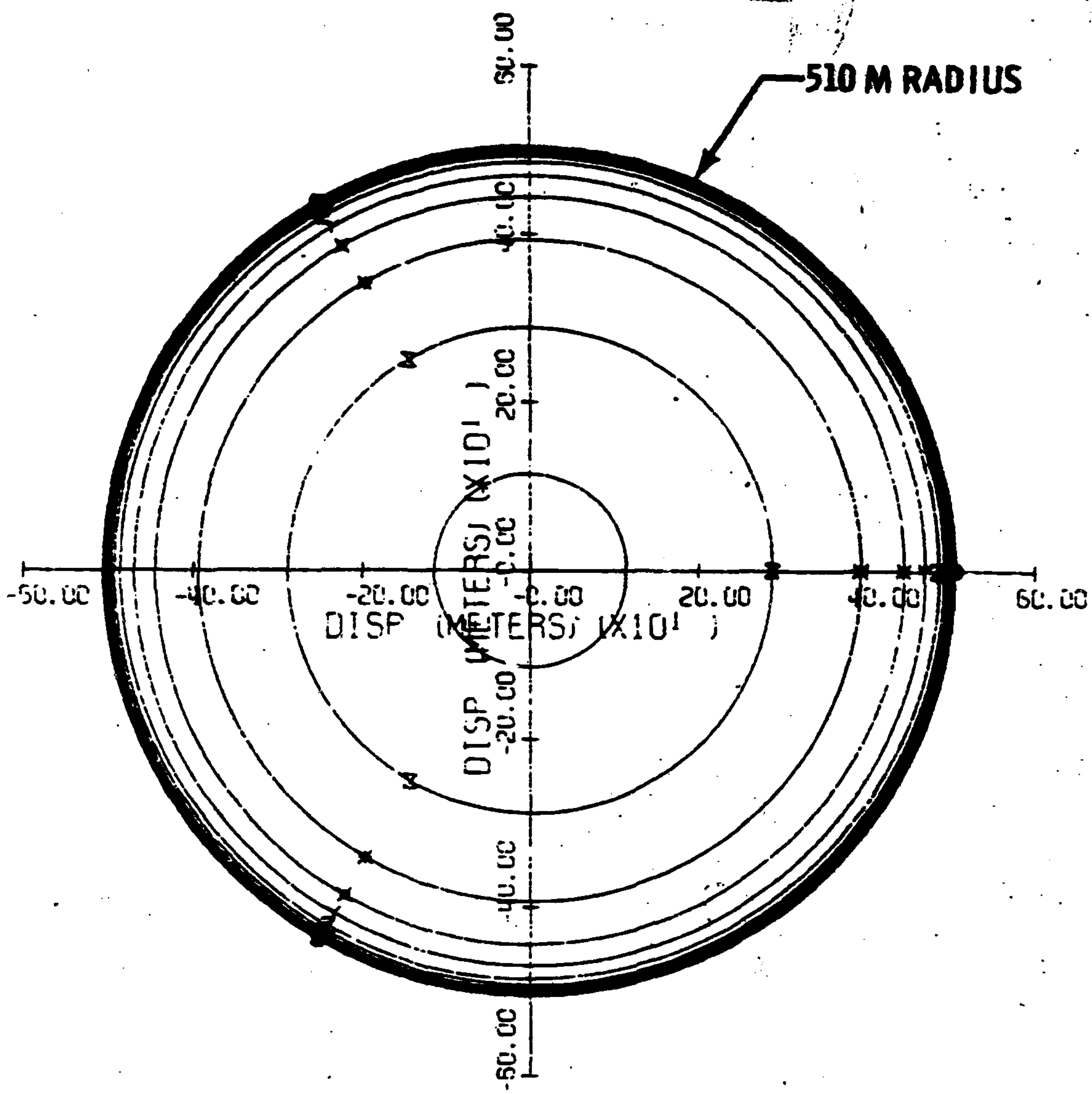

Figure 5. The circles shown represent the horizontal motion of the current meters when the mooring is subjected to the uniformly rotating current profile. The outer circles are for the uppermost current meters, and the origin of the coordinate system shown corresponds to the anchor.

TABLE 1

Mooring Response to Uniformly Rotating Current Profile

Component	Depth (m)	Horizontal excursion (m)	Tilt (degrees)	V (cm/s)	V_m (cm/s)	E_m (%)	E_p (degrees)
ACM #1	146	510	4	67.7	7.4	0.6	6.3
ACM #15	244	498	8	46.7	7.3	1.2	8.8
VACM #1	283	491	9	41.2	7.2	1.5	9.9
VACM #2	385	475	9	30.7	6.9	2.5	12.7
VACM #3	534	450	10	21.7	6.5	4.4	16.7
VACM #4	830	398	10	10.0	5.8	15.7	30.2
VACM #5	1421	292	10	-11.4	4.2	6.7	20.4
VACM #6	2405	118	10	-24.6	1.7	0.2	4.0

Dynamic Analyses

Two methods were used to solve the dynamic problems presented in this section. In one method, the mooring line was modeled as a continuous elastic material. In the other method, the mooring was represented by a lumped parameter model consisting (as shown in Figure 6) of seven masses joined by elastic springs that are capable of stretching only. The former method was used to solve the first problem given below, and the latter method the two remaining problems.

All three problems were solved in the time-domain by the computer programs described in References 6 and 7. In solving these problems, the following important features were considered: mooring line elasticity, nonlinear hydrodynamic drag forces, and inertia forces with added mass included.

Response to a Time-Varying Current Profile

In this problem, the mooring excitation is provided by ocean currents that change in magnitude and direction with depth and time. These currents, obtained from physical oceanographers who derived them from a Garrett-Munk spectrum, are believed to be the most expected currents in the area of the experiment.

Figure 7 presents the motion response of the top buoy. It can be seen that the motion is dominated by a semidiurnal oscillation, and has maximum horizontal excursions of 100 m and maximum vertical excursions of 2 m. This motion was observed throughout the mooring, but with excursions reducing from a maximum at

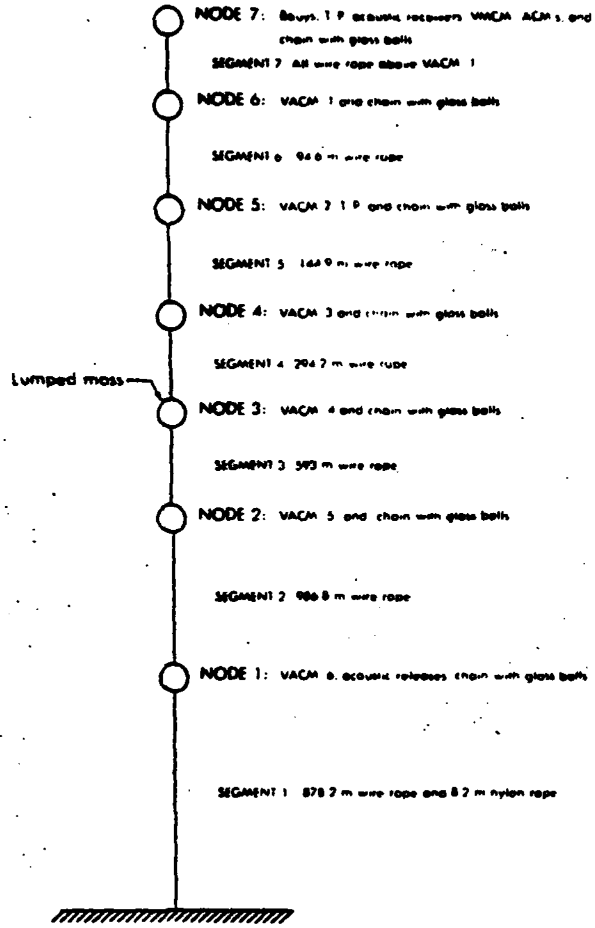

Figure 6. Lumped parameter model the subsurface mooring shown in Fig

the top buoy to zero at the anchor. In particular, excursions were reduced slightly down to the fifth VACM and by about 70% at the sixth VACM (see Figure As shown on the left of Figure 7, the horizontal motion is not circular and, o the two successive cycles shown, has a zero mean displacement.

Response to Surface Gravity Waves

Three cases were considered to examine the effect of sea state on moorin response. The mathematical model used to simulate sea state is a simple harm wave whose direction of propagation is constant with time and whose amplitude decreases with depth in the classic fashion of surface gravity waves. To pro a worst case condition, no case included ocean currents which, if present, wo mitigate the effect of waves on the mooring. Each case, described by sea sta below, has the following physical characteristics:

	Case	Wave Period (Seconds)	Surface Wave Amplitude (Meters)	Percent Attenuatio at 70 meter depth
I.	Sea State 4	7.5	1.0	0.6
II.	Sea State 6	10.0	2.0	6.0
III.	Sea State 7	15.0	5.6	29.0

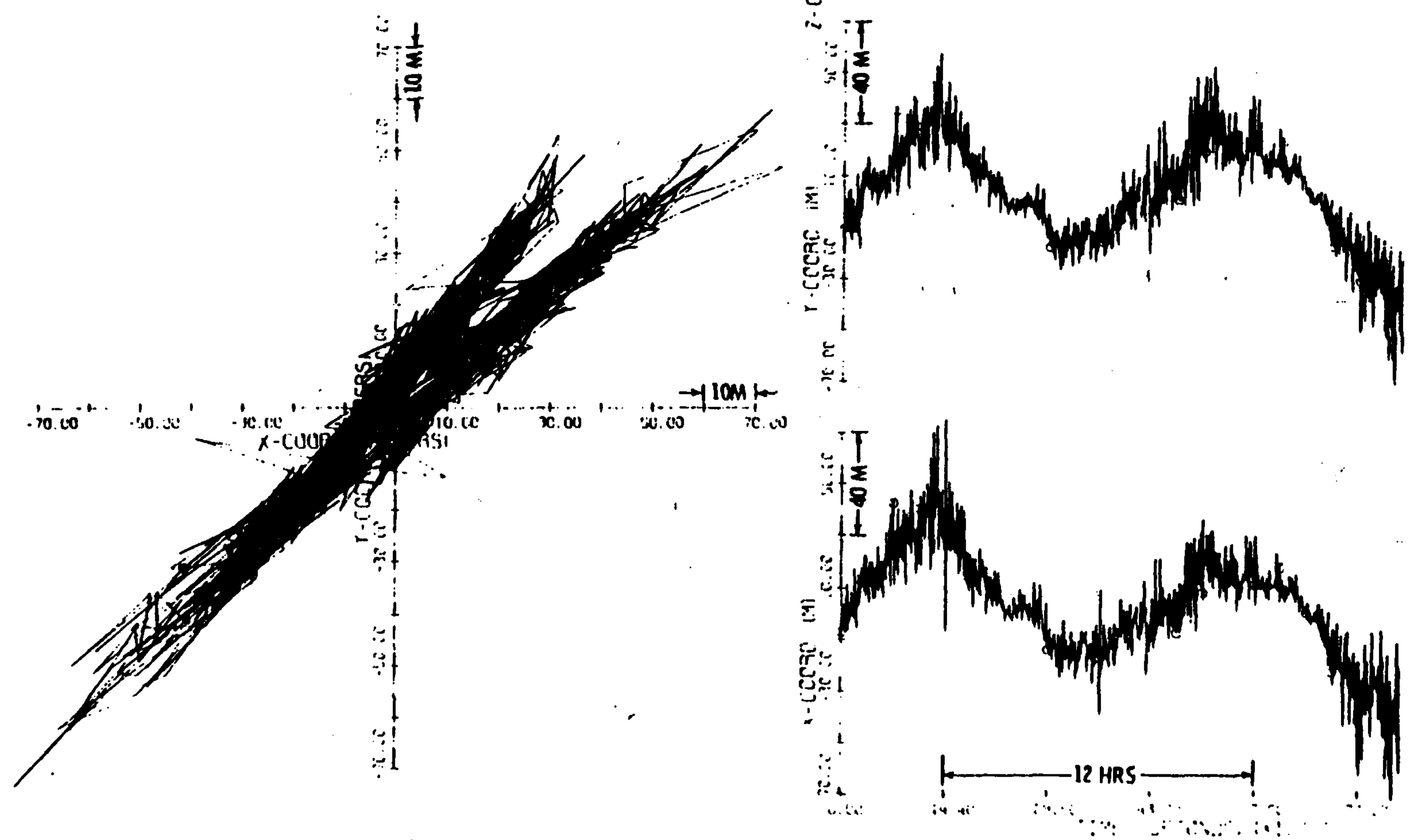

Figure 7. Motion response of the top buoy to ocean currents that change in magnitude and direction with depth and time: A time series of vertical (z-coordinate) and horizontal motion is shown on the right, and a top view of horizontal motions on the left.

where the wave period is the period of maximum wave energy, and the surface amp tude is one-half the significant wave height.

The third case, corresponding to sea state 7, has a wave period correspond to a natural frequency of the system, and was therefore selected to provide a worst case condition. Natural frequencies of the system were determined by analyzing the undamped, longitudinal vibration response of the mooring model. first three of these, found by this eigenvalue analysis, have periods of 15.0, and 2.1 seconds. For all practical purposes, surface gravity waves with periods of 3.9 seconds, or less, are completely attenuated at a 70 meter depth. Consequently, such waves were not considered.

Figure 8 presents the motion versus time response of two locations on the mooring to the 15.0 s period wave, Case III. Results for the upper portion of mooring, where 16 current meters are positioned, are shown on the left and resul for a lower portion on the right. As shown, the upper portion of mooring fluctuates 1.6 m horizontally and about 1.8 m vertically. Under the more expected s conditions given by the 7.5 s and 10.0 s period waves, it was found that the vertical fluctuations of the upper portion of mooring are 1 and 13%, respectively, of that of the 15 s period wave. Also, it is seen that the maximum tension occu in the lower portion of the mooring where fluctuations are 1330 N. More importantly, these dynamic tensions should not break the mooring line by over stressi it or by kinking it.

Transient Response During Deployment

The mooring will be deployed by the anchor-last technique. In this techniq the floats at the top of the mooring are the first components to be launched. These are then followed by the remaining mooring components up to the anchor. Finally, the anchor is dropped when on location. This problem considers the moo ing response to the free-falling anchor's impact with the ocean floor. It negle the effects of ocean currents and waves. And, it assumes that the mooring is vertical, and is falling at its terminal velocity just before impact. It furthe assumes that the anchor does not move after impact.

The results of this one-dimensional analysis are presented in Figure 9 wher longitudinal motion and tension are plotted versus time for selected points on t mooring. They are shown converging to their static values after about 1-1/2 minutes, without much overshoot. More importantly, the tensions shown remain we above any slack condition, indicating that kinking will not occur during this phase of deployment.

Summary

The response of the proposed mooring design to excitation sources related t its planned operating environment and deployment has been analyzed both statical and dynamically. Using computer programs developed for such purposes, tensions, in and motions of the subject mooring were predicted to evaluate and, if necessa to optimize the design. The static analysis type-problems have concerned the response of the mooring to steady-state currents, which are intended to represen typical and extreme conditions for the operating area. Motions caused by tidal and inertial currents, the primary cause of low frequency mooring motion, were computed using a uniformly rotating current profile. These motions were then us to estimate errors in the measured currents, assuming ideal current meters. Und these slowly changing currents, it was found that the errors in the uppermost current meters are considerably less than those found in most of the lower meter

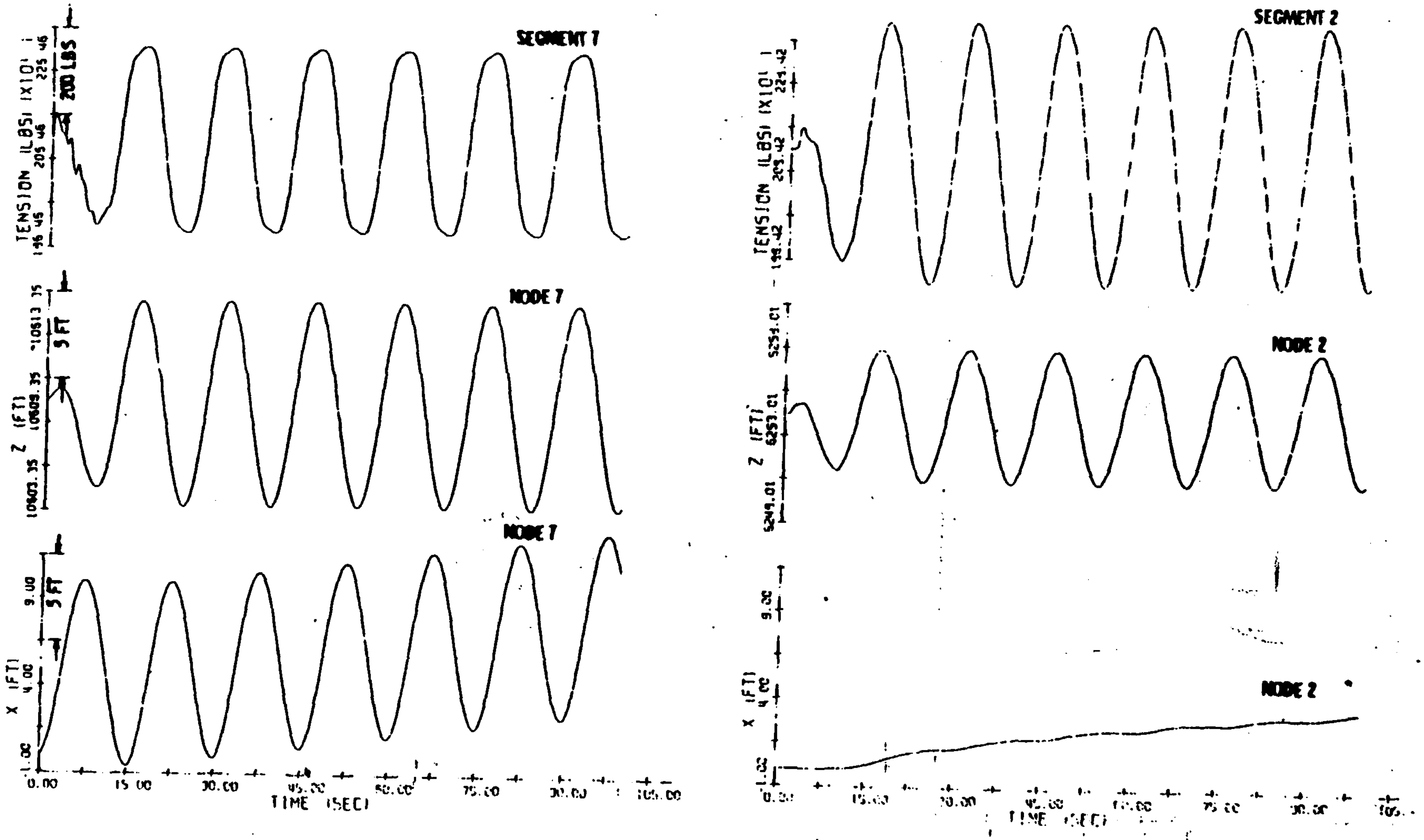

Figure 8. Response of the mooring to a surface gravity wave having a period of 15 seconds and a surface wave amplitude of 5.6 m. Refer to Figure 6 for the correspondence of mooring components to the segments and nodes shown. Note that z is the vertical coordinate measured relative to the ocean floor, and that the wave is propagating in the positive x-direction.

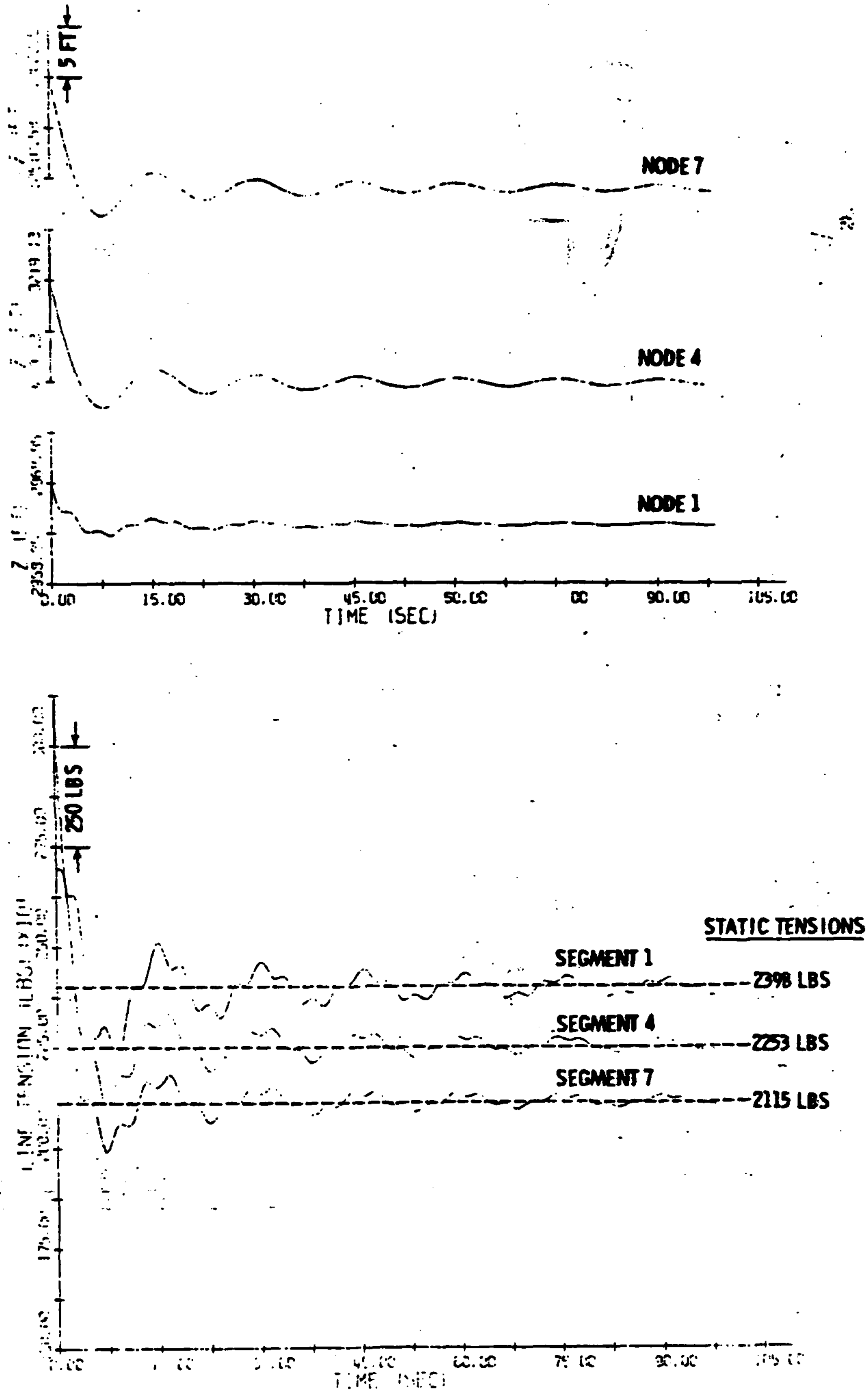

Figure 9. Response of the mooring to the free-falling anchor's impact with the ocean floor. See Figure 6 for the definition of the segments and nodes shown.

Also, at any instant in time, it was found that the mooring, although inclined, was quite straight with tilt angles varying from 7 to 10 degrees.

Using this same current profile, analyses were made to determine the effect of increased buoyancy and cable drag on mooring performance. It is concluded that the addition of buoyancy is not an attractive design consideration, and that increased cable drag caused by cable strumming only slightly effects mooring performance. Based on the analyses using the extreme steady-state currents, the following major recommendations concerning mooring components are made: Add five more glass balls above the acoustic releases for back-up recovery capability; and, use a dead-weight anchor (weighing about 13.3 kN in water) in conjunction with a Danforth anchor to keep the mooring on station for the duration of the experiment.

Three dynamic analyses were made to determine separately the effect of time-varying currents, ocean waves, and deployment on the mooring's performance. In regard to these analyses, it is concluded that under normal environmental conditions the mooring will be reasonably rigid and uneffected by ocean waves. Moreover, with high probability it should survive these and the other extreme conditions assumed.

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