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MOORING MECHANICS - A COMPREHENSIVE COMPUTER STUDY. VOLUME I. THREE DIMENSIONAL STATIC ANALYSIS AND DESIGN OF SINGLE POINT TAUT AND SLACK MOORED BUOY SYSTEMS. PART I. SURFACE MOORING LINES. PART II. SUBSURFACE MOORING LINES

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Prepared for:

Office of Naval Research

November 1973

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER R-775	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) MOORING MECHANICS - A COMPREHENSIVE COMPUTER STUDY - Three Dimensional Static Analysis and Design of Single Point Taut and Slack Moored Buoy Systems		5. TYPE OF REPORT & PERIOD COVERED Final 6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Narender K. Chhabra		8. CONTRACT OR GRANT NUMBER(s) N00014-67-A-0204-0047
9. PERFORMING ORGANIZATION NAME AND ADDRESS The Charles Stark Draper Laboratory, Inc. 68 Albany Street Cambridge, Massachusetts 02139		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS		12. REPORT DATE November 1973 13. NUMBER OF PAGES 133
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)		15. SECURITY CLASS. (of this report) UNCLASSIFIED 15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited

D D C

DEC 20 1973

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

1. Mooring Line
2. Mooring Mechanics
3. Buoy Systems Static Analysis
4. Computer Simulation of Mooring Systems

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Part I of this report deals mainly with the static case of a single point surface mooring line, and presents a computer solution to provide, with reasonable accuracy, the system's steady-state configuration with regard to geometry and line tension.

The work reported here is an extension of work presented in reference 2, and presents a three-dimensional solution to the general three-dimensional buoy system.

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The computer program presented is written in FORTRAN. A complete listing and detailed instructions for its use are included.

On IBM 360/75 typical central processor time to complete this computation for a line divided into 100 segments including I/O and plotting calculations is 6 seconds. Computational time for one integration cycle alone (from top to bottom of the line) for the same system is 0.2 seconds.

Part II of this report deals mainly with the static case of a single point subsurface mooring line, and presents a computer solution to provide, with reasonable accuracy, the system's steady-state configuration with regard to geometry and line tension.

The work reported here is an extension of work presented in reference 2, and presents a three-dimensional solution to the general three-dimensional buoy system.

The computer program presented is written in FORTRAN. A complete listing and detailed instructions for its use are included.

On IBM 360/75 typical central processor time to complete this computation for a line divided into 50 segments including I/O and plotting calculations is 3 seconds. Computation time for one integration cycle alone (from top to bottom of the line) for the same system is 0.08 seconds.

MOORING MECHANICS - A COMPREHENSIVE COMPUTER STUDY

VOLUME I

Three Dimensional Static Analysis and Design of
Single Point Taut and Slack Moored Buoy Systems.

Part I - Surface Mooring Lines
Part II - Subsurface Mooring Lines

by

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November 1973

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ACKNOWLEDGMENT

With gratitude the author acknowledges the criticism and encouragement given by Mr. John Dahlen of the Charles Stark Draper Laboratory.

I am initially indebted to the Woods Hole Oceanographic Institution and Messrs. Henri Berteaux and Robert Walden for providing encouragement and direction in my early efforts.

Help given by Barry Zack in working numerous details of the report is also gratefully acknowledged.

This report was prepared under Draper Laboratory Project 53-30210, sponsored by the Ocean Science and Technology Group of the Office of Naval Research, Department of the Navy, through Contract N-00014-67-A-0204-0047 with the Massachusetts Institute of Technology.

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PART I

SURFACE MOORING LINES

ABSTRACT

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1.0 General

1.1 Introduction

An economical and accurate analysis of mooring lines is imperative in the present days of large ships and buoys which must be anchored in the deep sea. Buoys are used by oceanographers to place instruments at relatively fixed points in the deep sea. In the past, design criteria were based mainly on intuition and/or emperical knowledge gained through a long and costly process of trial and error. It is also well known that the buoy system dynamics has considerable effects on the oceanographic data recorded by certain instruments. Mooring motion must occur in response to a change in the oceanic velocity field. If an instrument measures current, it records the current relative to the mooring line. As a result mooring motion is present as an extraneous signal in the measurements. The motion of a mooring line is thus an important feature in the interpretation of oceanographic data.

In recent years analysis of the steady-state forces acting on a deep-sea moored buoy system have been made by many people (References 1, 2, 5, 6, 9, 11), however, most of the work conducted has been restricted to taut or slightly slack mooring lines in planar flow. The presence of high currents in certain areas forces the design of slack moors. Also, relatively little work has been reported on the dynamic response of mooring lines (References 3, 4, 5, 7, 8, 10).

This report is Part 1 of a four part report and deals mainly with the static case of a single point surface mooring line. The mooring lines may vary in content and more often than not are compound. Velocity in the deep sea varies from place to place and in depth, and time.

For these reasons a computer program has been developed to study the steady-state configuration of a mooring line, making it as general as possible. The program in its present state is in three dimensions and takes into account:

a. Mooring lines made of any type or number of materials.

b. Nonlinear elasticity dependent on the prior loading history.

c. Concentrated forces applied anywhere, including ends, along the line.

d. Current profiles of any nature.

e. Gravitational and drag forces in both normal and tangential directions.

f. Any type or any number of instruments along the line including subsurface buoys.

A typical surface mooring line is shown in Fig. 1.

1.2 Assumptions, Limitations and Suggestions for Further Study

The main objective of this program is to provide with reasonable accuracy the system's steady-state configuration with regard to geometry and line tension. The mooring system is limited to a single surface buoy, an anchor on the ocean bottom and a single connecting line made up of different materials and components. The connecting line may also support any number of buoys along its length.

In its present form no allowance for shrinkage or creep of the synthetic ropes is taken into account. Elongations due to rotation of non-torque balanced cables is also not considered.

An important area which may be a cause of errors in the present program is the input information required for the solution. One of these is the drag forces experienced by various surface buoy hulls. It is important to know the effects of wave and wind drags on various buoy hulls used in the analysis. Drag coefficients for other mooring components may not be known accurately enough and need further investigation. Elastic and plastic properties of different mooring materials under the deep ocean environment is another area which needs further investigation.

2.0 Theoretical Analysis

2.1 Analysis of Forces - Static or Steady State

A mooring system has static forces applied to it which need to be analyzed with care so that the critical elements in the line can be designed to adequately withstand the stresses it would experience during its life time. The forces applied may be on the mooring line or on the surface buoy.

2.1.1 Static Forces Applied to the Mooring Line

a. Continuous Forces

These are the gravitational forces on the various components of the system, the drag forces caused by the water moving past the system and other distributed forces if any.

b. Discrete Forces

These are the concentrated forces applied along the length of the mooring line. The mooring line may have instruments placed along its length which along with their weights have drag forces applied to them. Glass balls and/or subsurface instruments placed along the mooring line may have net upward buoyancy and drag forces applied to them. Other concentrated forces may be applied to the line through a connection with another line.

2.1.2 Static Forces Applied to the Surface Buoy

The static forces applied to the surface buoy are the wind drag, water drag and the upward force at the surface. The upward force is equal and opposite to the vertical component of the tension in the line connected at the buoy. Wind and water drags are dependent on the shape of the buoy, the upward force and the water and wind velocity at the surface. The effect of waves on the drag force is not considered, but can be taken into account by adding a concentrated force at the buoy.

2.2 Stress-Strain Relations

Elasticity is allowed both in metallic and fibre parts of the mooring line to obtain realistic solutions. The stress-strain relationships for cables or ropes are different from those of the materials they are made of. These relationships depend largely on the type of construction for the cable or rope.

a. Metallic Cables

It has been observed by many investigators that a typical steel wire mooring line under tension stretches by an amount which is partly elastic elongation and partly permanent or semipermanent set probably resulting from the wires and strands becoming more tightly interlocked.

For mooring line materials as the elongations in the metallic components are very small compared to elongations in the fibre ropes a linear relationship of the type:

$$\frac{\text{Stress}}{\text{Strain}} = \text{Constant}$$

is used for metallic components. The value of this Constant is an input and is left to the discretion of the user. This Constant is usually not the same as the published value of E (Young's Modulus) for the material of the cable.

b. Fibre Ropes

Fibre ropes being much more elastic than metallic components, the permanent or semipermanent elongation is separated from elastic elongation and both elongations are calculated separately to find the total elongation. In the regions of tensions met in practice we use a relationship of the type:

$$T/d^2 = C_1 \, (\epsilon)_{200d^2}^{C_2} \tag{1}$$

where: T is the tension in cable.

d is the nominal diameter.

$(\epsilon)_{200d^2}$ is the percentage elongation with respect to length at $200d^2$ tension and, C_1, C_2 are the experimental coefficients (constants). This relationship was verified by experimentation as explained in section 4. 3. Two different equations of the type (1) are required to find the two parts (permanent and elastic) of total elongation. Then a third equation of the type:

$$(\text{length})_{200d^2} = C_3 \times \text{slack length} \tag{2}$$

is used to find the length at $200d^2$ tension. Constant C_3 is a statistical average of many experiments and is required so that a standard initial length can be achieved from which all percentages can be calculated. From these equations the total stretched length can be calculated.

2. 3 Mooring System Analysis - Static

The static analysis permits the prediction of position and tensions of each point of the cable after the forces acting on the system have been defined. This analysis would enable the designer to decide if the system meets the functional requirements.

2. 3. 1 Mooring Line Equilibrium Equations

a. Uniformly Loaded

In this analysis, the forces on the mooring line are computed based on the stretched length and reduced diameter of the line. The stretched length is computed as explained in section 2. 2.

A free body diagram of a differential element of the mooring line is shown in Fig. 2. The internal tension and the inclination of the line element change to keep all the indicated forces in equilibrium. In the figure $\hat{v}$ is a unit vector along the mooring line given by:

$$\hat{v} = \hat{i} \cos \phi_1 + \hat{j} \cos \phi_2 + \hat{k} \cos \phi_3$$

where ϕ_1, ϕ_2, and ϕ_3 are the angles of inclination of the differential line element with respective orthogonal axes x_1, x_2, and x_3, and $\hat{i}$, $\hat{j}$, and $\hat{k}$ are unit vectors along directions x_1, x_2, x_3 respectively. Let $\hat{n}_1$, $\hat{n}_2$ and $\hat{n}_3$ be unit vectors normal to $\hat{v}$ in the respective planes made by vector $\hat{v}$ and directions $\hat{i}$, $\hat{j}$, and $\hat{k}$. $\overline{P}$ is the distributed tangential force, along $\hat{v}$, and N_1, N_2 and N_3 are components of the distributed normal force $\overline{N}$, per unit stretched length of the line. These forces give rise to change in tension of dT and changes in inclination of $d\phi_1$, $d\phi_2$, and $d\phi_3$ along the length ds. $\overline{T}$ is the line tension.

Forces $\overline{P}$ds and $\overline{N}$ds are exerted due to the velocity and gravitational field on this differential element. The velocity field can be represented as

$$\overline{U} = \hat{i}U_1 + \hat{j}U_2 + \hat{k}U_3$$

In all future representation subscript i takes on the values 1, 2, and 3 and the summation is done on all values of i.

For the computation of drag, it is useful to resolve $\overline{U}$ into vectors parallel and normal to the cable axis:

$$\overline{U} = \overline{UN} + \overline{UT}$$

We find:

$$\overline{UT} = (\overline{U} . \hat{v})\,\hat{v} = (\Sigma U_i \cos\phi_i)\,\hat{v}$$

and,

$$\overline{UN} = \overline{U} - \overline{UT} = \Sigma(U_i \sin\phi_i \,\hat{n}_i)$$

From $\overline{UT}$ and $\overline{UN}$ normal and tangential drags can be calculated using the pertinent pressure and friction drag coefficients. Representative areas of the differential element can be calculated using the reduced diameter and stretched length.

The standard formulation is given by:

$$\overline{DN}ds = \frac{\rho}{2}(CDN)(dAN)/\overline{UN}/\overline{UN}$$

and

$$\overline{DTds} = \frac{\rho}{2}(CDT)(dAT)/\overline{UT}/\overline{UT}$$

The other force acting on the differential element is the gravitational force, which is also resolved into normal and tangential components, $\overline{WN}$, and $\overline{WT}$. If W is the weight per unit length of the line then,

$$\overline{W} = W\hat{k}$$

$$\overline{WT} = [\overline{W} . \hat{v}]\hat{v} = W\cos\phi_3\,\hat{v}$$

$$\overline{WN} = \overline{W} - \overline{WT} = W\sin\phi_3\,\hat{n}_3$$

Now,

$$\overline{N} = \overline{DN} + \overline{WN}$$

and,

$$\overline{P} = \overline{DT} + \overline{WT}$$

Therefore,

$$Pds = (\frac{\rho}{2} (CDT) (dAT) \left| \sum U_i \cos \phi_i \right| (\sum U_i \cos \phi_i) + Wds \cos \phi_3)$$

It's easy to show that,

$$\hat{n}_1 = \hat{i} (\sin \phi_1) - \hat{j} (\frac{\cos \phi_1 \cos \phi_2}{\sin \phi_1}) - \hat{k} (\frac{\cos \phi_1 \cos \phi_3}{\sin \phi_1})$$

$$\hat{n}_2 = -\hat{i} (\frac{\cos \phi_1 \cos \phi_2}{\sin \phi_2}) + \hat{j} (\sin \phi_2) - \hat{k} (\frac{\cos \phi_2 \cos \phi_3}{\sin \phi_2})$$

$$\hat{n}_3 = -\hat{i} (\frac{\cos \phi_1 \cos \phi_3}{\sin \phi_3}) - \hat{j} (\frac{\cos \phi_2 \cos \phi_3}{\sin \phi_3}) + \hat{k} (\sin \phi_3)$$

$$\overline{UN} = U_1 \operatorname{Sin} \phi_1 \hat{n}_1 + U_2 \sin \phi_2 \hat{n}_2 + U_3 \sin \phi_3 \hat{n}_3$$

Hence,

$$UN_1 = U_1 \sin^2 \phi_1 - U_2 \cos \phi_1 \cos \phi_2 - U_3 \cos \phi_1 \cos \phi_3$$

$$UN_2 = -U_1 \cos \phi_1 \cos \phi_2 + U_2 \sin \phi_2^2 - U_3 \cos \phi_2 \cos \phi_3$$

and $UN_3 = -U_1 \cos \phi_1 \cos \phi_3 - U_2 \cos \phi_2 \cos \phi_3 + U_3 \sin \phi_3^2$

$$WN_1 = -W \cos \phi_1 \cos \phi_3$$

$$WN_2 = -W \cos \phi_2 \cos \phi_3$$

and $WN_3 = W \sin \phi_3^2$

$$N_i ds = (\frac{\rho}{2} (CDN) (dAN) \sqrt{\Sigma (UN_i)^2} \; UN_i + WN_i ds)$$

As shown in the Fig. 2 forces $\overline{T}$, $\overline{N}$, and $\overline{P}$ act in the same plane containing the differential element ds. For a differential element as ds approaches zero $\overline{N}$ and $\overline{P}$ can be approximated to act at the beginning of ds. Then, vectorially:

$$(T + dT) (\hat{v} + d\hat{v}) = T\hat{v} + Pds \; \hat{v} + \overline{N}ds$$

or,

$$T d\hat{v} + dT\hat{v} = P ds\hat{v} + \bar{N} ds$$

as $\bar{N}$ is $\perp$ to $\hat{v}$ and $d\hat{v} \,||\, \bar{N}$

$$dT = P ds \tag{3}$$

and

$$d\hat{v} = \frac{\bar{N} ds}{T}$$

Now $\bar{N} ds = N_1 ds\,\hat{i} + N_2 ds\,\hat{j} + N_3 ds\,\hat{k}$

and $d\hat{v} = -\hat{i}\sin\phi_1\, d\phi_1 \;\; -\hat{j}\sin\phi_2\, d\phi_2 \;\; -\hat{k}\sin\phi_3\, d\phi_3$

Therefore

$$d\phi_i = -\frac{N_i\, ds}{T\sin\phi_i} \tag{4}$$

b. <u>Discretely Loaded</u>

Whenever a concentrated mass like an instrument, glass ball or a subsurface buoy is attached to the cable or whenever any other concentrated force is applied to the cable its effect is to cause a discontinuity, in the inclinations ϕ_i and tension T of the line, at the point of attachment. For this purpose a model of the concentrated force on the cable must be postulated which is different than that of the continuously loaded cable.

Consider a force F applied between segments n and n + 1. (Fig. 3)

For the case of an instrument the force $\bar{F}$ will include all the drag forces along with its weight or buoyancy. Equilibrium demands vectorially,

$$\bar{T}_{n+1} = \bar{T}_n + \bar{F} \tag{5}$$

where $\bar{T}_n$ is the tension in the segment before the instrument or force and $\bar{T}_{n+1}$ the tension after the instrument or force.

For a cylindrical instrument drag is calculated similar to explained in Part a.

$$\overline{DN} = \frac{\rho}{2}(CDN)\,(AN)\,|\overline{UN}|\,\overline{UN}$$

and

$$\overline{DT} = \frac{\rho}{2}(CDT)\,(AT)\,|\overline{UT}|\,\overline{UT}$$

$$DN_i = \frac{\rho}{2}(CDN)\,(AN)\sqrt{\Sigma(UN_i)^2}\;UN_i$$

$$= (CD1N)\sqrt{\Sigma(UN_i)^2}\;UN_i$$

Total drag force on the instrument is:

$$\overline{DD} = \overline{DN} + \overline{DT}$$

$$= \hat{i}\,DD_1 + \hat{j}\,DD_2 + \hat{k}\,DD_3$$

where,

$$DD_i = DN_i + \left|\overline{DT}\right|\cos\phi_i$$

For a spherical, or any other shaped instrument

$$\overline{DD} = \frac{\rho}{2}(CD)\,(A)\,\left|\overline{U}\right|\overline{U}$$

where,

CD is the drag coefficient in the direction of $\overline{U}$ and A is the area normal to this vector $\overline{U}$.

or,

$$DD_i = (CD1A)\sqrt{\Sigma(U_i)^2}\;U_i$$

2.3.2 Surface Buoy Equilibrium Equations

Consider the free body diagram of a surface buoy piercing the surface (Fig. 4). The steady state forces acting on it are the drag and the lift forces. Equilibrium requires vectorially,

$$\overline{T}_1 = \overline{B}_B + \overline{D}_{AB} + \overline{D}_{WB} + \overline{W}_B \qquad (6)$$

$\overline{B}_B$, the buoyancy is a function of the tension $\overline{T}_1$ in the first segment. Submerged area (A) of the surface buoy is a function of the buoyancy ($\overline{B}_B$) ; drag coefficients (CD) of the buoy are functions of surface velocities ($\overline{U}$) of water and wind, and the shape of the buoy.

Hence,

$$\overline{D}_{AB} \text{ and } \overline{D}_{WB} = f\,(CD,\, A,\, V) \qquad (7)$$

3.0 Method of Solution

A numerical integration and iteration is carried to solve the mooring line equations as given by equations (3), (4) and (5).

A finite element break-up of the cable is done whereby the cable is divided into a finite number of segments. Equations (3) and (4) are solved by incremental method. In a finite element representation

$$\Delta T = P \tag{8}$$

$$\Delta \phi i = \frac{-N_i}{T \sin \phi_i} \tag{9}$$

where;

Ni = components of the force normal to mooring line vector $\hat{v}$.

P = resultant of forces tangential to the segment.

and, ΔT and $\Delta \phi_i$ are the respective changes in tension and orientations along the segment.

3.1 Program Logic

A comprehensive computer program was written to solve the above mooring line equations. To initiate the solution procedure certain initial conditions are assumed. The method was that of considering straight line segments with incremental integration from segment to segment and then converging the solution by successive iterations, knowing certain physical constraints. The mooring scope as defined by the program for surface mooring lines is given by the total slack length of mooring components divided by the depth of water.

3.1.1 Segmentation of the Mooring Line

Within the program the entire mooring line is broken into a finite number of segments. The number can be varied at the user's will and hence is kept as an input to the program. Any instruments in the line are considered as additional segments and are placed at the junction of two line segments. A compound mooring line can have many parts, each part (steel, nylon, etc.) having a different set of parameters. The number of mooring parts and the slack length of each part is an input to the program, which makes an integral number of segments for each part. The length of all mooring parts is summed to give total length of mooring line. The number of segments in a mooring part is computed by dividing the length of the part by the total length of mooring line and then multiplying the resultant with the desired number of segments for the total line. The resulting number is then rounded to the nearest integer. If the answer is zero it is made one. This rounding off may make the total number of segments vary by one or two from the desired number. Segment length for each part is then computed by dividing the mooring part length by the number of segments in the part. Computations for each part are done in a loop, segment by segment, and whenever the number of segment, exceeds the total number of segments in the part, control is shifted to the outer loop which changes the mooring parameters.

3.1.2 Initialization of Integration Procedure

To begin the solution procedure an educated guess at the tension magnitude for the first segment is made. In order to position this segment it is necessary to orient this segment. The orientation of this segment along with the tension magnitude depends on buoy drag which is a function of the tension magnitude, buoy type, buoy size and the surface velocities of water and wind. Assuming this relation is known (refer to section 4), the first segment can be oriented. The efficiency of the computer program and hence the computational time for the solution procedure depends on how accurately this tension magnitude is estimated.

For surface currents less than three knots, tension magnitude is taken equal to the static weight of the mooring components, neglecting the buoyancy of any glass balls, if present. Any mooring part below and the first buoyant mooring part is also neglected in this calculation. The tension magnitude for surface currents greater than or equal to three knots is initially assumed by multiplying the value as calculated above by a factor of 2.5, which was found to be reasonably good for rapid convergence. If the first mooring part happened to be a buoyant one a value of one hundred pounds minimum is taken for the tension assumption at the top, to start the integration procedure.

3.1.3 Integration Procedure

Having established the orientation and tension in the first segment and knowing the stress-strain relations of the mooring parts, elongation is calculated. This gives the position of the end of the first segment.

The tension and inclination of the second segment can be calculated by the use of mooring line equations (8) and (9) after having determined the forces acting on the first segment. The drag forces for the segment are calculated with representative velocity components at its med-depth, H_2. The velocity components in the three orthogonal directions, x_1, x_2, x_3, are determined by entering into "Subroutine Speed" which chooses the velocity profiles to be used (an input) and gives values for the components at depth H_2. These components are then resolved into components normal and tangential to the segment. From these components normal and tangential drags are calculated as explained in section 2.3.1.

The other force acting on the mooring line segment is the gravitational force, which is also resolved into components normal and tangential to the segment. These are summed with the corresponding drag values to obtain N_i and P, which are then substituted in equations (8) and (9) to determine the tension and orientation of the second segment. This procedure is repeated for all the segments.

At the top of each segment a check is made whether any instrument or concentrated force is placed anywhere within half the segment length on each side. If so the control is shifted to "Subroutine Forces" which finds the additional change in line tension and orientation due to the instrument or point force. Instruments are introduced as additional segments with its length, weight and drag characteristics introduced instead of the mooring parameters. If a concentrated force is applied, its length is taken as zero and the force is inputed in three orthogonal components. The change in tension and orientation is calculated by adding vectorially previous force vector acting along the segment and the applied force vector. At the end of each segment a check is made if a different mooring part is encountered when all the mooring parameters are changed. When all the segments have been included in the solution, a check is made whether any more instruments or forces are applied near the end of the line, which are then taken into account in "Subroutine Forces," Fig. 5 is a block diagram of the integration procedure.

3.1.4 Iteration Procedure

After having completed the integration procedure through all the mooring line segments, instruments and concentrated forces, the anchor is met. The depth of anchor will probably not agree with the actual depth, as it depends on the tension estimate at the surface buoy. Hence the tension at the surface buoy has to be modified to get a better value for the depth of anchor and this results in an iterative solution.

The iterations are done by two procedures. One for high currents and the other for low currents and large mooring scopes. A reasonable breakup for using one or the other iterative procedure was found to be as follows: Procedure number two is used whenever the surface current value is less than or equal to 25 cm/sec or if the surface current is less than 50 cm/sec and the mooring scope is greater than unity. For all other cases procedure number one is used. This breakup was established after analyzing outputs for various systems. Two procedures were incorporated to save computer time in one case and to get a converging solution in the other. It was observed that in certain conditions of large scope, buoyancy placements and low currents the solution by the first procedure may diverge whereas this procedure is economical to use for higher currents. These procedures are explained next.

Procedure 1 (for high current)

At the end of first computation (integration procedure) the depth error, E, the difference in anchor depth reached and actual depth, is computed. If this error lies within acceptable error, which is an input, the problem is solved. If not, fifty pounds is added or subtracted from the surface line tension, depending on whether E is negative or positive, and the entire computation is repeated. This second computation yields a new depth error, E1. The difference, DE, between this error and that obtained on the previous computation is due to the fifty pounds change in surface line tension. A weighting factor is now used to determine an improved surface tension estimate, i.e., if:

$$DE = E - E1 \tag{10}$$

then,

$$T_{new} = T_{old} \pm [E/DE] \times (50) \tag{11}$$

The sign depending on whether fifty pounds was added or subtracted. This procedure is shown in Fig. 6a.

Procedure is thus repeated with successive linear interpolations till a valid solution is obtained.

Procedure 2 (for low currents)

This procedure is a scanning procedure. At the end of first computation if the absolute error is greater than the allowable limits, then a factor 'Z' (in this program an initial value of 300 lbs is chosen) is subtracted or added, depending upon the sign of error, to the initial surface tension estimate and the new depth error E1 is calculated. This process is continued, i.e., getting a new value of E1 each time and putting previous E1 equal to E till E1 is greater in absolute magnitude or different in sign to that of E. At this time the factor (Z) is divided by −3 and the new factor (Z) is subtracted algebraically from the new tension estimate. The procedure is repeated as shown in Fig. 6b till E1 becomes less than the allowed error.

During the solution procedure if at any stage tension in the mooring line or the depth reached by the mooring line becomes less than or equal to zero, control is shifted to a statement which adds 300 lbs to the surface tension estimate to start computations afresh, if iteration procedure 1 is being used, and half the present value of factor Z if iteration procedure 2 is being used. This was done because a value of 300 lbs may be too much for low currents and is just enough for high currents to give a rapid convergent solution. This addition is done 25 times and if no solution is reached by that time, the computer writes "The tension or depth is getting less than zero at segment....."

Also, during the integration procedure a check is made for the vertical component of tension. If at any segment or instrument the value of vertical component of tension is less than 2 x seg. wt. and the depth reached is within twice the segment length of the particular mooring part from the actual water depth, control is shifted to a statement which writes:

'The rest of mooring line ----- meters long is lying on the ocean floor', which indicates that the current is too small to pick up all the mooring line for high scopes.

3.2 Control Parameters

In the computer program, solution procedure is controlled by certain indexing procedures. These are described below:

a. Index: This variable takes three values from 1 to 3 and controls the iteration and printing procedures. An initial value of 2 is given to this variable. When Index = 2, normal computation is being carried out. When Index = 1, a correction is being sought for the surface tension. When Index = 3, a valid solution has been found and the system is being recomputed to print the required output.

b. IE: This variable takes the values 1 or 2 and controls the error bound calculations as explained in section 5.3. When IE = 1, normal computation is being carried out. When IE = 2, computation is redone to determine the error bounds on the resulting solution. Drag coefficients, surface buoy drag and stress-strain relationships are changed to their range of uncertainty. This is done only for systems which use iteration procedure one, where variation in above mentioned parameters is critical.

c. NPO: This variable is used to restrict detailed output printing for a specified number of solutions for different velocity profiles in a buoy system. It has a value equal to the number of solutions for which detailed output is required. IJ is a dummy index for the inner control loop which is indexed one unit for each complete solution. When IJ exceeds NPO, control is no longer shifted to Index = 3 mode, which makes detailed output printing.

d. L: It controls the number of iterative cycles allowed for each solution. It is indexed one unit for each cycle and control is shifted to the next system if convergence is not achieved in the allowed number of cycles. For the first iteration procedure it is not allowed to exceed ten. In this case the variable is indexed once for every cycle containing two computations. In the second iteration procedure it is not allowed to exceed twenty where each cycle has one computation.

e. IZ: This is indexed one unit each time tension or depth reached anywhere along the line becomes less than or equal to zero, when surface tension is increased, during the integration procedure. It is not allowed to exceed a value of twenty-five at which stage the computer prints:

'The tension or depth is getting less than zero at segment.....'.

These control parameters are shown in Fig. 7.

4.0 Physical Parameters as Input Information

4.1 Surface Buoy

Surface piercing objects in water have complex drag characteristics which makes force analysis on surface buoys difficult. The computer program described in this report requires the surface mooring angles as a function of surface tension, buoy type, buoy size and surface velocity. The mooring line at the surface is in the direction of the resultant vector of the forces acting on the buoy. These forces are a complex combination of form drag, wave drag, friction drag, static and dynamic lift, and are amenable to theoretical calculation. A series of physical model tests were carried out on three buoy shapes; namely, the toroid and the disk (with and without feet) at the Massachusetts Institute of Technology towing tank (Ref. 6) and analytic expressions describing their drag characteristics were formulated.

These three expressions along with a provision to add these drag forces as input forces are included in the computer program (Refer Appendix C).

4.2 Instrumentation, Discrete Buoyancy and Concentrated Forces

Instrumentation and discrete buoyancy can be inserted anywhere in the mooring system. These are considered as concentrated forces having a specified length. Other concentrated forces with zero length can also be specified. Certain physical parameters like the position, length, components of force, drag constants and the name are to be inputed for each, or a group of instruments, discrete buoyancy or a concentrated force. The instrument or concentrated force position refers to its position in the mooring line based on slack lengths measured from the surface buoy to its centerline.

In the case of instruments whose drag constants are not known but their hydrodynamic resistance is known, this can be inputed as a concentrated force. The length, weight and drag of an instrument are integrated into the mooring line as a segment. No elongation is allowed in an instrument. Lengths of chain can be considered as mooring parts or instruments at user's discrection.

Various instrument, used commonly in present day oceanographic research, are listed with their characteristics in Fig. 8.

4.3 Elastic Response of Mooring Line Materials

Mooring ropes are made of different materials - mainly steel and fibre, latter being either natural or synthetic. Plastic characteristics of steel are well known and ropes made of steel can be treated to have linear elongation, as, in a compound moor, the amounts of elongations in a wire cable are negligible when compared to elongations in fibre ropes. Thus elastic characteristics of the wire part of a compound mooring can be represented by a single constant whereas fibre parts need a nonlinear relationship to represent its nonlinear behavior.

4.3.1 Loads Experienced by a Mooring

In most cases a mooring line experiences the maximum loading during its launch. For taut moors (mooring scope less than unity), during launch, a point in the mooring line experiences a maximum load equal to the net resultant of gravitational and hydrodynamic forces below it including the submerged weight of the anchor. And for moorings which do not experience any excessive velocity fields, it may be the highest load they ever experience. On the other hand moorings may experience a load higher than the launching load if the currents get excessively high. This maximum load which a mooring line experiences during its previous life history is critical in determining its total elongation. The launching transient peak load is an input to the computer program and is inputed for each mooring part. If the tensions at anytime get higher than the launching tensions the computer program automatically makes the higher value, as the maximum load ever experienced by the line. A typical mooring line, under tension, stretches by an amount which is partly elastic elongation and partly permanent or semipermanent set which in the case of steel wire mooring lines may be due to the wires and strands becoming more tightly interlocked. In the case of fibre ropes it is due to the unrecoverable stretch of the individual fibres and due to a tighter interlock of strands. This permanent set can be determined and depends on the maximum load a mooring line has experienced in its previous life history.

4.3.2 Experimental Results for Fibre Ropes

Certain laboratory tests were performed on synthetic ropes to determine their stress-strain behavior, under repeated loading and unloading. These tests were made similar to tests performed on British ropes by Basil W. Wilson as explained in Reference 12.

Under tensile testing the stress-strain relationship for mooring ropes assumes the form shown in Figs. 9-17. If the load is removed, the curve of unloading follows a different path on the stress-strain diagram and establishes the permanent set on the abscissa. If the load is reimposed, the new loading curve forms a hysteresis loop with the unloading curve, the area of which represents energy absorbed in the system during the cycle. In general, if the cycle is repeated the successive hysteresis loops superimpose upon each other and exhibit a drift (toward greater extension) indicative of further increments of permanent set. The increments become smaller with each cycle and it is seen that for new nylon ropes, at 75% of ultimate strength, the ropes attain maximum permanent set after about three cycles of loading and unloading. In the various tests performed, three to four cycles of loading and unloading were made to get a reasonably accurate value for permanent set.

All these tests show one thing in common; namely, that the centerlines of stable hysteresis loops tend to have the same shape (for any given rope type) regardless of elongation or age of the rope. In Fig. 13 which is schematic, the hysteresis loop axes a'g and c'f are identical, although c'f applies at a different stress from a'g. This observation enables the test results of Figs. 9-12 to be generalized for any nominal rope diameter, d, by plotting them in stress-strain form, and separating out the permanent elongation from the elastic parts. In Fig. 13 for example, for any given stress bg, the permanent part of strain is oa' and the elastic part is a'b. At another stress ef, the permanent part of strain is oc' and the elastic part is c'e.

In Fig. 14 the test results of Figs. 9-10, for plaited nylon (Columbian) plotted in this way, suggest a strongly nonlinear relationship governing the permanent part of the elongation, which as expected, tends to become asymptotic to the ultimate breaking limit. The elastic part of stress-strain behavior of synthetic ropes is also nonlinear. Fig. 15 for braided dacron (Samson) shows the test results of Figs. 11-12 plotted in a similar way to Fig. 14. Fig. 16 was drawn for braided nylon in a similar way to Figs. 14 and 15. Fig. 17 presents a direct comparison of the elastic parts of the elongation, for plaited nylon, braided dacron and braided nylon ropes.

Nonlinear analytic expressions to represent Figs. 14, 15, and 16 closely, were derived and are given in a tabular form in Fig. 18.

4.4 Hydrodynamic Drag Coefficients

In general, both friction and gravity forces play a role in the determination of the flow pattern around a body submerged in a flow. For mooring lines where the velocity of flow is small, effects of compressibility and gravity can be neglected for drag calculations. Drag is given by:

$$\frac{D}{\rho V^2 \ell^2} = f_1 \left(\frac{\rho V \ell}{\mu} \right) \tag{12}$$

where ℓ is the characteristic length of the body and other symbols have their usual meaning. The independent variable $\frac{\rho V \ell}{\mu}$ is called Reynold's number R.

Drag coefficient C_D is defined as:

$$C_D = \frac{D}{(\rho/2) V^2 A} \tag{13}$$

'A' stands for a characteristic area for the body. Hence

$$C_D = f_2 (R) \tag{14}$$

The exact value of the drag coefficient for round cables is a point of dispute in the literature and is difficult to specify. From the tabulation in "Fluid Mechanics for Hydraulic Engineers," by Hunter Rouse, it is seen that a cylinder exhibits different regimes of flow. We assume C_D invariant with R which is a reasonable assumption for R range significant for this problem $(10^2 < R < 3 \times 10^4)$.

Also the alternating shedding of vortices from the two points of separation on the surfaces of a circular cylinder produces transverse forces on the cylinder and causes the cylinder to oscillate. These transverse oscillations sometimes called strumming increase the drag coefficient, but the magnitude of this increase is not well known. Different experimental curves between C_D and Reynold's number have been proposed by different people. The choice of these coefficients is left to user's discretion.

4.5 Current Profile Formulation

Within the solution procedure, it is required to know the functional relationships between depth and the current speeds, in the three directions

x_1, x_2, and x_3. This is an input to the solution procedure, which should be accurate enough to give reliable results. Prediction of such a relationship is usually a difficult one as it is itself a function of position and time. Many times it is the desire to obtain this relationship which requires the use of a buoy system. Hence it may be a potential source of error and unreliability.

Considerable work has been done in this area to collect the required information. As the current profiles in the three directions do not remain the same or of the same nature at different positions in the ocean a set of six different types of current profiles, with selectable constants, have been incorporated into the computer program, to give the user a flexibility in choosing the appropriate current profiles. Any additional types of current profiles can be incorporated by the user by entering the appropriate expressions in 'subroutine speed'.
The current profiles incorporated in the computer program are discussed here.

Profile No. 1

This is the most flexible of the current profile types and least knowledge of the ocean environment is required. The profile requires the specification of number of points at which the velocity vector is to be given and this vector is inputed in the computer program in terms of its three components along with the depth of the point. The number of points is unlimited and is an input. This profile is most useful when approximate values of currents are known at certain discrete points and not much is known of the region in between. It is also very useful for design purposes.

The program interpolates the values of currents in the three directions from the two immediate vectors, one on each side, which are inputed. If any line is above the topmost inputed vector the vector is assumed to be constant to the top of the line. The velocity vector at the bottom if not inputed is assumed to be zero. This profile is shown in Fig. 19.

Profile No. 2

If stepped currents were desired, velocity vectors could be inputed as for profile number 1, and a profile shown in Fig. 20 would be computed by the computer.

Profile No. 3

This profile represents a monotonous decrease in current with depth, as is generally apparent in most portions of the ocean. The surface current vector, $\overline{V}$, is a program input, inputed in components and determines the amplitudes of the entire profiles. Current speed is expected to decrease as $H_2^{-\alpha_i}$, where H_2 is the depth in meters and α_i is a constant less than unity. The relationship is therefore of the form

$$U_i = \begin{bmatrix} V_i & H2 \leq HO_i \\ V_i(HO_i/H2)^{\alpha_i} & H2 > HO_i \end{bmatrix}; \quad i = 1, 2, 3 \tag{15}$$

where V_i is surface current speed in cm/sec. It is assumed that the first HO meters of water will be moving at the surface current speed, V_i.
The profile is shown in Fig. 21. Here V_i, HO_i and α_i are the three input parameters for each profile.

Profile No. 4

In this case a profile is generated which reverses directions with depth. The depth at which the direction is reversed depends on the user and is inputed as a selectable constant in the program. The profile is shown in Fig. 22.

Profile No. 5

In this case a profile was derived with the current reversing directions more than once, or increasing in magnitude after having decreased in magnitude with depth. The profile is shown in Fig. 23.

Profile No. 6

A profile was derived with trignometric functions, to represent a profile which is common in many areas. The current changes direction twice with good flexibility of amplitudes. The profile is shown in Fig. 24.

5.0 Program Instructions and Details

A main program with four subroutines constitute the complete solution program. The computer program has been described adequately by the help of comment statements placed in the program listing and by the variable definitions both of which are included in Appendix A.

Any user wanting to use the computer program will have to provide the input data cards of his own, written as specified in section 5.4. A sample input data set is provided as a reference. Some instructions and details are given in this section to help the user understand the program more critically. The program is made adequately general to solve most of the mooring lines being used presently.

Segmentation of the mooring line and initial estimate of surface tension magnitude were explained in section 3.1 under Program Logic.

5.1 Mooring Pile-Up at Ocean Floor

Slack mooring lines are apt to pile up on the ocean floor for low currents. Also the intended taut mooring line may have an amount of permanent elongation during its launch so as to make it slack during low currents. Thus we may have a situation where the tension becomes zero in the line and hence no theoretical solution can be found. To overcome this difficulty, during the integration procedure, a check is made at each step to see if the vertical component of tension becomes adequately low at or near the ocean floor. This condition specifies that the rest of the mooring line is lying on the floor and further calculations are terminated. It was found that the absolute value of the vertical component of tension if less than twice the weight of the current segment, in a band of depth within two segment lengths on each side of the ocean floor gave a good check. This criteria was chosen as the solution program deals with discrete points which are a segment length apart and the tension varies discretely with these points. If this condition is satisfied anywhere along the mooring line during integration, control is shifted to a statement which makes the rest of the mooring line to lie on the floor, and prints out the length of line below the point where absolute vertical component of tension is less than twice the weight of the current segment. This is also transmitted to plotting subroutines which plot a straight line parallel to the water depth whenever this condition is met.

5.2 Tension or Depth Becoming Less Than Zero

The integration procedure starts with an estimated tension magnitude at the surface. This magnitude or any other magnitude assumed at the surface, during iteration, may make the tension equal to or less than zero at some point along the mooring line. Also, if the top tension is too small the line may start bending upwards and soon the depth reached may become less than zero. This is more apt to happen in systems which have regions of low tensions, i.e., for a system with large scope and many buoyancy packages. Whenever the tension or depth is getting less than zero, control is shifted to a statement which checks the depth if tension is getting less than zero. If it is at a depth greater than the ocean depth, the assumed surface tension is more and should be reduced. This also implies that some of the line will be lying on the floor, but during integration it did not satisfy the check of section 5.1 for the previous tension assumption at the surface. If tension was getting less than zero at depth less than the ocean depth or if depth was getting less than zero, control is shifted to a statement which adds 300 pounds for iteration procedure one, or half the current value of factor Z for iteration procedure two, to the value of surface tension magnitude and calculations are repeated. This procedure is repeated till the tension or depth do not become less than zero anywhere along the mooring line. Control can be shifted to this statement only twenty-five times for one solution, when control is automatically shifted to the next solution.

5.3 Calculation of Error Bounds

After the mooring configuration has been solved, a slightly modified system is calculated, if iteration procedure one is being used, to determine the combined effect of several emperical inputs on the maximum tension and mooring configuration. This is controlled by the parameter IE. When IE = 1, normal calculations are being carried. When IE = 2, vertical inclination at the surface are increased by one degree (equivalent to increasing drag on the surface buoy), both normal and tangential drag coefficients for the mooring line are increased by ten percent and strain in all parts is reduced by ten percent. All these changes tend to increase the tension. The change in maximum tension in each mooring part due to these changes is computed and printed out as the possible maximum error bounds on tension. These calculations do not make any change in the assumed current profiles.

5.4 Data Input Required by Computer Program

The user must provide the input data for the mooring systems he wishes to study. Instructions for writing the input data are hereafter outlined.

a. Number of Mooring Systems. The first card specifies the total number of mooring systems being studied in one computer run and hence controls the outermost 'Do Loop'. Any change in the system configuration (surface buoy type; length, size and material of mooring parts; distribution, number or type of instrumentation) or in the environmental parameters, like ocean depth or launching transient loads results in a different system. Variable is NSY and Format (I5).

This card is followed by NSY sets of cards each containing:

b. (1) Card of Constants - Format (11 I5). This includes information about:

NI - Number of instruments
NP - Number of mooring parts
NS - Number of segments desired
IKK - Number of velocity vectors being inputed if velocity profile is numbered one or two.
JMAX - Number of solutions desired for the same mooring system with different velocity profiles
NPO - Number of complete outputs to be printed
NVP(I) - Velocity profile number in Ith direction (I = 1, 2, and 3)
NB - Number of the surface buoy
IFPL - Number of plots required

c. (NI) Instrument or Concentrated Force Specifications Cards - Format (7F8.0, A8). These cards list:

PI(J) - Slack length position of Jth instrument
SI(J) - Length of Jth instrument
F(I, J) - Force component(including weight and buoyancy) of Jth instrument in Ith direction (i = 1, 2, and 3)
CDIN(J) - Normal drag constant ($\rho/2\, C_{DN} A_N$) of Jth instrument
CDIT(J) - Tangential drag constant ($\rho/2\, C_{DT} A_T$) of Jth instrument
Type (J) - Name of Jth instrument

d. (1) Buoy Card. Format (3F10.0, A8) This card lists:

DB -For buoy type (No.) 1 it holds the drag constant where:
$\overline{\text{drag}} = DB \times (\text{surface velocity})\,|\text{surface velocity}|$ otherwise,
it is the diameter of the buoy.

Depth - Ocean depth

ER - Acceptable depth error after integration

Buoy - Name of the buoy

e. (NP) Parameter cards for mooring parts. Format (5F 10.0, A8) These cards list DIAL(I), SLL(I), WWL(I), RBSL(I), TPL(I) and MOOR(I) which represent diameter, slack length, weight per unit length, rated breaking strength, transient peak load and name of I^{th} part. TPL(I) for wire cables holds value of elastic modulus.

f. (NP) Elastic and Drag characteristics cards for mooring parts: Format (7F 10.0) These cards list CO1(I), PO1(I), CO2(I), PO2(I), AO(I), CDN(I), and CDT(I) representing five elastic constants as explained in section 2.2 and normal and tangential drag coefficients of the I^{th} part.

g. (3 x JMAX) Velocity Profile Cards: Format (7F 10.0) These are three cards for each of JMAX solutions. These list depths and velocities at IKK number of points if velocity profile number one or two is specified, and list surface velocity and three profile constants if velocity profile number is greater than two. Thus, there are JMAX sets of three cards, each representing one direction.

5.5 Program Capabilities and Limitations

The computer program was written to be a very general program which could be used effectively for any sensitivity analysis. The work carried out has been to provide with reasonable accuracy the configuration and tensions along a mooring line. Mooring lines with mooring scopes less than, equal to, or greater than one with many combinations of mooring line materials, and with various instruments placed along the line have been tested. The mooring configuration can consist of any number of instruments and concentrated forces and be made of any number of mooring materials. Stress-strain characteristics of plaited nylon, single braided nylon, and braided dacron have been presented in this report. Instruments and concentrated forces can be located anywhere along the mooring line and can be buoyant (e.g. a subsurface buoy). Chain may be considered as a mooring part or an instrument. Minimum tension (often an important design consideration) may be determined by setting velocity fields equal to zero. Elongation is permitted in all components of the mooring line except instruments and can be linear or nonlinear.

Six types of current profiles are built into the computer program as explained in section 4.5 and any number of other profiles can be included in the program by entering the desired expression in SUBROUTINE SPEED.

As drag coefficients for surface-piercing objects are difficult to determine, analytic expressions relating top tension with top angles were found experimentally for three types of surface buoys, namely, Toroid, Disk, and Disk with feet. These are included in SUBROUTINE ANGLE with another general expression by which drags on the buoy are calculated as:

$$\overline{\text{Drag}} = \text{DB} * \overline{\text{V}} * |\overline{\text{V}}|$$

where DB and $\overline{\text{V}}$ are inputed. $\overline{\text{V}}$ represents the surface velocity vector.

Any other relationship between top tension and top orientation for a particular buoy shape can be included in SUBROUTINE ANGLE. Some of the principal outputs of the computer program are:

1. Maximum tension and safety factor for each mooring part (SF = RBSL|TMAX).
2. Maximum elongation in each mooring part as percentage of slack length or 200D^2 length.

3. Coordinates of the surface buoy with respect to the anchor.
4. If required, the segment number, stretched length, coordinates of end point, tension, inclination, speed values in x_1 and x_2 directions and mooring part number can be printed out at each segment including the instruments. This allows a graphic presentation of mooring configuration.
5. Plots of depth versus excursions and velocities in x_1 and x_2 directions can be obtained by computer. Also plot of x_1-excursion versus x_2-excursion can be plotted.
6. In addition, for iteration procedure number one, a slightly modified system with regard to surface angles, cable drag coefficients and elongation characteristics in synthetic mooring parts is computed and printed out. These parameters are changed to the assumed limits of their uncertainty. The resulting changes in tensions are taken as rough error bounds on the program outputs.

No allowance is made for wave and wind drag on the surface buoy. This can be taken into consideration by applying a force at the top of the line, which will be included as an instrument or concentrated force, or drag constants for the surface buoy can be inputed as explained in Appendix C.

The solution is a purely steady-state solution making no allowance for dynamic effects.

6.0 Case Study

Case study of a surface mooring line which was actually deployed is presented here to illustrate the use of the computer program and the type of results obtained. The mooring system presented here is an unusual case, and is useful under high velocities. All the dead weight at the anchor is supplied by 360 feet of 1 - 1/8" chain. This gives a variable mooring scope to the system as more chain is lifted off the ocean bottom with increasing currents. The system is highly instrumented and the results show the length of chain lying on the ocean floor. The outputs at two different current regimes and three types of velocity profiles representing each regime are presented. Fig. 25 shows the mooring system being studied and input data is shown in Fig. 26. Results for one run are shown in Fig. 27 and detailed results for other runs are shown in graphical form in Figs. 28 thru 33.

7.0 REFERENCES

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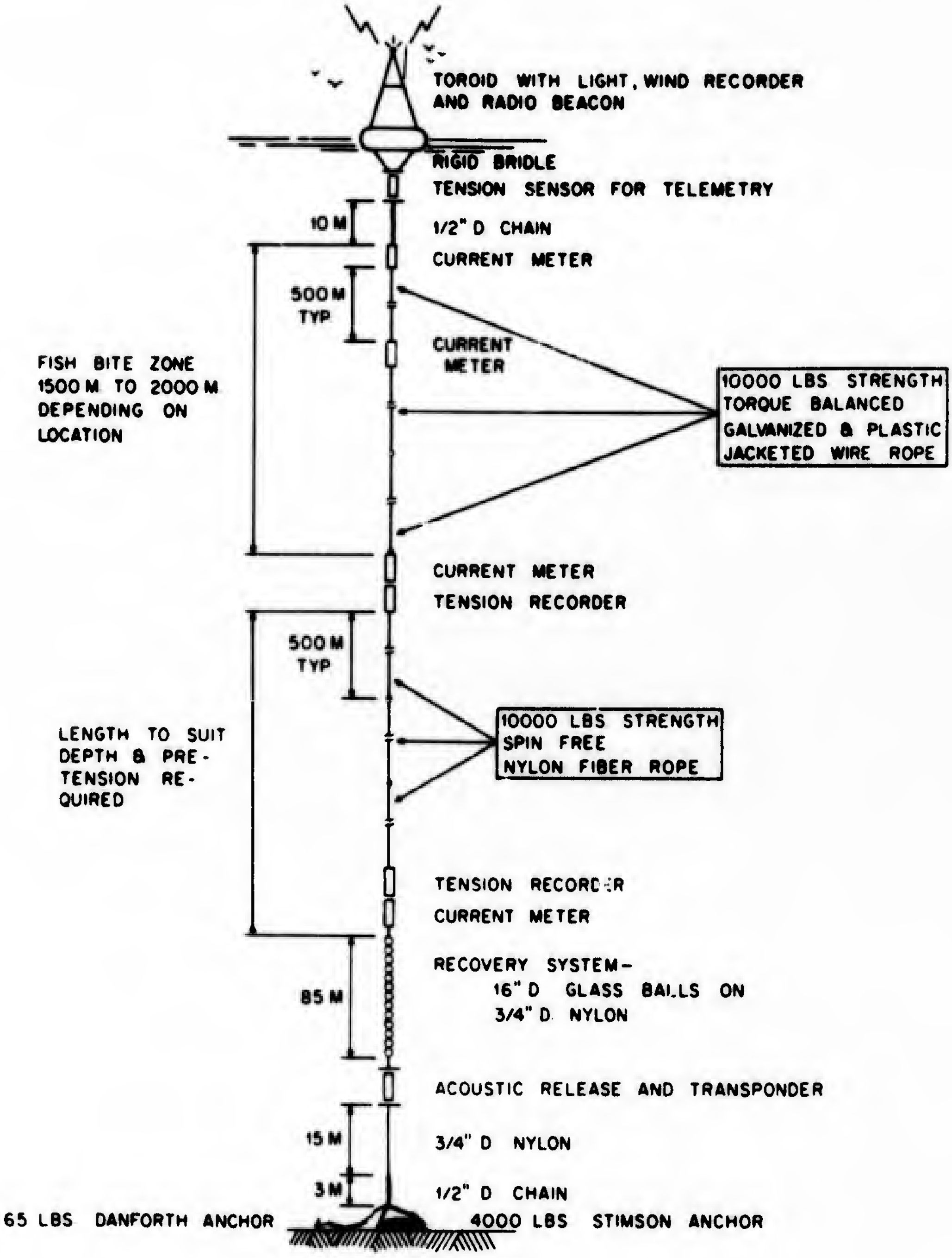
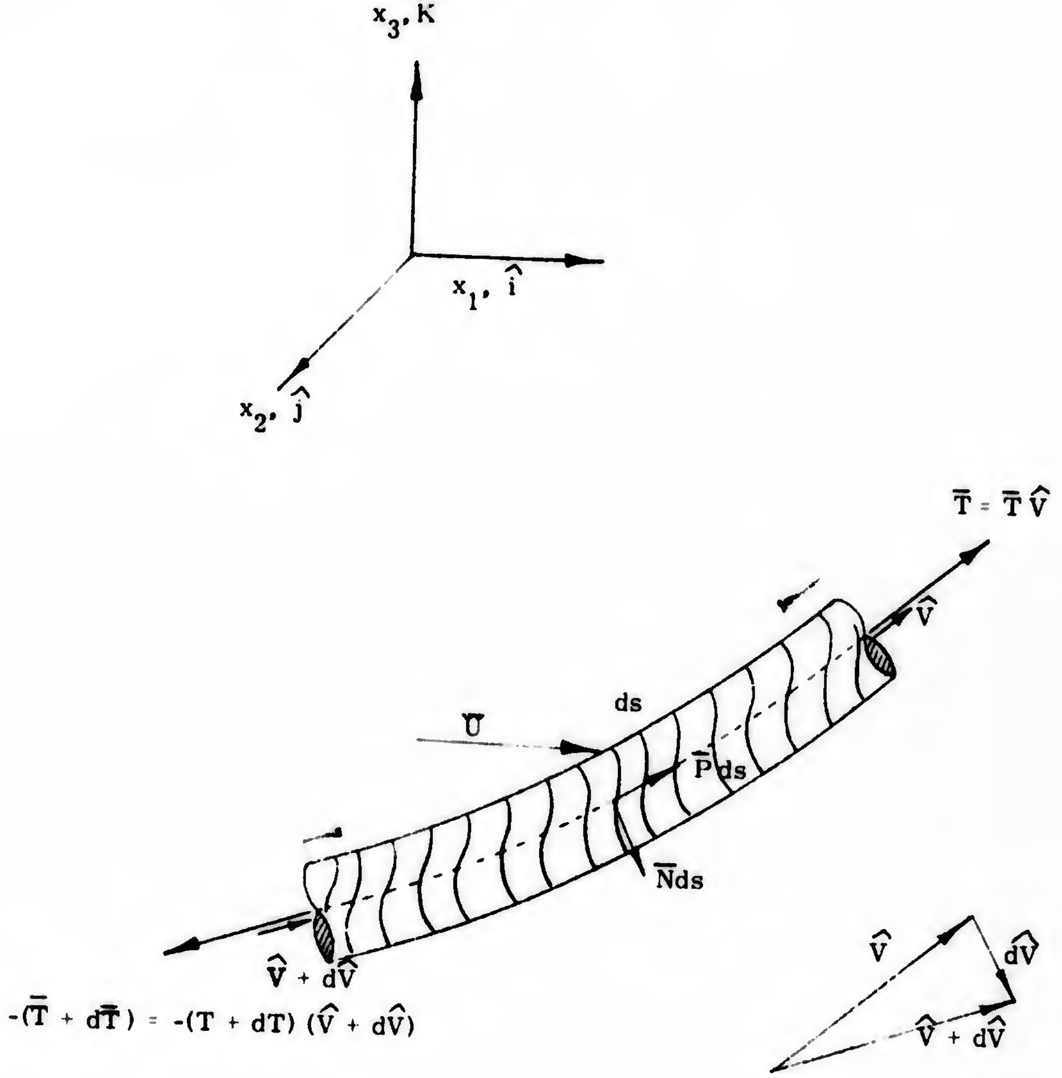


Figure 1. Typical W.H.O.I. Surface Mooring

(From Reference 2)



PLANE OF DIFFERENTIAL ELEMENT

Figure 2. DIFFERENTIAL MOORING ELEMENT

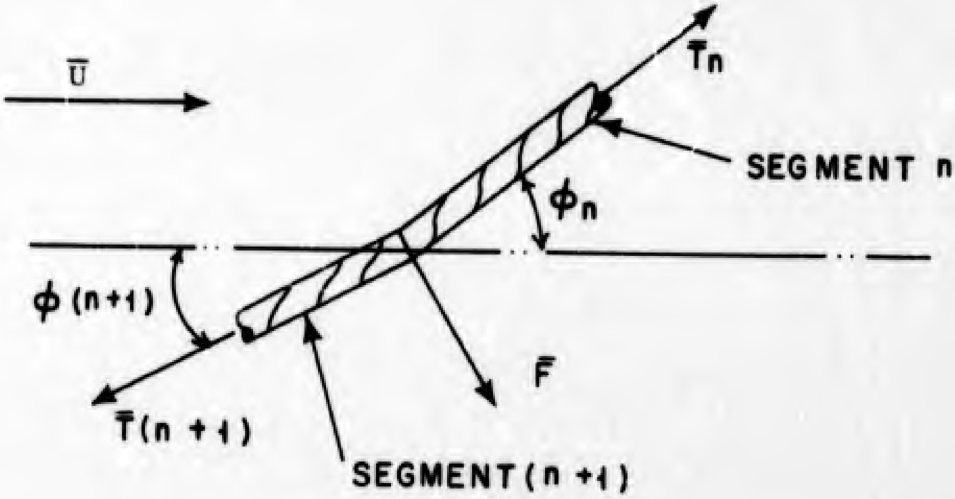


Figure 3. Discretely Loaded Mooring Line

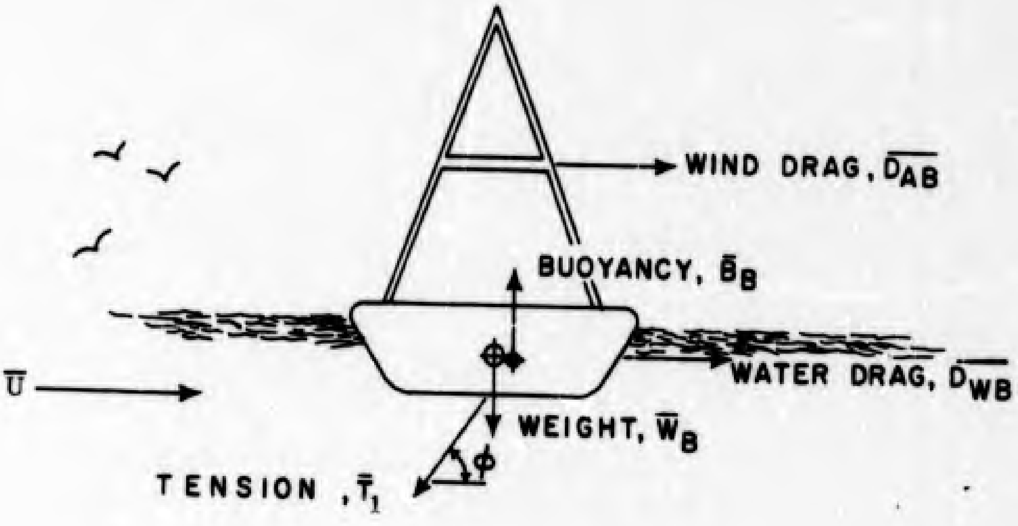


Figure 4. Forces on a Surface Buoy

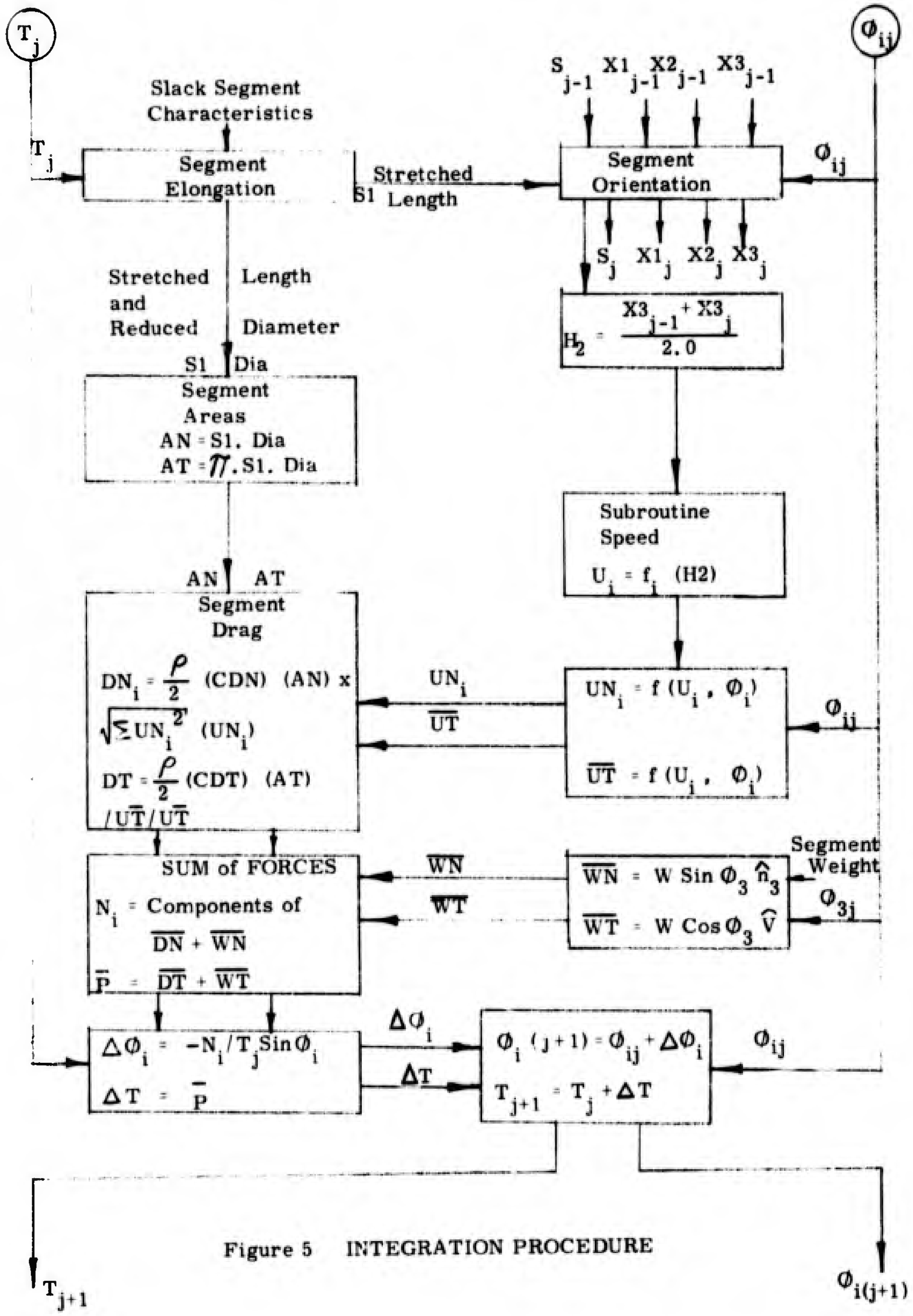


Figure 5 INTEGRATION PROCEDURE

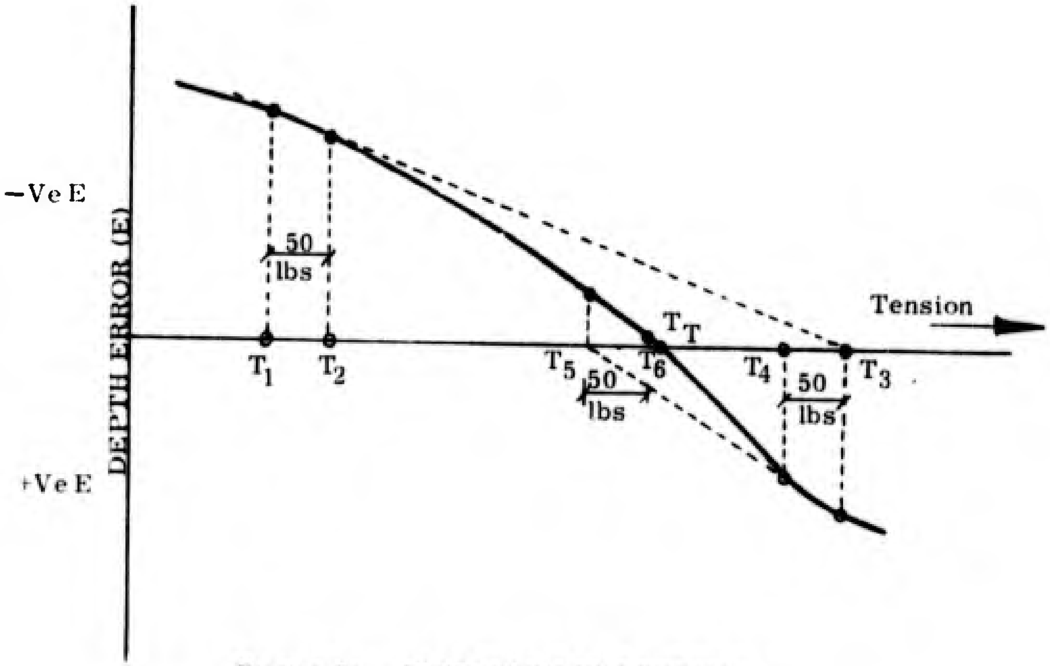


Figure 6a ITERATION PROCEDURE 1

T_i = I th Tension Assumption

T_T = True Tension

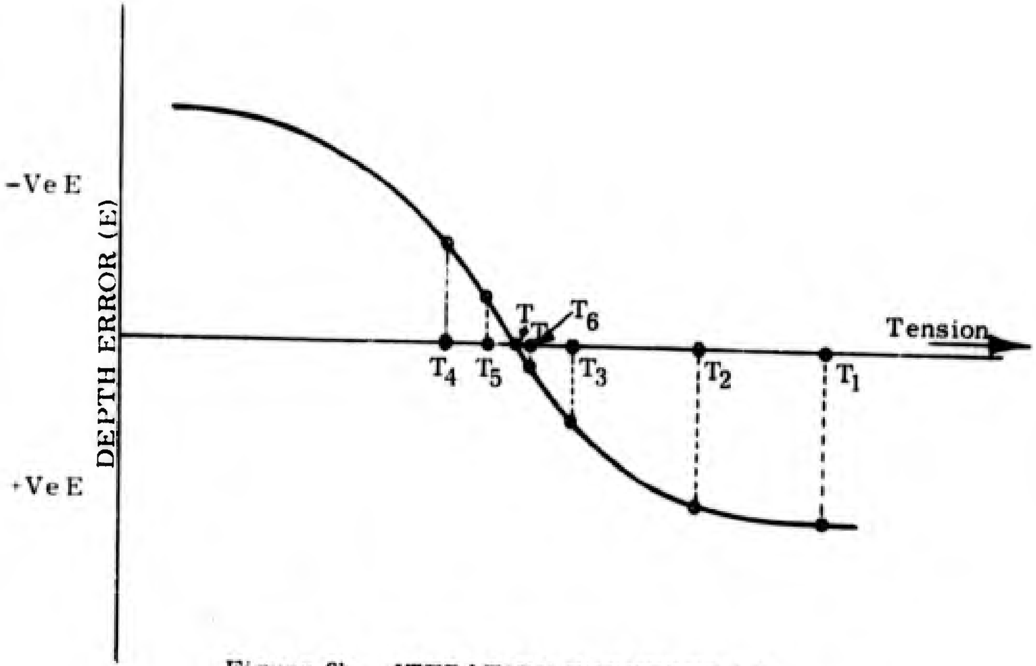


Figure 6b ITERATION PROCEDURE 2

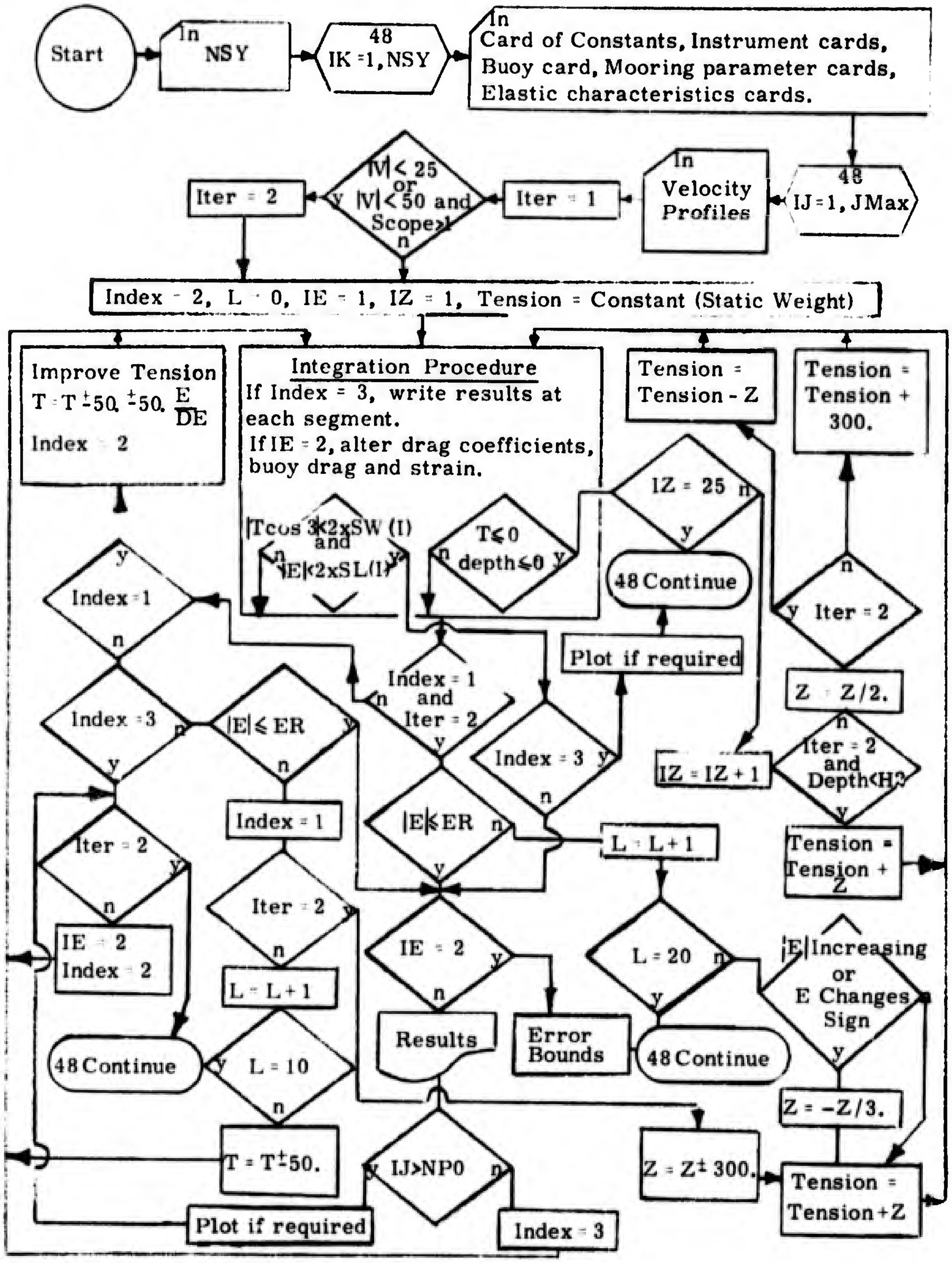


Figure 7. CONTROL PROCEDURES

Instrument Description	Weight in Water (lbs)	Length (meters)	Normal Drag Constant (sq. ft.)	Tangential Drag Const. (sq. ft.)	Comments
Radio Float	+45	0.0	1.75	-	2 Glass balls
16" Glass Ball	+48	0.0	0.7	-	Spherical ball in net
17" Glass Ball	+56	0.0	2.2	-	Drag constant includes casing
AMF Sea Link #323	-72	1.7	3.7	0.11	With timer
Vector Averaging Current Meter	-77	2.0	6.0	0.2	Cylinder
850 Current Meter (12,000 PSI)	-50	2.0	4.1	0.12	Cylinder
850 Current Meter (8000 PSI)	-40	2.0	4.0	0.12	Cylinder
Engineering Current Meter	-28	1.0	1.3	0.06	Cylinder
Temp/Pressure Recorder	-19	0.0	0.4	-	Sphere on a rod
Depth Recorder (1/2" wall)	-22	1.0	1.5	0.05	Cylinder
Depth Recorder (1" wall)	-40	1.0	1.7	0.05	Cylinder
Recording Tensiometer (1"wall)	-40	1.0	1.5	0.04	Cylinder
Inclinometer	-21	1.0	1.5	0.05	Cylinder
1/2" Ø Chain	-8	1.0	0.3	0.01	Drag for two links
3/8" Ø Chain	-5	1.0	0.23	0.006	Drag for two links
Connections (2 shackles, 1 sling link)	-3	0.0	0.0	-	Typical Connection

Figure 8 - INSTRUMENT CHARACTERISTICS

TYPICAL HYSTERESIS LOOPS AT CONSTANT LOADS

9/16" PLAITED NYLON (NEW) (COLUMBIAN ROPE)

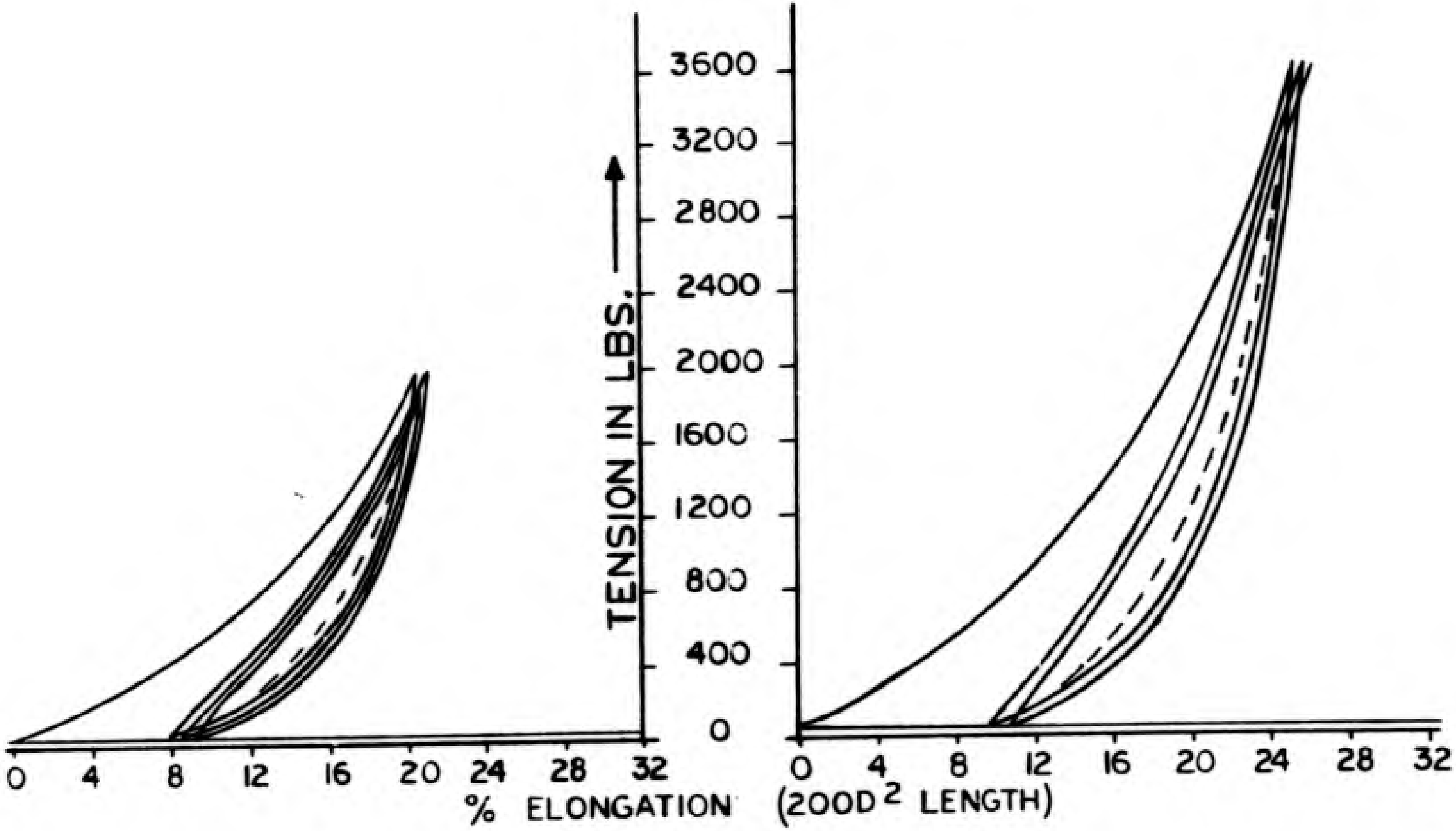


Figure 9. Typical Hysteresis Loops - 9/16 Plaited Nylon

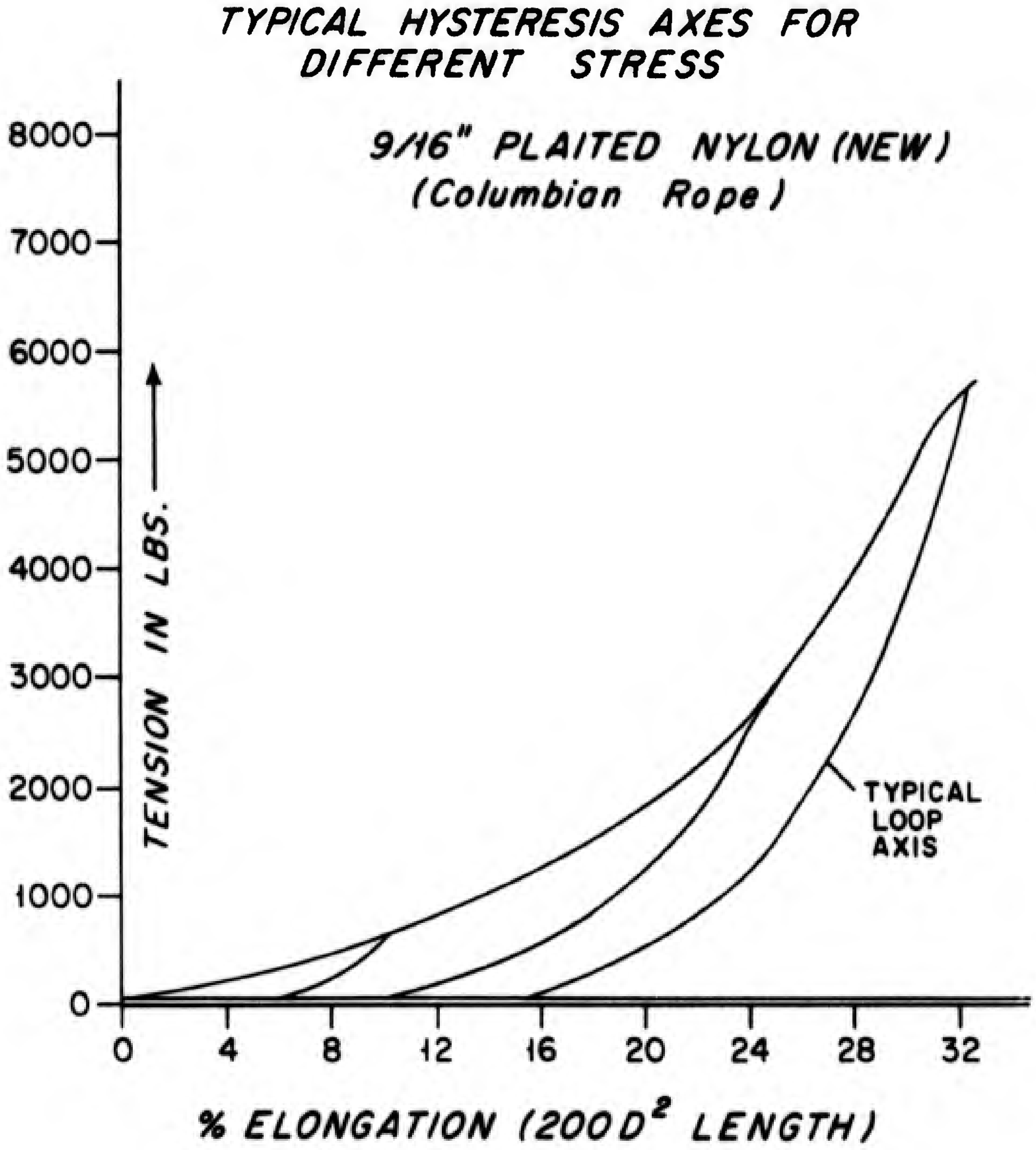


Figure 10. Typical Hysteresis Axes - 9/16 Plaited Nylon
(From Reference 2)

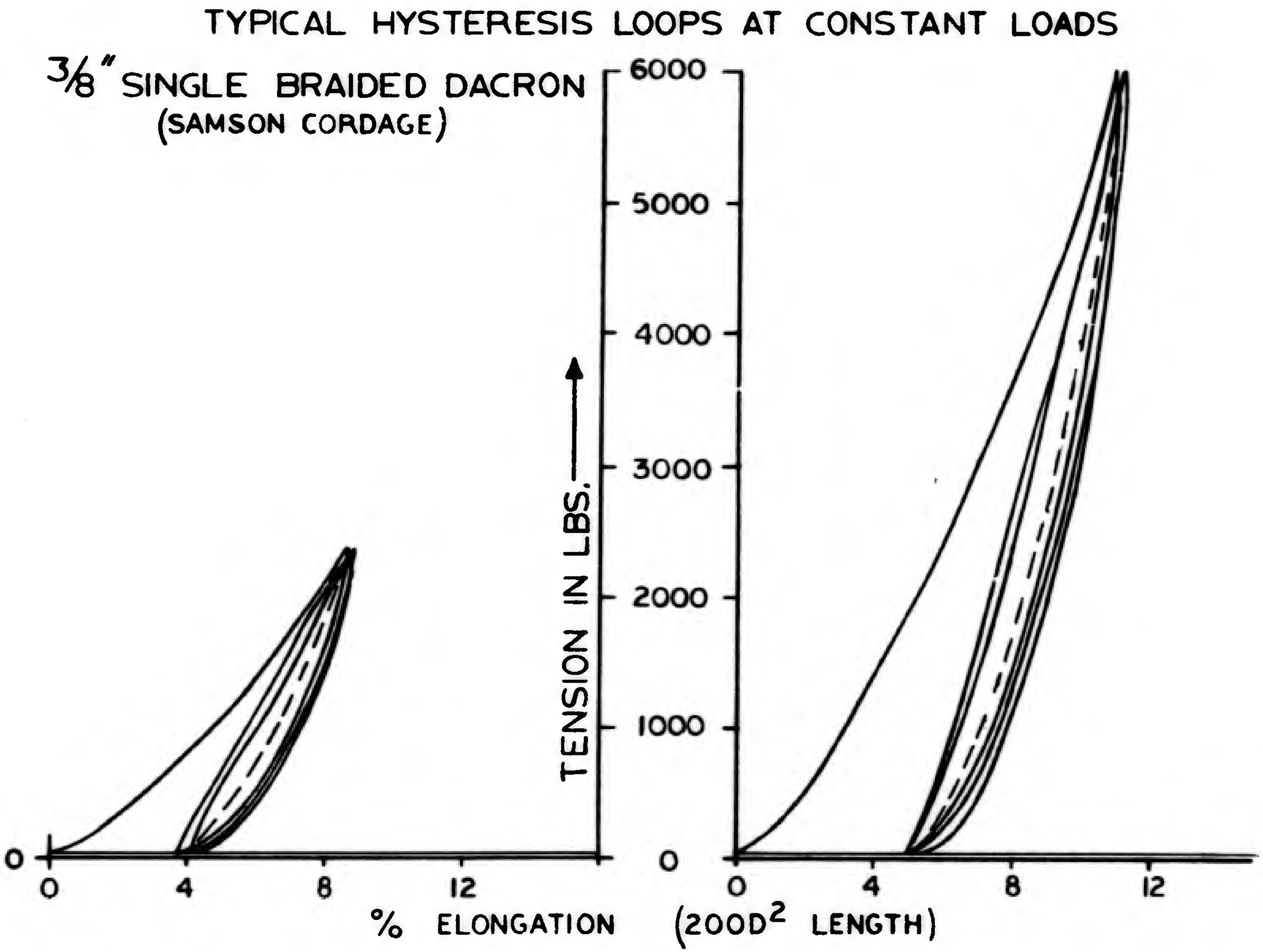


Figure 11. Typical Hysteresis Loops - 3/8 Single Braided Dacron

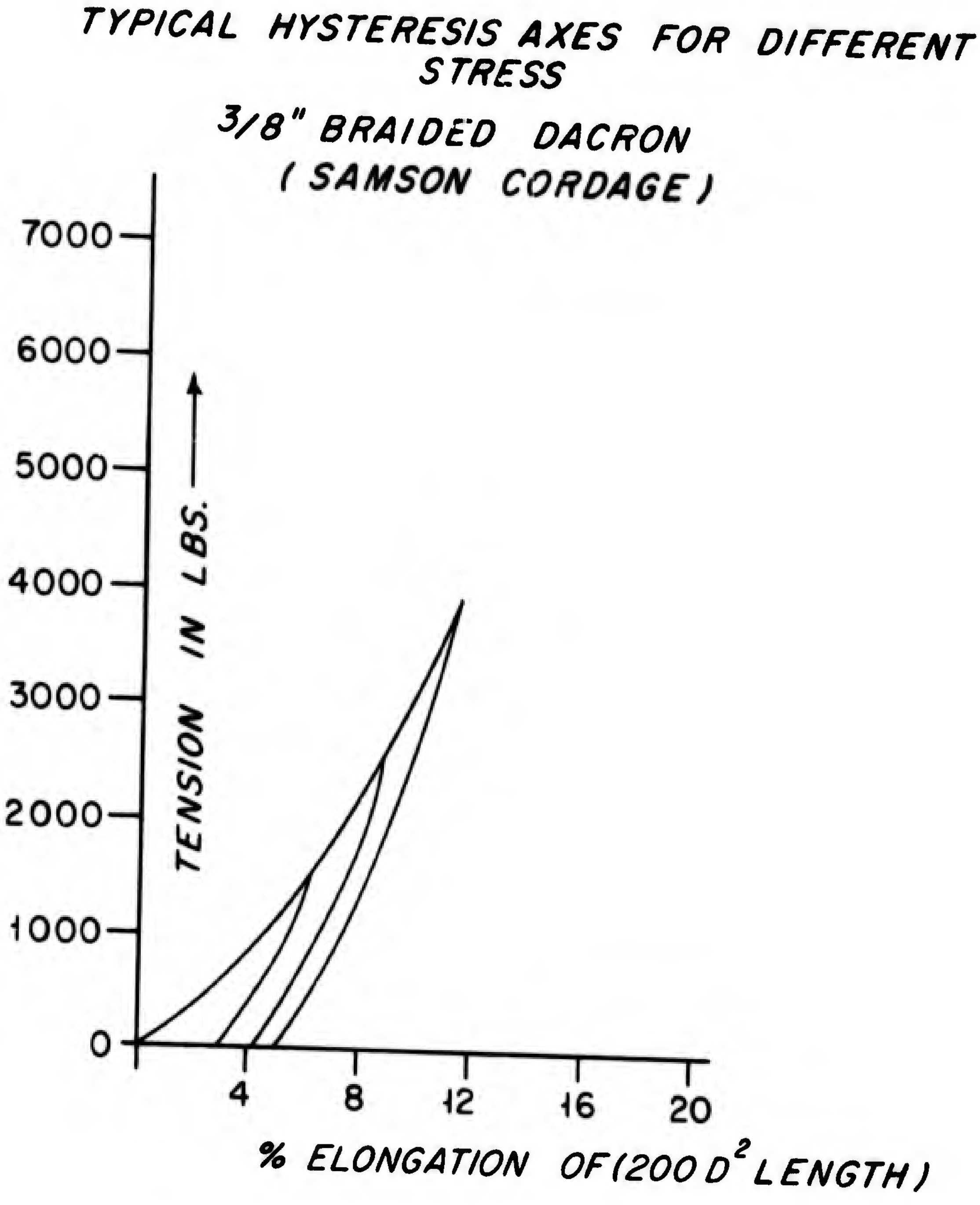


Figure 12. Typical Hysteresis Axes - 3/8 Single Braided Dacron
(From Reference 2)

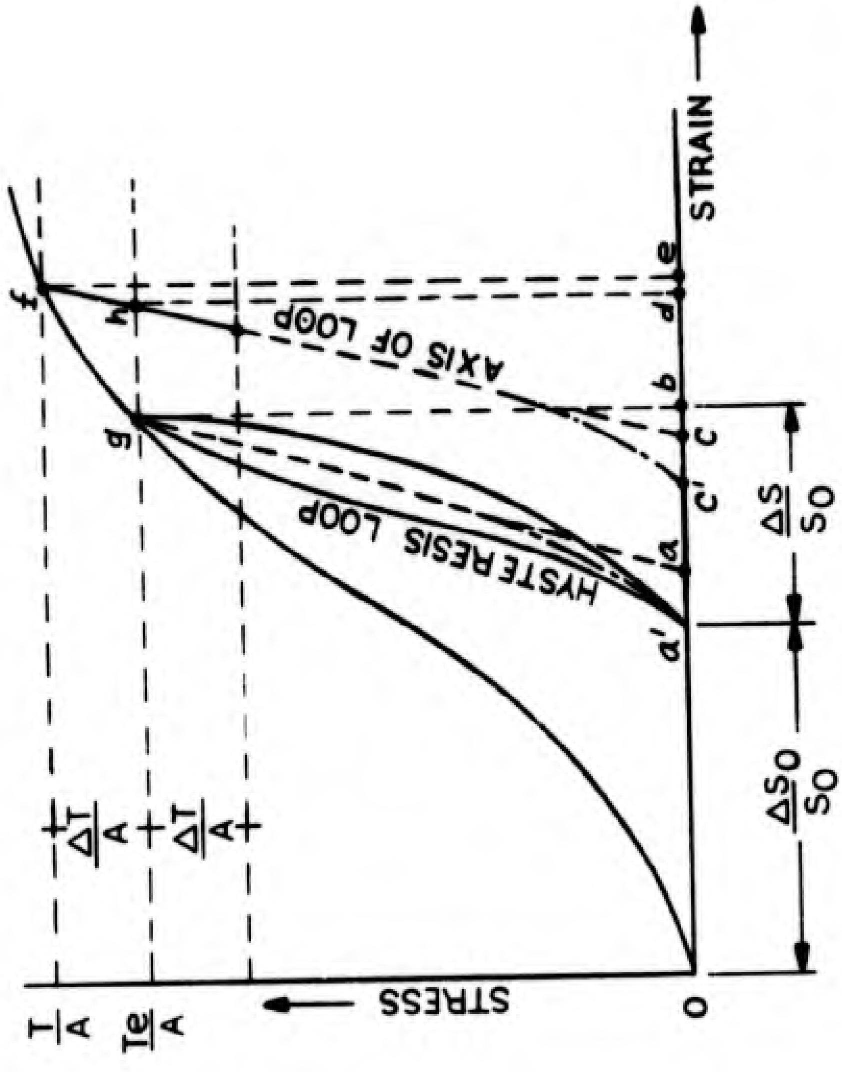


Figure 13. Schematic Diagram of Stress-Strain Relationships for a Typical Mooring Rope

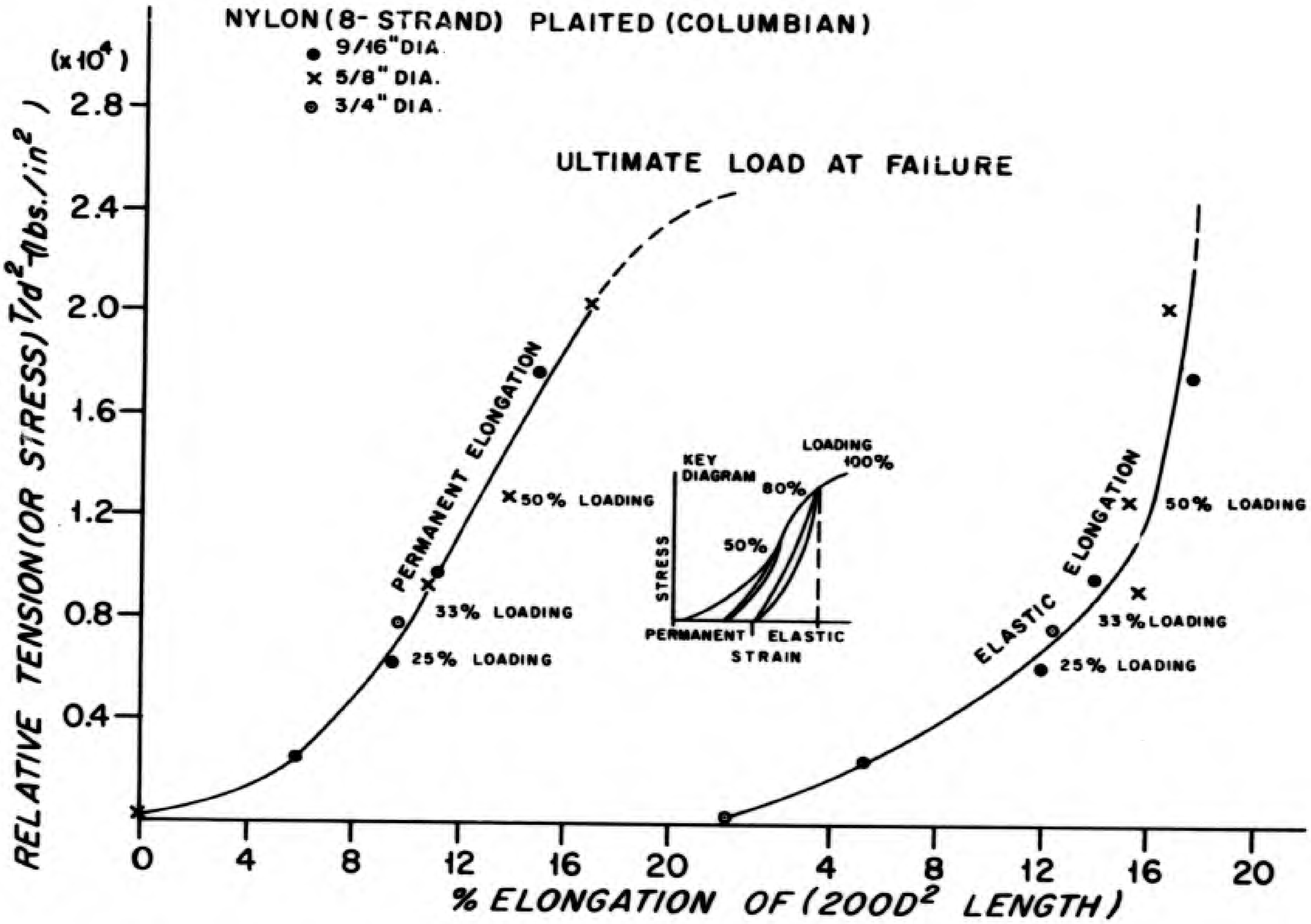


Figure 14. General Stress Strain Relations Plaited Nylon (From Reference 2)

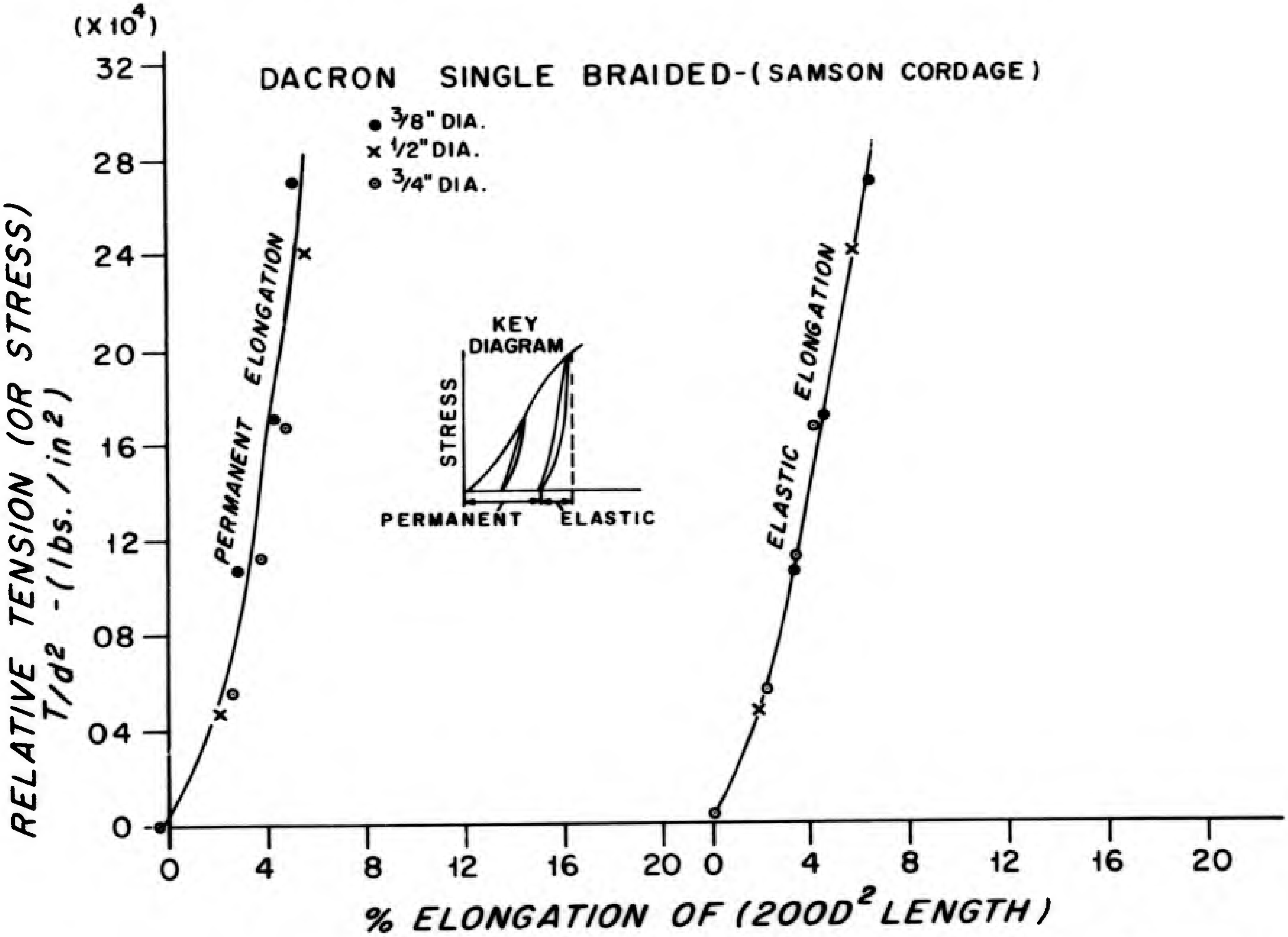


Figure 15. General Stress Strain Relations Single Braided Dacron (From Reference 2)

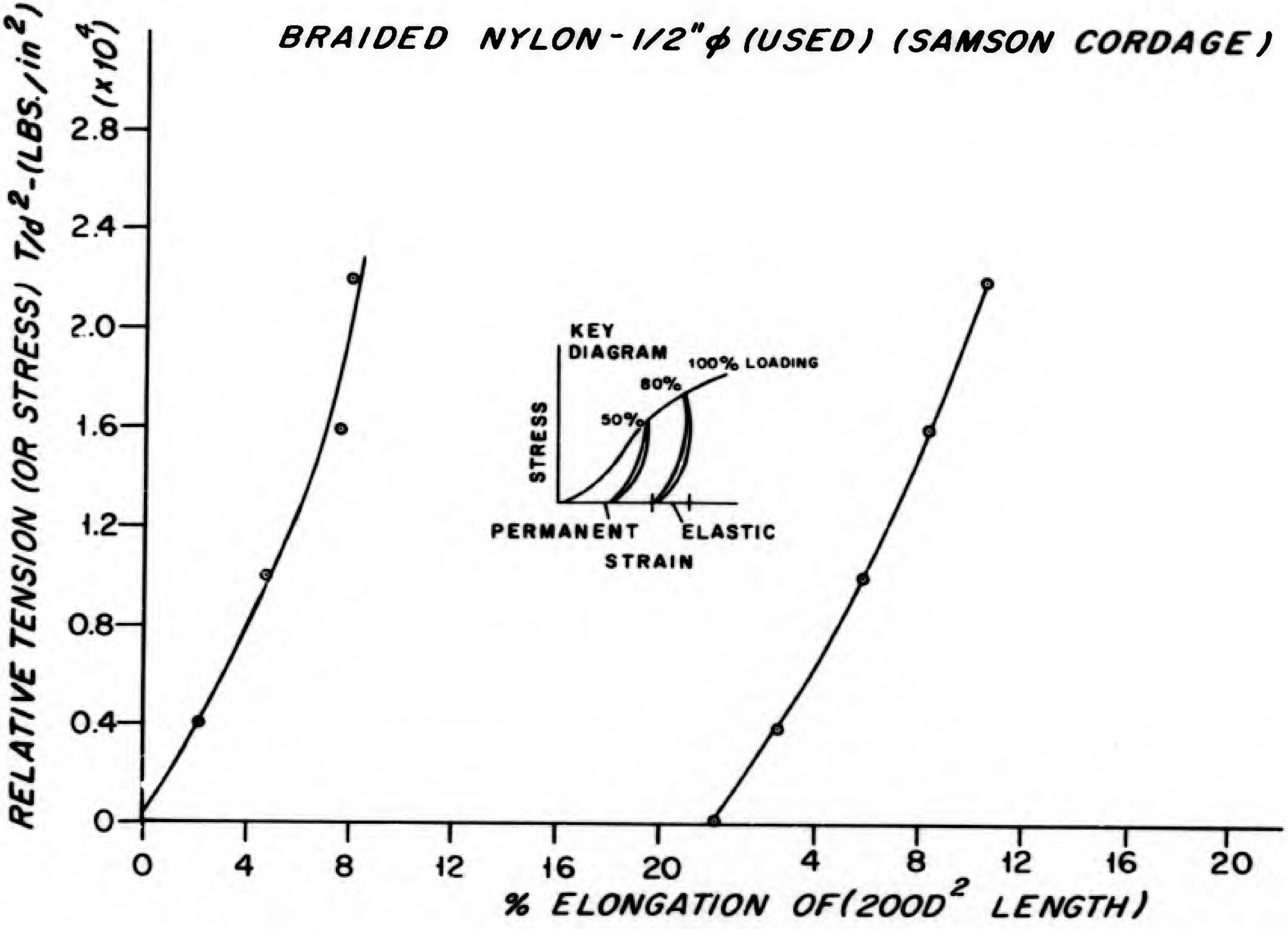


Figure 16. General Stress Strain Relations Single Braided Nylon (From Reference 2)

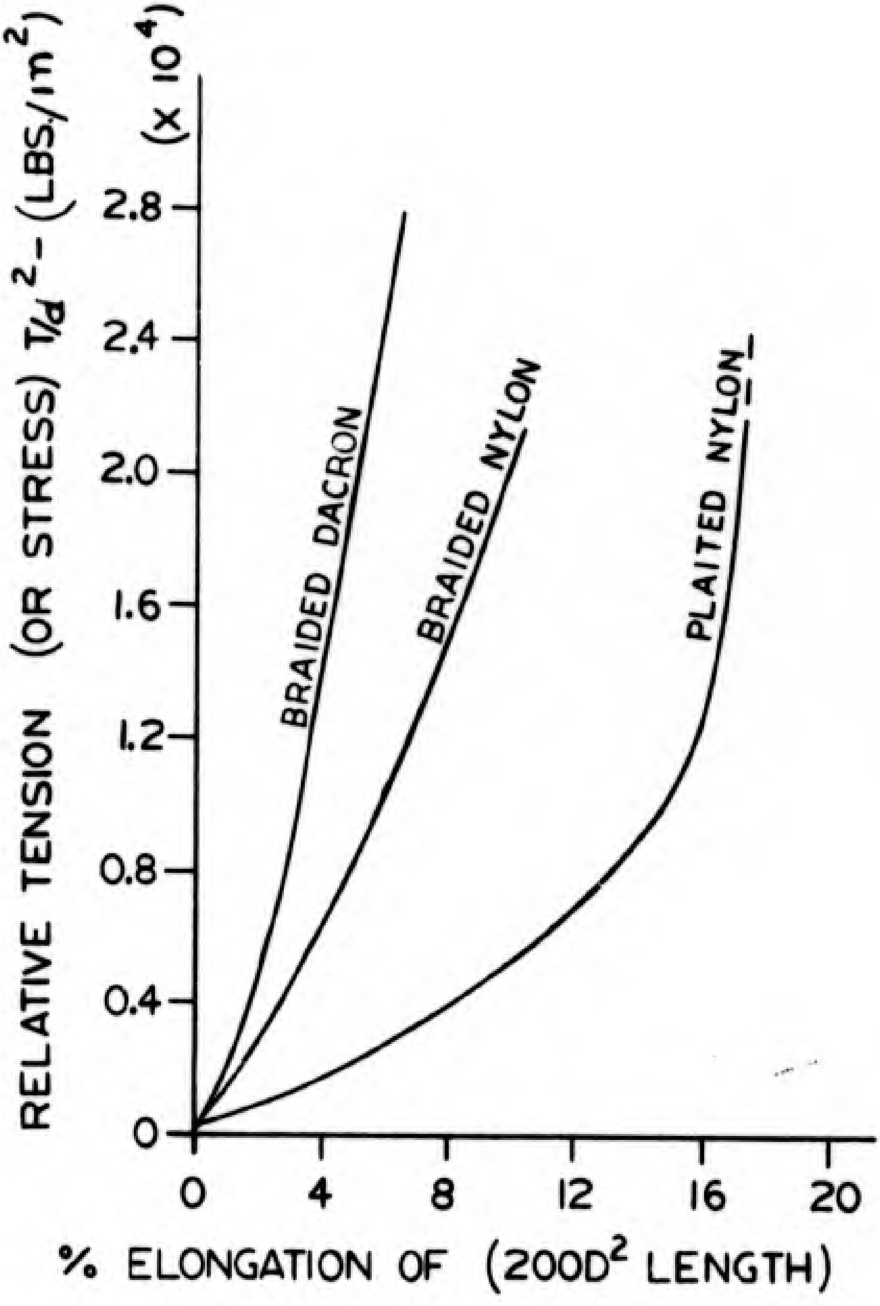


Figure 17. Comparison of elastic elongations

ANALYTIC EXPRESSIONS FOR FIBRE ROPE STRETCH

$$(T/D^2 - 200) = \alpha(\varepsilon)^{\beta}$$

$$200\ D^2\ \text{Length} = \gamma\ \text{(Slack Length)}$$

Type of Rope	$200\ D^2$ Elongation Coefficient	Permanent Elongation		Elastic Elongation	
	γ	α	β	α	β
8 Strand Plaited Nylon (Columbian)	1.042	88	1.94	74.8	1.87
Braided Nylon - Used (Samson)	1.022	1200	1.35	1250	1.20
Braided Dacron (Samson)	1.032	1250	1.80	1350	1.60

ε = Percentage Elongation of 200 D^2 Length

T = Static Tension in lbs

D = Diameter in inches

Figure 18 ELONGATION COEFFICIENTS

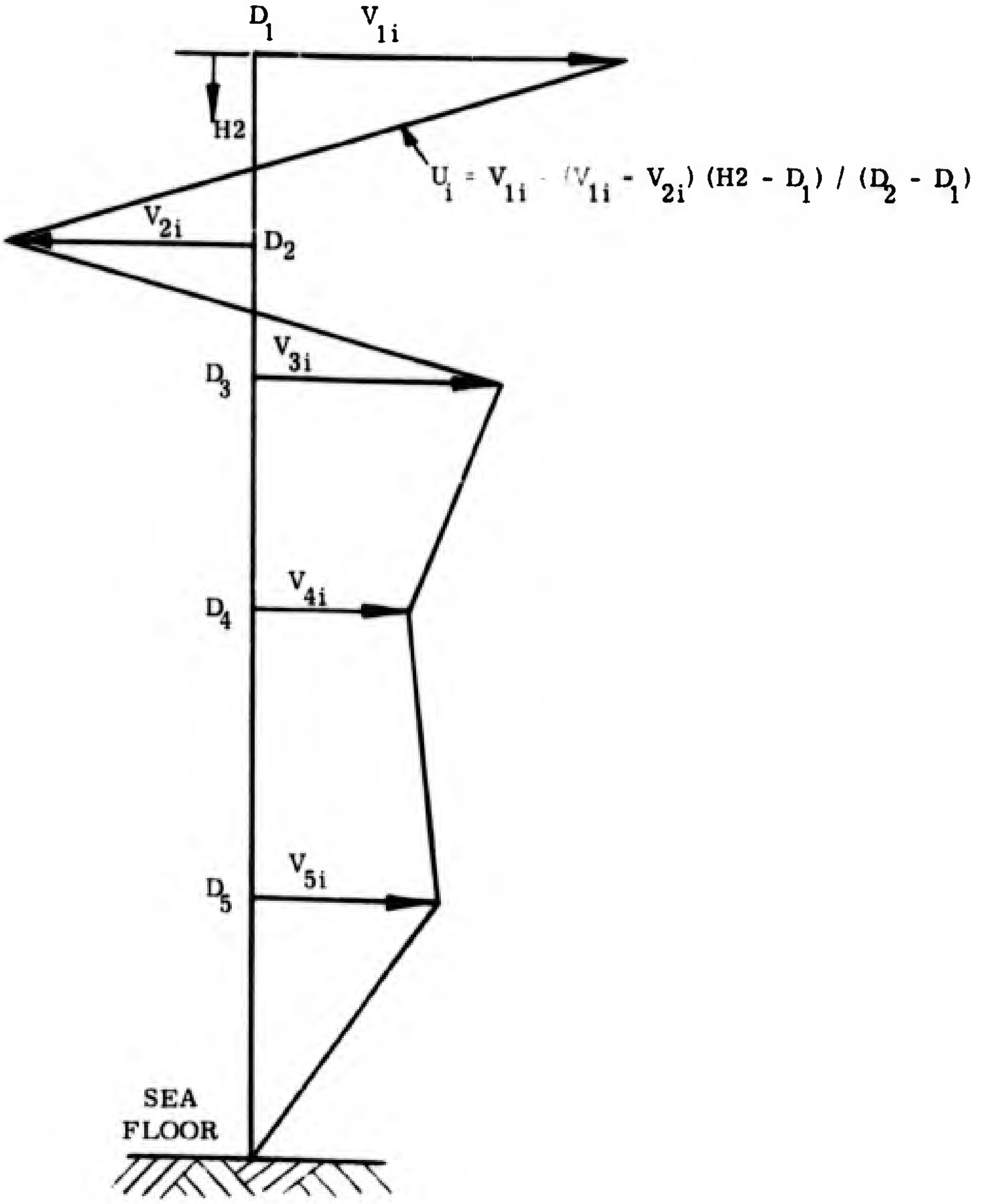


Figure 19 CURRENT PROFILE NUMBER 1

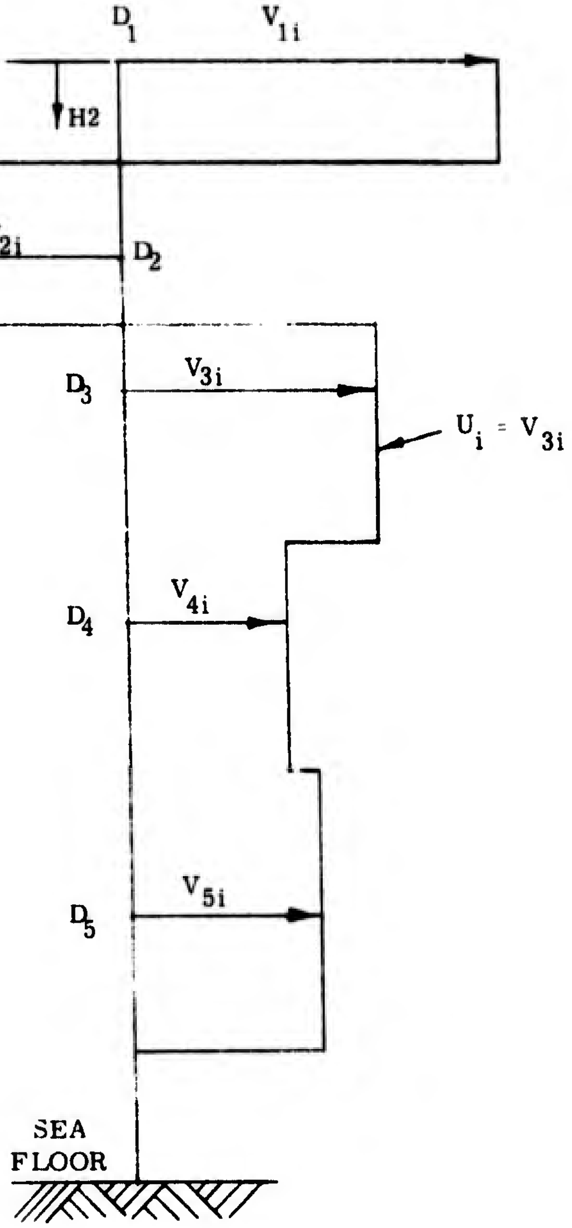


Figure 20 CURRENT PROFILE NUMBER 2

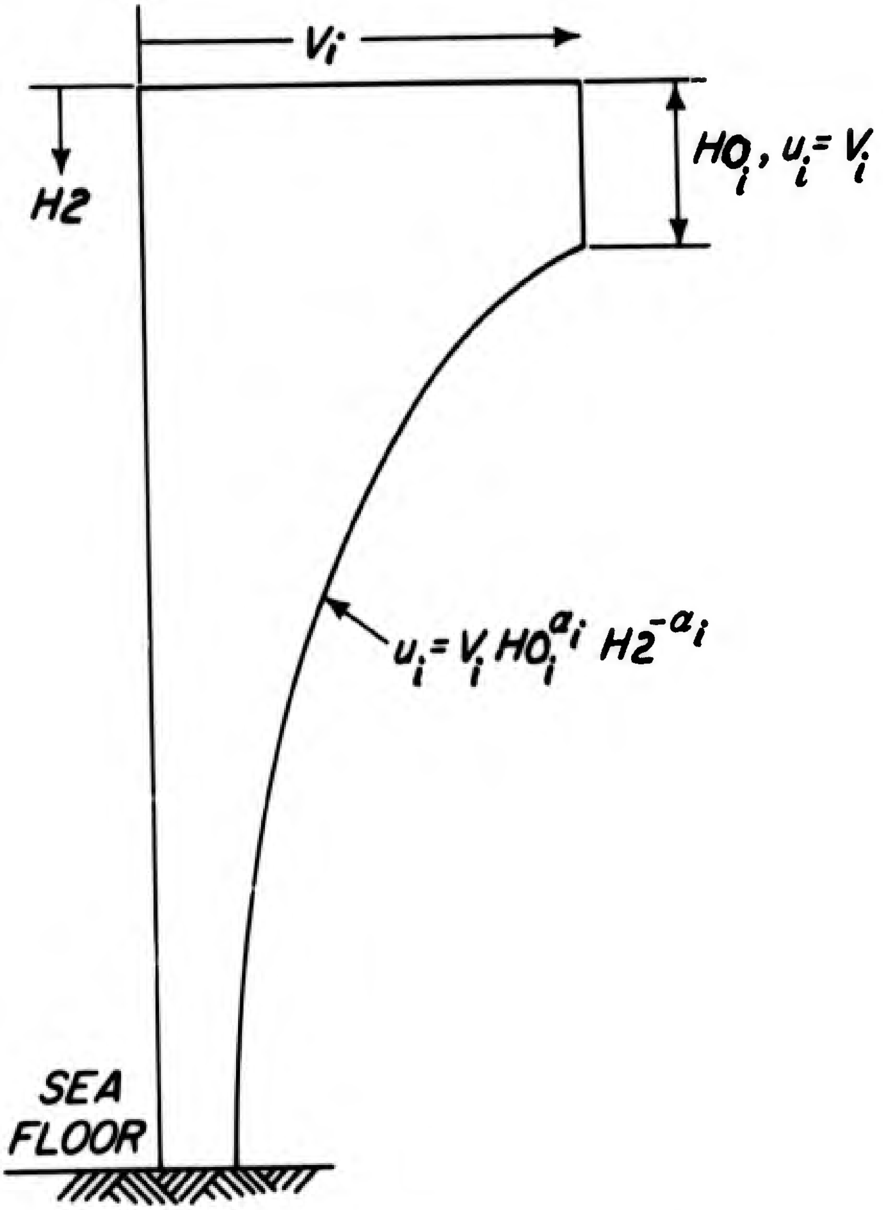


Figure 21. Current Profile Number 3

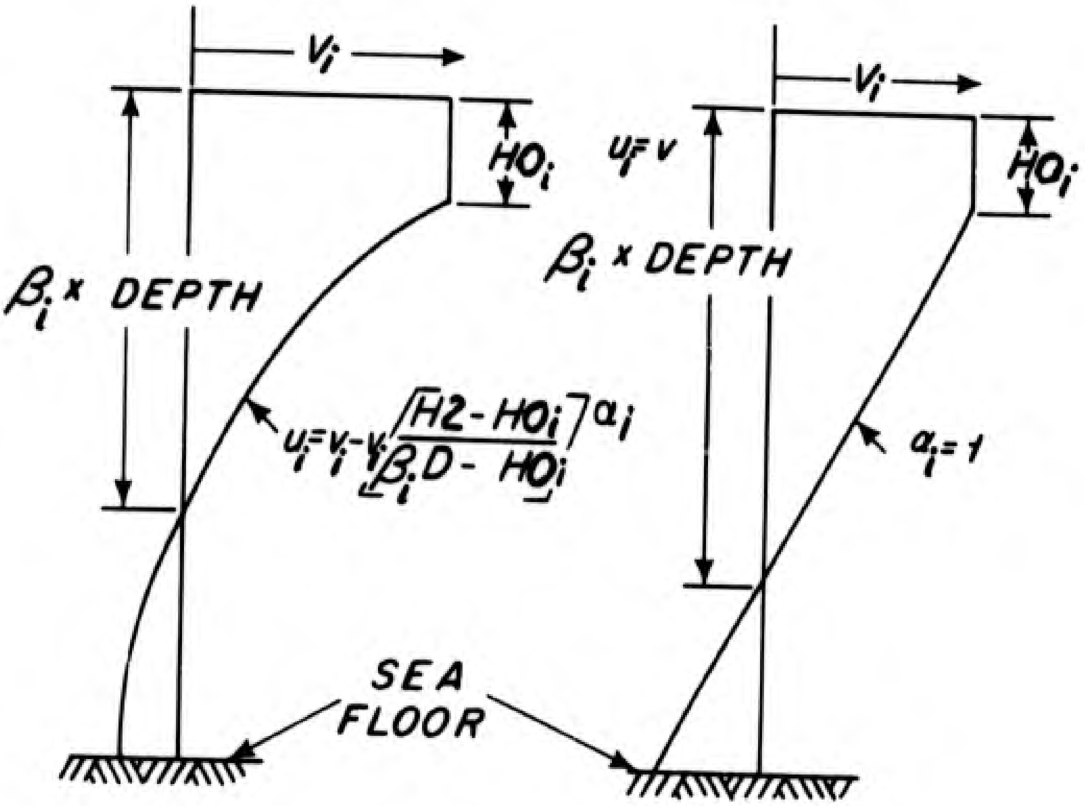


Figure 22. Current Profile Number 4

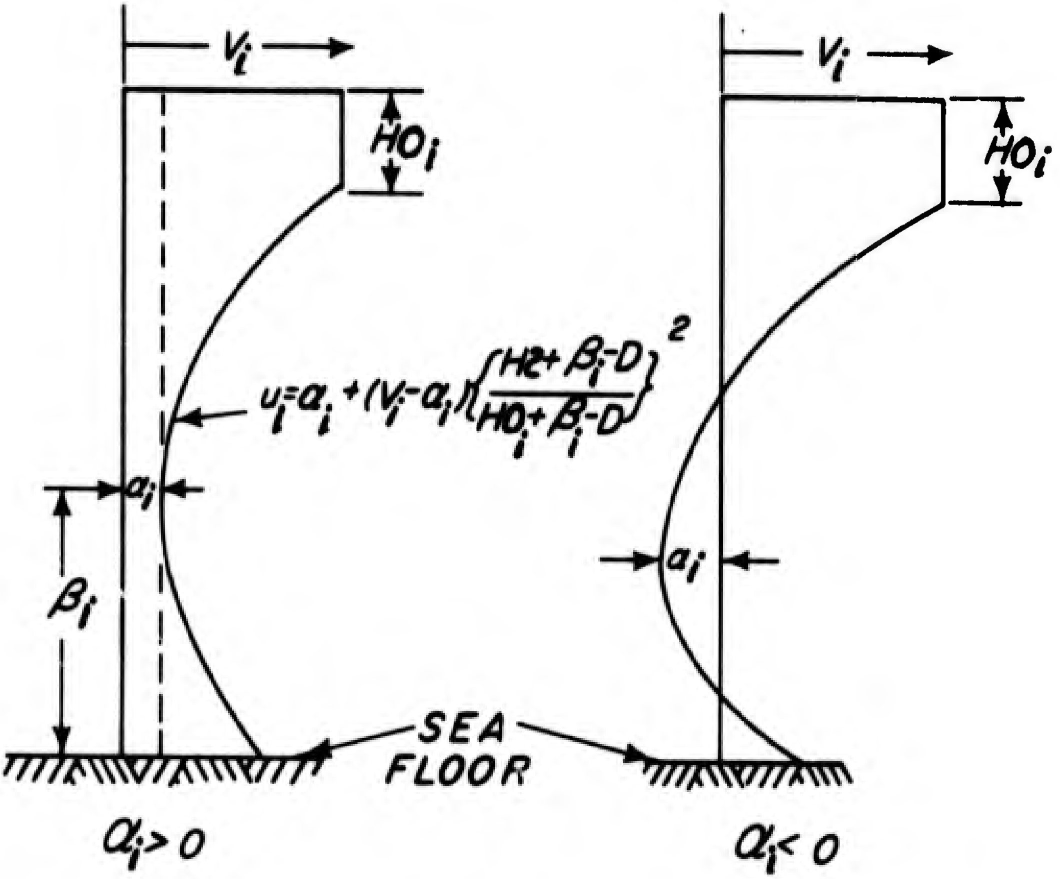


Figure 23. Current Profile Number 5

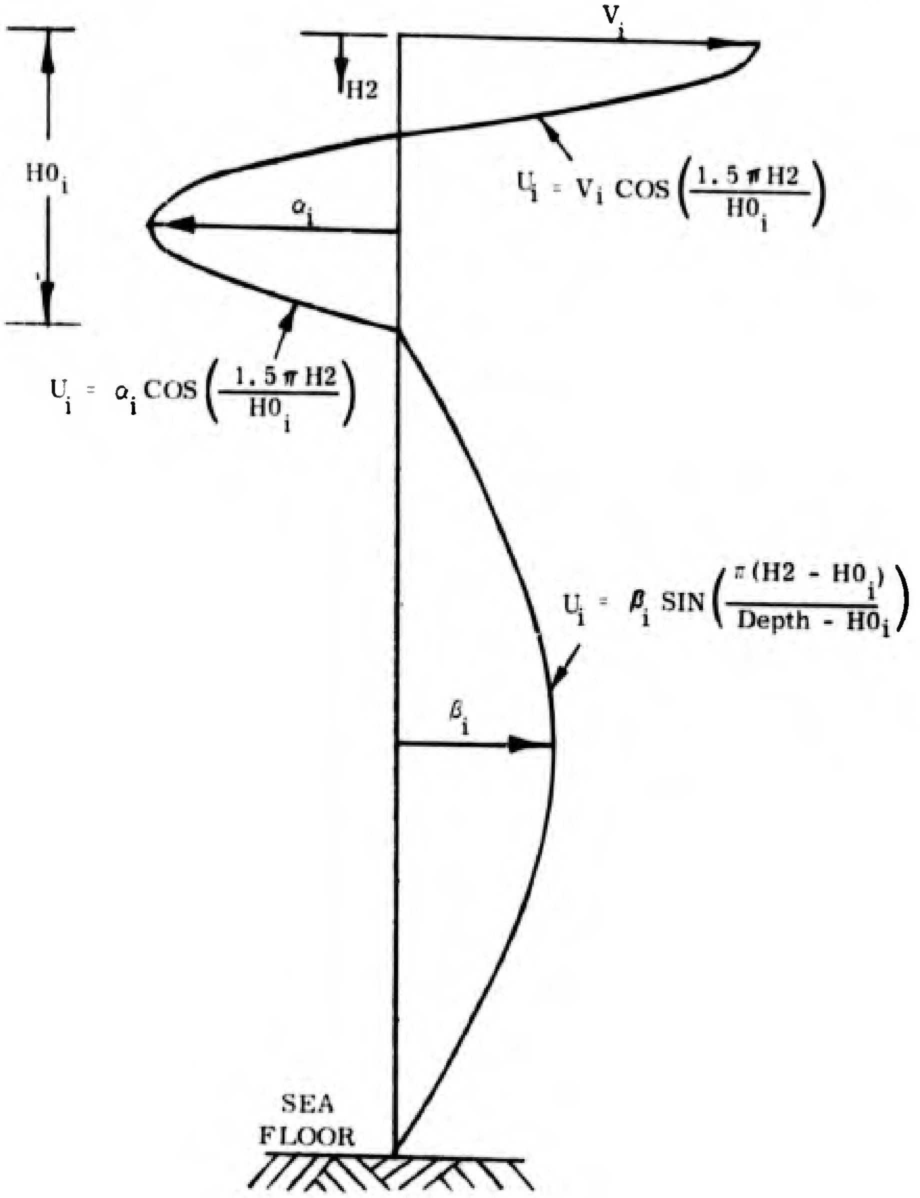
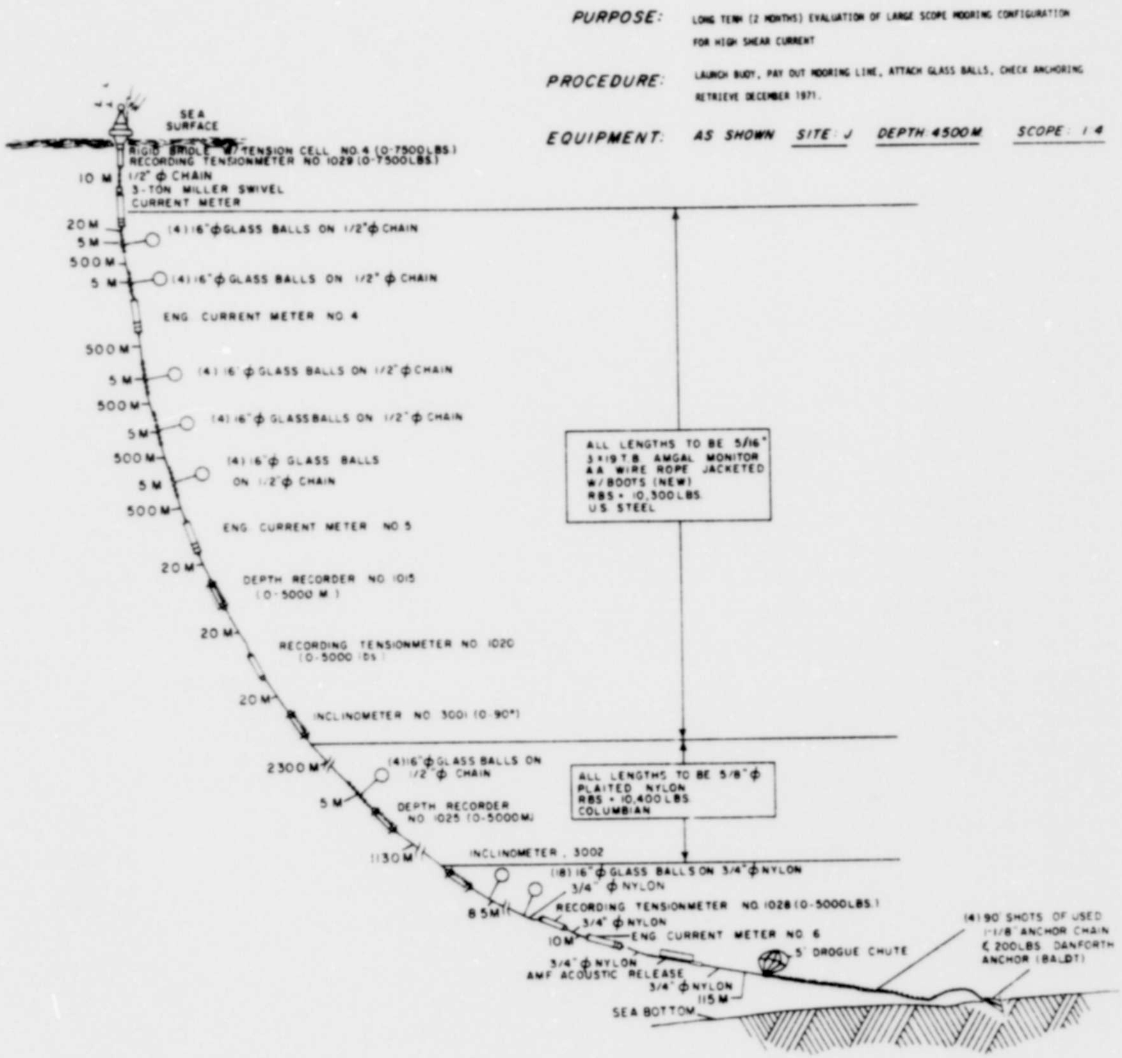


Figure 24 CURRENT PROFILE NUMBER 6



PURPOSE: LONG TERM (2 MONTHS) EVALUATION OF LARGE SCOPE MOORING CONFIGURATION FOR HIGH SHEAR CURRENT

PROCEDURE: LAUNCH BUOY, PAY OUT MOORING LINE, ATTACH GLASS BALLS, CHECK ANCHORING RETRIEVE DECEMBER 1971.

EQUIPMENT: AS SHOWN SITE: J DEPTH 4500M SCOPE: 1:4

Figure 25. Case Study - Surface Buoy System (From Reference 2)

```
00001 C*****LISTING OF DATA FILE S33.DATA FOR SS3.FORT*****************
00010      1
00020     24     5  100     4     1     1     2     5     1     1     1
00030  0.5    1.0      0.        0.        -46.     1.5      0.04     REC TEM1
00040  12.    2.       0.        0.        -46.     4.0      0.12     C. M. 1
00050  35.5   0.       0.        0.        192.     2.8      0.       4 CL. B.
00060  35.5   5.       0.        0.        -46.     1.5      0.05     1/2CHAIN
00070  540.5  0.       0.        0.        192.     2.8      0.       4 CL. B.
00080  541.   6.       0.        0.        -77.     2.8      0.11     F.C.M. 1
00090  1046.5 0.       0.        0.        192.     2.8      0.       4 CL. B.
00100  1046.5 5.       0.        0.        -46.     1.5      0.5      1/2CHAIN
00110  1551.5 0.       0.        0.        192.     2.8      0.       4 CL. B.
00120  1551.5 5.       0.        0.        -46.     1.5      0.05     1/2CHAIN
00130  2056.5 0.       0.        0.        192.     2.8      0.       4 CL. B.
00140  2056.5 5.       0.        0.        -46.     1.5      0.05     1/2CHAIN
00150  2559.5 1.       0.        0.        -34.     1.3      0.06     F.C.M. 2
00160  2580.5 1.       0.        0.        -28.     1.5      0.05     D REC. 1
00170  2601.5 1.       0.        0.        -46.     1.5      0.04     REC TEM2
00180  2622.5 1.       0.        0.        -27.     1.5      0.05     INCLIN 1
00190  4925.5 0.       0.        0.        192.     2.8      0.       4 CL. B.
00200  4926.  6.       0.        0.        -71.     3.0      0.10     D REC. 2
00210  6059.5 1.       0.        0.        -27.     1.5      0.05     INCLIN 2
00220  6088.  0.       0.        0.        432.     6.3      0.       9 CL. B.
00230  6116.  0.       0.        0.        432.     6.3      0.       9 CL. B.
00240  6145.5 1.       0.        0.        -46.     1.5      0.04     REC TEM3
00250  6156.5 1.       0.        0.        -34.     1.3      0.06     F.C.M. 3
00260  6168.  2.       0.        0.        -78.     3.3      0.1      AMF REL.
00270  8.0        4500.       5.         TOROID
00280  0.797      10.         8.        30000.     30000000. 1/2CHAIN
00290  0.392      2580.       0.41      10300.     10000000. 5/16WIRE
00300  0.625      3430.       0.033     10400.     500.      5/8 NYL.
00310  0.75       220.        0.0457    14200.     1000.     3/4 NYL.
00320 1.50        100.8       50.       50000.     30000000. 9/8CHAIN
00330  0.         0.          0.        0.         1.        1.4        0.028
00340  0.0625     0.          0.        0.         1.        1.4        0.028
00350  88.        1.94        74.8      1.87       1.042     1.4        0.028
00360  88.        1.94        74.8      1.87       1.042     1.4        0.028
00370  0.          0.          0.        0.         1.        1.4       0.028
00380  13.0        525.0       2550.0    4362.0
00390  99.77       -23.10      49.57     6.01
00400  99.67       -24.69      24.95     2.83
00410  0.          0.          0.        0.
```

Figure 26. Input data for surface buoy system

```
        OCEANOGRAPHIC BUOY SYSTEM-SURFACE
        RUN NUMBER  1

              INPUT:    BUOY IS TOROID  NO.  2
                        OCEAN DEPTH=4500.0 METERS   MOORING SCOPE=1.421

VEL. PROFILE INFO.:
DIREC. PROF. NO. DEPTHS/VELS. OR TOP VEL. & 3 CONSTANTS
  1      1    13.0  99.770  525.0 -23.100 2550.0  49.570 4362.0   6.010
  2      1    13.0  99.670  525.0 -24.690 2550.0  24.950 4362.0   2.880
  3      1    13.0   0.0    525.0   0.0   2550.0   0.0   4362.0   0.0

---------------------------MOORING PARTS DATA---------------------------
NO.  TYPE  LAUNCH TRAN PEAK DRAG COEFFS. SLACK LEN. DIAMETER R.B.S.  WEIGHT
           LOAD OR E.MODUL. NORM.  TANG.  (METERS)  (INCHES)  (LBS) (LBS/M)

 1 1/2CHAIN   30000000.0    1.400  0.028     10.00     0.707   30000.0  8.000
 2 5/16WIRE   10000000.0    1.400  0.028   2580.00     0.392   10300.0  0.410
 3 5/8 NYL.        500.0    1.400  0.028   3430.00     0.625   10400.0  0.033
 4 3/4 NYL.       1000.0    1.400  0.028    220.00     0.750   14200.0  0.046
 5 9/8CHAIN   30000000.0    1.400  0.028    109.80     1.590   50000.0 50.000

          OUTPUT:     ANALYSIS

                            ITERATION PROCEDURE

ESTIM. TENSION TOP ANGLE1 TOP ANGLE2 DEPTH REACHED DEPTH ERROR COMMENTS
   7495.0         1.55       1.55       7691.5       -3191.5   TRIAL RUN
    950.0         1.49       1.49       2013.5        2486.5   TRIAL RUN
   1315.2         1.51       1.51       3545.9         954.1   TRIAL RUN
   1660.5         1.51       1.51       4500.1          -0.1  CONVERGENT RUN

RESULTS:  BUOY XEXCURSION= 3956.13 METERS   BUOY YEXCURSION= 2987.03 METERS

          -----------------------MOORING PARTS DATA-------------------
          NO.    TYPE    MAXIMUM TENSION  SAFTEY FACTOR  MAXIMUM ELONGATION
                              (LBS)                        (% 200 D SQ.)

          1  1/2CHAIN     1660.48            18.07            0.000
          2  5/16WIRE     1648.56             6.25            0.002
          3  5/8 NYL.     1166.79             8.91           12.787
          4  3/4 NYL.     1554.36             9.14           12.294
          5  9/8CHAIN     1549.28            32.27            0.000
```

Figure 27. Detailed output for input data shown in Fig. 26.

```
                          MOORING CONFIGURATION

SEG. NO. STR.LEN. XEXCUR. YEXCUR.    DEPTH TENSION XANG YANG XVEL. YVEL. M.P. NO.
REC TEN1     1.00    0.06    0.06     1.00 1615.02 1.50 1.50 99.77 99.67 REC TEN1
    1       11.00    0.77    0.77    10.95 1535.44 1.47 1.47 99.77 99.67    1
C. M. 1     13.00    0.97    0.97    12.93 1492.71 1.43 1.43 99.77 99.67 C. M. 1
4 GL. B.    13.00    0.97    0.97    12.93 1692.97 1.42 1.42 99.77 99.67 4 GL. B.
1/2CHAIN    18.00    1.73    1.73    17.81 1648.56 1.40 1.40 99.20 99.09 1/2CHAIN
    2       81.05   12.28   12.27    79.07 1623.68 1.33 1.33 91.26 91.06    2
    3      144.10   27.17   27.13   138.52 1599.62 1.28 1.28 76.78 76.40    2
    4      207.14   45.00   44.93   196.34 1576.21 1.25 1.25 62.71 62.16    2
    5      270.18   64.80   64.68   252.88 1553.26 1.23 1.23 48.99 48.27    2
    6      333.23   85.87   85.68   308.50 1530.61 1.22 1.22 35.53 34.65    2
    7      396.27  107.75  107.47   363.50 1508.14 1.21 1.21 22.26 21.22    2
    8      459.30  130.14  129.76   418.10 1485.80 1.20 1.20  9.11  7.91    2
    9      522.34  152.89  152.40   472.40 1463.58 1.20 1.20 -3.96 -5.32    2
4 GL. B.   522.34  152.89  152.40   472.40 1631.68 1.24 1.24-10.48-11.91 4 GL. B.
E.C.M. 1   528.34  154.86  154.36   477.72 1563.81 1.22 1.22-11.11-12.56 E.C.M. 1
   10      591.38  176.43  175.82   532.93 1541.18 1.22 1.22-18.38-19.91    2
   11      654.42  198.17  197.45   588.01 1518.59 1.22 1.22-21.83-23.82    2
   12      717.46  220.05  219.16   643.00 1496.04 1.21 1.22-19.85-22.47    2
   13      780.50  242.08  241.01   697.87 1473.54 1.21 1.21-17.88-21.12    2
   14      843.53  264.30  263.02   752.60 1451.11 1.21 1.21-15.91-19.78    2
   15      906.57  286.76  285.21   807.16 1428.75 1.20 1.21-13.95-18.44    2
   16      969.60  309.47  307.61   861.52 1406.48 1.20 1.20-12.00-17.11    2
   17     1032.63  332.46  330.26   915.66 1384.30 1.19 1.20-10.05-15.78    2
4 GL. B.  1032.63  332.46  330.26   915.66 1551.28 1.23 1.24 -9.08-15.11 4 GL. B.
1/2CHAIN  1037.63  334.11  331.88   920.10 1510.60 1.23 1.23 -9.00-15.06 1/2CHAIN
   18     1100.67  355.45  352.83   975.59 1487.87 1.22 1.23 -7.93-14.32    2
   19     1163.70  377.07  374.02  1030.88 1465.23 1.22 1.22 -5.94-12.97    2
   20     1226.74  399.00  395.47  1085.95 1442.69 1.21 1.22 -3.96-11.61    2
   21     1289.77  421.25  417.20  1140.77 1420.25 1.20 1.21 -1.99-10.27    2
   22     1352.80  443.85  439.24  1195.34 1397.91 1.20 1.21 -0.02 -8.93    2
   23     1415.83  466.81  461.59  1249.62 1375.69 1.19 1.20  1.93 -7.59    2
   24     1478.86  490.14  484.27  1303.60 1353.59 1.18 1.20  3.87 -6.27    2
   25     1541.89  513.86  507.29  1357.27 1331.63 1.18 1.19  5.80 -4.95    2
4 GL. B.  1541.89  513.86  507.29  1357.27 1497.67 1.22 1.23  6.77 -4.29 4 GL. B.
1/2CHAIN  1546.89  515.56  508.94  1361.67 1457.33 1.21 1.23  6.85 -4.23 1/2CHAIN
   26     1609.92  537.61  530.30  1416.72 1434.80 1.21 1.22  7.91 -3.51    2
   27     1672.95  560.04  551.97  1471.50 1412.38 1.20 1.21  9.88 -2.16    2
   28     1735.99  582.85  573.96  1525.99 1390.08 1.19 1.21 11.84 -0.82    2
   29     1799.01  606.07  596.29  1580.16 1367.91 1.19 1.20 13.79  0.51    2
   30     1862.04  629.73  618.97  1634.00 1345.88 1.18 1.20 15.73  1.84    2
   31     1925.07  653.86  642.01  1687.47 1324.00 1.17 1.19 17.66  3.15    2
   32     1988.09  678.50  665.43  1740.55 1302.29 1.16 1.18 19.57  4.46    2
   33     2051.12  703.67  689.23  1793.20 1280.76 1.15 1.18 21.47  5.75    2
4 GL. B.  2051.12  703.67  689.23  1793.20 1444.58 1.20 1.22 22.41  6.40 4 GL. B.
1/2CHAIN  2056.12  705.49  690.94  1797.54 1404.90 1.19 1.21 22.49  6.45 1/2CHAIN
   34     2119.15  729.07  713.04  1851.65 1382.77 1.18 1.21 23.54  7.17    2
   35     2182.17  753.21  735.52  1905.36 1360.82 1.17 1.20 25.47  8.49    2
   36     2245.20  777.96  758.41  1958.61 1339.06 1.16 1.19 27.39  9.80    2
   37     2308.23  803.36  781.71  2011.38 1317.51 1.14 1.18 29.29 11.10    2
   38     2371.25  829.46  805.45  2063.60 1296.20 1.13 1.18 31.18 12.39    2
   39     2434.27  856.32  829.66  2115.23 1275.14 1.12 1.17 33.04 13.66    2
   40     2497.29  883.98  854.36  2166.20 1254.36 1.10 1.16 34.88 14.92    2
   41     2560.31  912.50  879.56  2216.45 1233.90 1.09 1.15 36.70 16.16    2
```

Figure 27. Detailed output for input data shown in Fig. 26. - Contd.

```
E.C.M. 2 2561.31  912.96  879.97 2217.23 1207.77 1.07 1.14 37.61 16.78 E.C.M. 2
D REC. 1 2562.31  913.44  880.38 2218.00 1186.32 1.06 1.13 37.64 16.80 D REC. 1
   42    2625.33  944.18  907.18 2266.05 1166.79 1.04 1.12 38.52 17.40    2
REC TEN2 2626.33  944.68  907.61 2266.79 1132.99 1.02 1.11 39.39 18.00 REC TEN2
INCLIN 1 2627.33  945.20  908.06 2267.52 1113.55 1.01 1.10 39.42 18.02 INCLIN 1
   43    2701.90  984.69  942.02 2320.89 1112.37 1.00 1.09 40.39 18.68    3
   44    2776.48 1025.19  976.22 2373.35 1111.26 0.98 1.09 42.29 19.98    3
   45    2851.05 1066.73 1010.68 2424.82 1110.23 0.96 1.09 44.15 21.25    3
   46    2925.61 1109.36 1045.40 2475.21 1109.29 0.94 1.08 45.98 22.50    3
   47    3000.18 1153.09 1080.40 2524.47 1108.45 0.93 1.08 47.77 23.72    3
   48    3074.74 1197.94 1115.66 2572.51 1107.71 0.91 1.07 49.52 24.91    3
   49    3149.30 1243.90 1151.20 2619.30 1107.01 0.89 1.07 48.47 24.39    3
   50    3223.87 1290.86 1186.97 2664.90 1106.33 0.87 1.07 47.36 23.83    3
   51    3298.42 1338.73 1222.95 2709.40 1105.67 0.86 1.06 46.27 23.28    3
   52    3372.98 1387.39 1259.09 2752.88 1105.03 0.85 1.06 45.22 22.74    3
   53    3447.54 1436.79 1295.39 2795.40 1104.40 0.83 1.06 44.18 22.22    3
   54    3522.09 1486.84 1331.82 2837.03 1103.78 0.82 1.06 43.17 21.71    3
   55    3596.64 1537.49 1368.36 2877.82 1103.18 0.81 1.06 42.18 21.21    3
   56    3671.20 1588.69 1405.01 2917.84 1102.58 0.80 1.06 41.21 20.71    3
   57    3745.75 1640.39 1441.75 2957.11 1101.98 0.80 1.05 40.26 20.23    3
   58    3820.30 1692.54 1478.57 2995.71 1101.39 0.79 1.05 39.32 19.76    3
   59    3894.84 1745.12 1515.47 3033.65 1100.79 0.78 1.05 38.40 19.29    3
   60    3969.39 1798.08 1552.43 3070.98 1100.20 0.77 1.05 37.49 18.83    3
   61    4043.93 1851.40 1589.45 3107.74 1099.61 0.77 1.05 36.60 18.38    3
   62    4118.48 1905.06 1626.52 3143.95 1099.02 0.76 1.05 35.73 17.94    3
   63    4193.02 1959.02 1663.65 3179.65 1098.42 0.76 1.05 34.86 17.50    3
   64    4267.55 2013.26 1700.83 3214.86 1097.82 0.75 1.05 34.01 17.07    3
   65    4342.09 2067.77 1738.04 3249.61 1097.22 0.75 1.05 33.17 16.64    3
   66    4416.63 2122.53 1775.30 3283.92 1096.61 0.74 1.05 32.34 16.22    3
   67    4491.16 2177.52 1812.60 3317.82 1096.00 0.74 1.05 31.52 15.80    3
   68    4565.70 2232.72 1849.93 3351.32 1095.39 0.73 1.05 30.71 15.39    3
   69    4640.23 2288.13 1887.30 3384.44 1094.77 0.73 1.05 29.91 14.99    3
   70    4714.76 2343.72 1924.69 3417.20 1094.15 0.73 1.04 29.12 14.59    3
   71    4789.29 2399.50 1962.12 3449.62 1093.52 0.72 1.04 28.33 14.19    3
   72    4863.81 2455.44 1999.58 3481.71 1092.89 0.72 1.04 27.56 13.80    3
   73    4938.34 2511.54 2037.07 3513.48 1092.25 0.72 1.04 26.79 13.41    3
   74    5012.86 2567.79 2074.59 3544.96 1091.61 0.71 1.04 26.03 13.02    3
   75    5087.39 2624.17 2112.13 3576.15 1090.96 0.71 1.04 25.28 12.64    3
   76    5161.91 2680.70 2149.70 3607.06 1090.31 0.71 1.04 24.53 12.26    3
   77    5236.43 2737.34 2187.30 3637.70 1089.65 0.70 1.04 23.79 11.89    3
   78    5310.95 2794.11 2224.92 3668.09 1088.99 0.70 1.04 23.06 11.52    3
4 GL. B. 5310.95 2794.11 2224.92 3668.09 1182.13 0.79 1.09 22.69 11.33 4 GL. B.
D REC. 2 5316.95 2798.33 2227.72 3671.30 1145.79 0.76 1.07 22.65 11.31 D REC. 2
   79    5391.59 2852.62 2263.62 3707.85 1144.93 0.75 1.07 22.17 11.07    3
   80    5466.24 2907.05 2299.57 3744.15 1144.06 0.75 1.07 21.30 10.63    3
   81    5540.88 2961.62 2335.55 3780.20 1143.19 0.75 1.07 20.43 10.19    3
   82    5615.52 3016.30 2371.58 3816.02 1142.31 0.75 1.07 19.57  9.75    3
   83    5690.16 3071.11 2407.64 3851.62 1141.43 0.74 1.07 18.71  9.31    3
   84    5764.80 3126.02 2443.74 3887.02 1140.54 0.74 1.07 17.85  8.88    3
   85    5839.44 3181.04 2479.88 3922.21 1139.65 0.74 1.06 17.01  8.45    3
   86    5914.07 3236.15 2516.05 3957.21 1138.76 0.74 1.06 16.16  8.02    3
   87    5988.70 3291.35 2552.25 3992.03 1137.86 0.74 1.06 15.32  7.60    3
   88    6063.33 3346.64 2588.49 4026.67 1136.96 0.73 1.06 14.49  7.18    3
   89    6137.96 3402.01 2624.76 4061.15 1136.05 0.73 1.06 13.66  6.75    3
   90    6212.59 3457.45 2661.06 4095.46 1135.14 0.73 1.06 12.83  6.34    3
```

Figure 27. Detailed output for input data shown in Fig. 26. - Contd.

```
   91     6287.21 3512.97 2697.40 4129.62 1134.23 0.73 1.06 12.01   5.92      3
   92     6361.83 3568.56 2733.76 4163.63 1133.32 0.73 1.06 11.19   5.50      3
   93     6436.45 3624.21 2770.15 4197.49 1132.41 0.73 1.06 10.37   5.09      3
   94     6511.07 3679.93 2806.58 4231.21 1131.49 0.73 1.06  9.56   4.68      3
   95     6585.68 3735.71 2843.03 4264.80 1130.57 0.73 1.06  8.75   4.27      3
   96     6660.29 3791.54 2879.52 4298.25 1129.66 0.72 1.06  7.94   3.86      3
INCLIN 2 6661.29 3792.29 2880.01 4298.70 1117.91 0.71 1.05  7.54   3.65 INCLIN 2
9 GL. B. 6661.29 3792.29 2880.01 4298.70 1360.13 0.90 1.15  7.53   3.65 9 GL. B.
   97     6746.02 3845.02 2914.46 4355.36 1357.90 0.90 1.15  6.85   3.31      4
9 GL. B. 6746.02 3845.02 2914.46 4355.36 1677.43 1.04 1.23  6.17   2.96 9 GL. B.
REC TEN3 6747.02 3845.53 2914.79 4356.16 1640.98 1.03 1.23  6.16   2.96 REC TEN3
E.C.M. 3 6748.02 3846.04 2915.12 4356.94 1614.35 1.02 1.22  6.14   2.95 E.C.M. 3
AMF REL. 6750.02 3847.09 2915.81 4358.50 1554.36 0.99 1.21  6.11   2.93 AMF REL.
   98     6835.52 3893.71 2946.25 4423.38 1551.82 0.99 1.21  4.75   2.28      4
   99     6921.32 3940.58 2976.85 4488.41 1549.28 0.99 1.21  1.92   0.92      4
  100     6923.35 3941.69 2977.58 4489.95 1472.32 0.96 1.19  0.47   0.23      5
  101     6925.38 3942.86 2978.34 4491.43 1398.29 0.92 1.17  0.41   0.19      5
  102     6927.41 3944.09 2979.14 4492.84 1327.63 0.89 1.14  0.34   0.16      5
  103     6929.45 3945.37 2979.98 4494.17 1260.89 0.84 1.12  0.28   0.14      5
  104     6931.48 3946.72 2980.86 4495.41 1198.69 0.80 1.10  0.23   0.11      5
  105     6933.51 3948.14 2981.79 4496.55 1141.75 0.75 1.07  0.18   0.08      5
  106     6935.54 3949.62 2982.76 4497.57 1090.85 0.71 1.05  0.13   0.06      5
  107     6937.57 3951.16 2983.77 4498.45 1046.88 0.66 1.03  0.09   0.04      5
  108     6939.60 3952.77 2984.83 4499.16 1010.77 0.62 1.01  0.05   0.03      5
  109     6941.63 3954.43 2985.92 4499.71  983.41 0.58 0.99  0.02   0.01      5
  110     6943.66 3956.13 2987.03 4500.06  965.66 0.55 0.98  0.01   0.00      5

 THE REST OF THE CABLE OF LENGTH    87.55 METERS IS  LYING ON THE FLOOR

MAXIMUM EXPECTED ERROR-ASSUMING VELOCITY PROFILE IS CORRECT AND
IF:TOP ANGLES ARE OFF BY ONE DEGREE AND DRAG COEFFS.
AND SYNTHETIC STRETCH OFF 10 PERCENT

MOORING PART NO.=  1  MAXIMUM TENSION OFF IN LBS=    162.063
MOORING PART NO.=  2  MAXIMUM TENSION OFF IN LBS=    162.503
MOORING PART NO.=  3  MAXIMUM TENSION OFF IN LBS=    162.693
MOORING PART NO.=  4  MAXIMUM TENSION OFF IN LBS=    160.336
MOORING PART NO.=  5  MAXIMUM TENSION OFF IN LBS=   2790.346
```

Figure 27. Detailed output for input data shown in Fig. 26. - Contd.

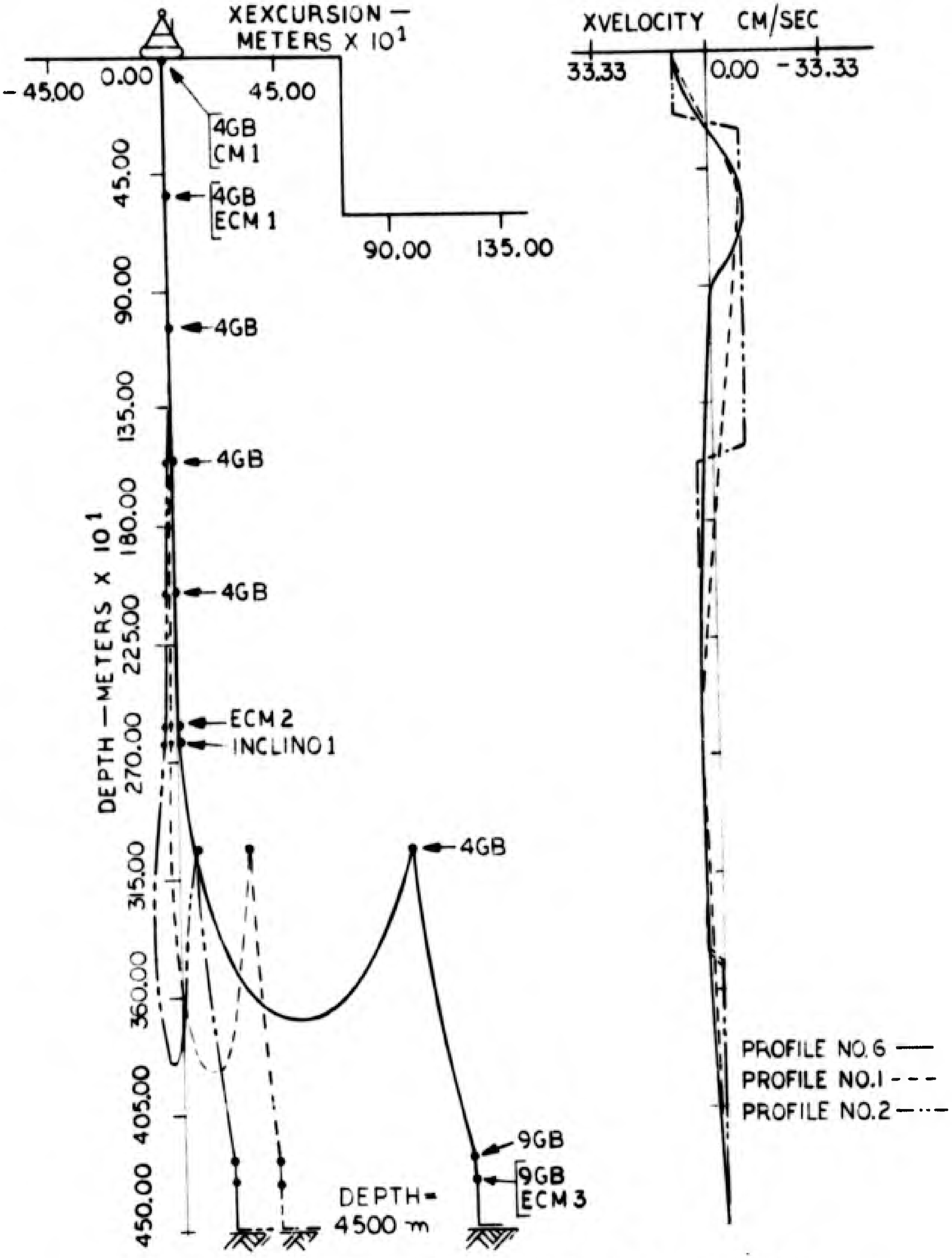


Figure 28. Mooring configuration in x-z plane - low velocity (For three different profiles through four fixed points)

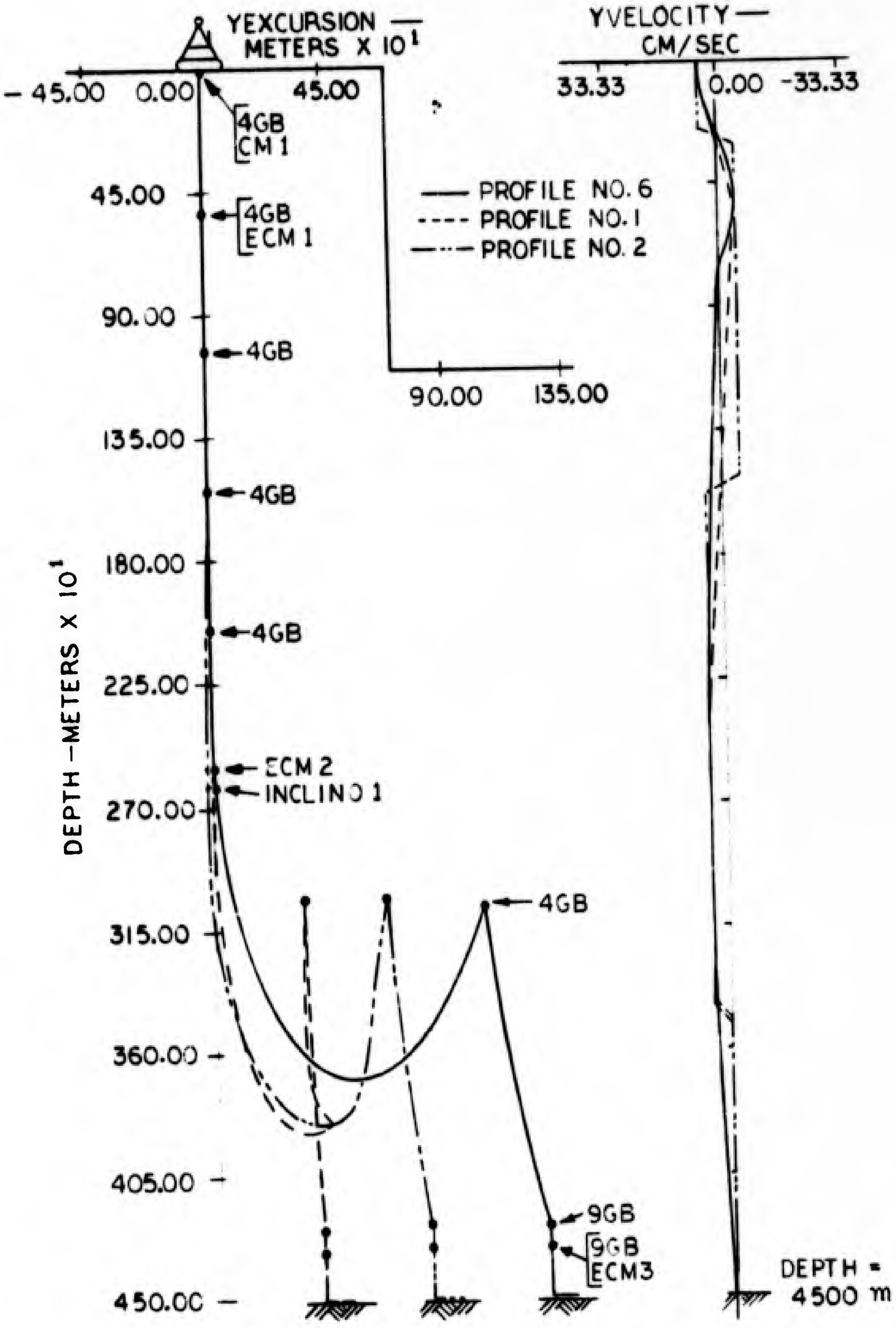


Figure 29. Mooring Configuration in y-z plane - low velocity

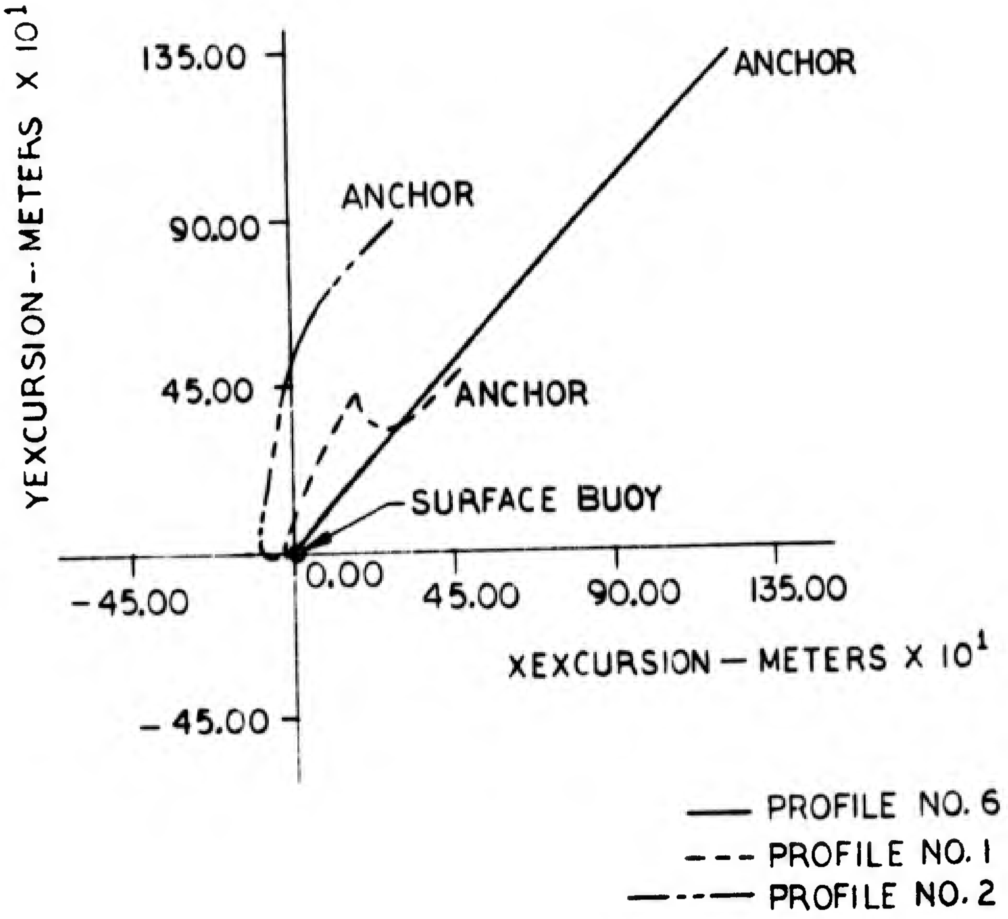


Figure 30. Mooring configuration in x-y plane - low velocity

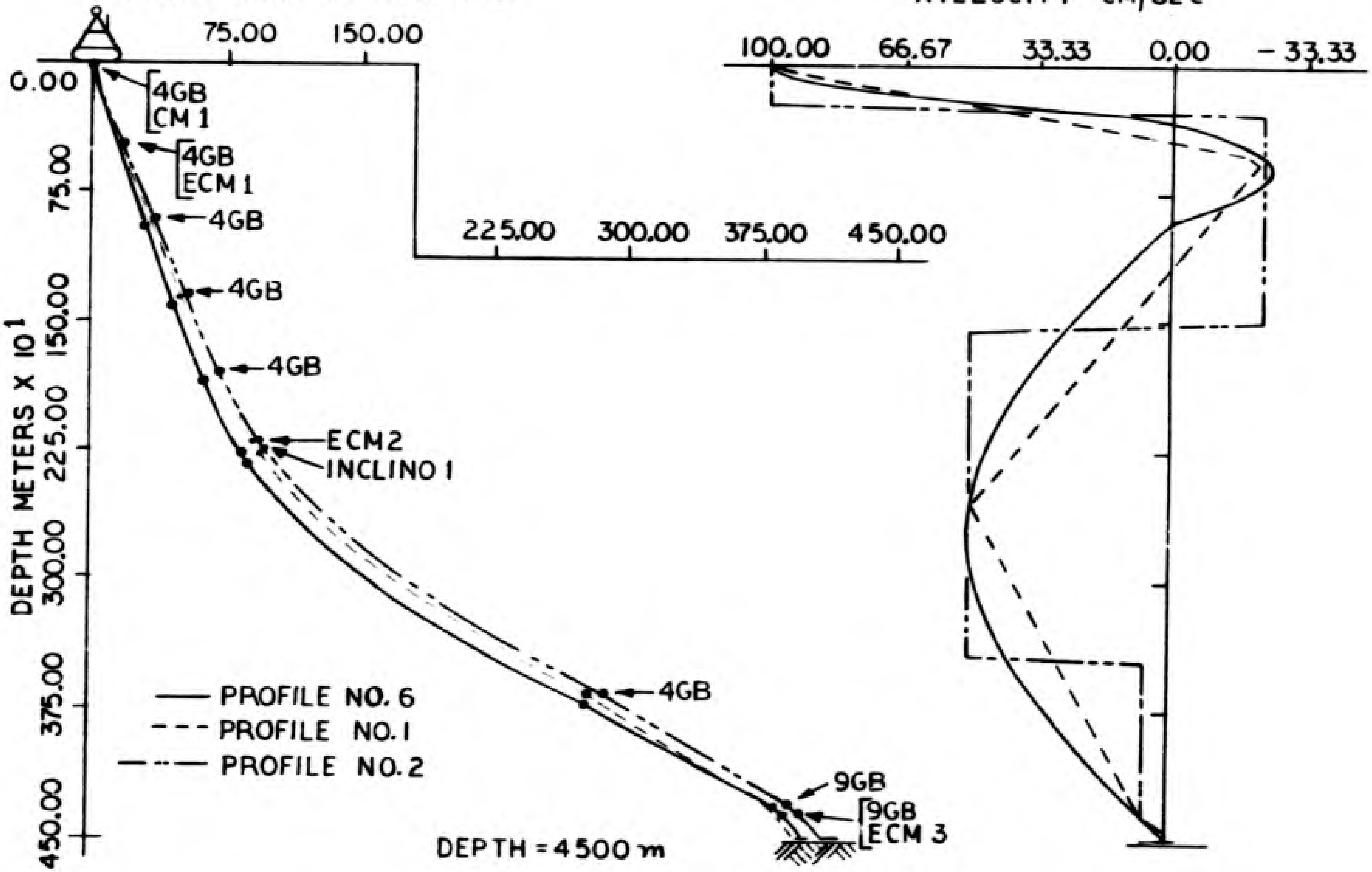


Figure 3'. Mooring Configuration in x-z Plane - High Velocity

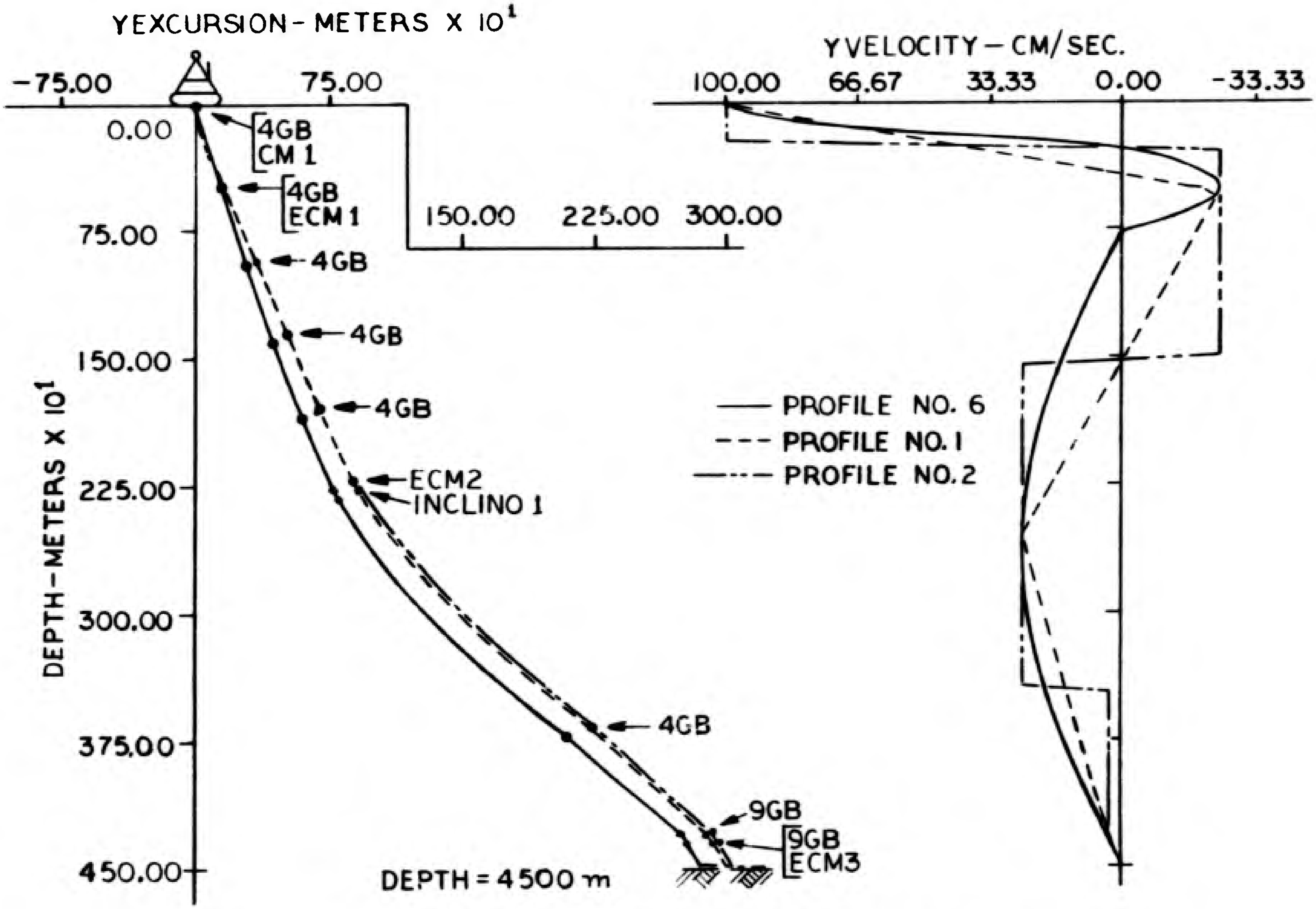


Figure 32. Mooring Configuration in y-z Plane - High Velocity

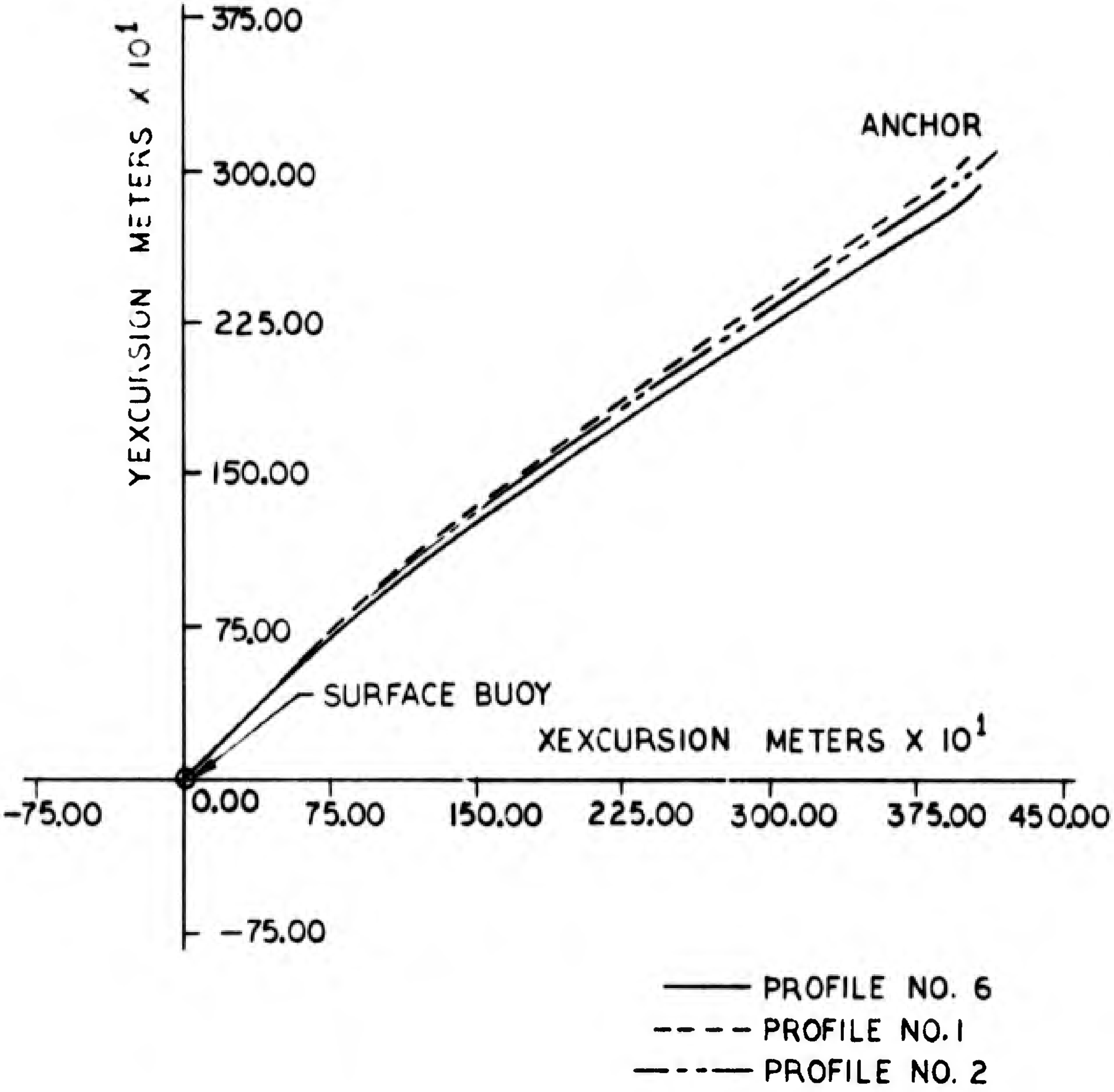


Figure 33. Mooring configuration in x-y plane - high velocity

APPENDIX A

Variable Definitions and Program Listing

AO (I) - Constant relating $200D^2$ length to slack length for I^{th} mooring part.

BUOY - Name of the surface buoy.

CDIA (I) - Variable holding slack length *(Diameter)**2 of I^{th} mooring part. This makes the reduction in diameter with increasing tension.

CDIN (J) - Normal drag constant $(\frac{\rho}{2}C_{DN}A_N)$ of J^{th} instrument.

CDIT (J) - Tangential drag constant $(\frac{\rho}{2}C_{DT}A_T)$ of J^{th} instrument.

CDN (I) - Normal drag coefficient of I^{th} mooring part.

CDT (I) - Tangential drag coefficient of Ith mooring part. It includes a factor of π (πC_{DT}).

CO1 (I) - Multiplying constant for permanent elongation curve of the I^{th} mooring part. Jacket diameter for wire ropes.

CO2 (I) - Multiplying constant for elastic elongation curve of I^{th} mooring part.

CONS (I) - Constant for velocity profile in I^{th} direction.

CS (IC) - Cosine of angle-theta (IC).

D (IKK) - Depth of IKK^{th} velocity vector.

DB - Drag constant (Drag = DB(V|V|)) for surface buoy number 1. Diameter of buoy for surface buoy numbers 2, 3, and 4.

DD (IC) - Tension component in IC direction.

DE - Change in depth error.

DEPTH - Ocean depth

DIA - Reduced diameter of a segment.

DIAL (I) - Outer diameter of I^{th} mooring part.

DN (IC) - Normal drag in IC direction.

DT (IC) - Tangential drag in IC direction.

E - Error in depth during iterations.

E1 - Error in depth during iterations.

EE - Sign of E (negative or positive)

ER - Acceptable error in depth during iterations.

ET (I) - Error bound on tension magnitude in I^{th} mooring part.

F (I, J) - Force component (including weight) of J^{th} instrument in I^{th} direction.

H2 - Depth of the middle point of a segment.

HO (I) - Constant for velocity profile in I^{th} direction.

HPL (N) - Array holding H2 - values of mooring line, segment by segment.

IE - Index controlling computation of maximum error bounds on the solution.

ITER - Variable, equals iteration procedure to be used.

IZ - Index controlling change in estimated surface tension whenever tension or depth becomes negative during integration.

IKK - Number of velocity vectors (inputed for velocity profile number one or two).

INDEX - Index controlling computation and printing.

JMAX - Number of solutions desired for the same mooring system with different velocity profiles.

L - Index controlling iterations.

MOOR (I) - Name of I^{th} mooring part.

NB - Buoy number.

NI - Number of instruments and/or concentrated forces.

NM (I) - Number of segments in the I^{th} mooring part.

NP - Number of mooring parts.

NPO - Number of complete printouts, out of Jmax solutions, desired in a system.

NPT - Number of total segments of mooring line.

NS - Number of segments desired in the mooring line.

NSY - Number of different mooring systems.

NVP (I) - Velocity profile number in I^{th} direction.

PI (J) - Slack length position of J^{th} instrument.

PL (I) - Maximum tension ever experienced by I^{th} mooring part.

PO1 (I) - Exponential constant for permanent elongation curve of I^{th} mooring part.

PO2 (I) - Exponential constant for elastic elongation curve of I^{th} mooring part.

POW (I) - Constant for velocity profile in I^{th} direction.

PSTRA - Permanent strain in a segment.

RBSL (I) - Rated breaking strength of I^{th} mooring part.

S - Total stretched length from surface to the end of a segment.

S1 - Stretched length of a segment.

S2 - Total slack length from surface to end of a segment.

SCOPE - Mooring scope for the total mooring line.

SF (I) - Safety factor for I^{th} mooring part.

SI (J) - Length of J^{th} instrument.

SIT - Total length of instruments.

SL (I) - Slack length of segment in Ith mooring part.

SLL (I) - Slack length of Ith mooring part.

SLLF - Length of mooring line piled up on the ocean floor.

SLT - Total length of all mooring parts.

SN (IC) - Sine of angle-theta (IC).

STR - Stress (T/d^2) in a segment

STRMAX(I) - Maximum strain in the I^{th}mooring part.

SW (I) - Weight of segment in I^{th} mooring part.

T - Tension at a point on mooring line.

TENS - Variable holding tension magnitude at the surface buoy.

THETA(IC) - Angle of mooring line with IC direction.

TLO (I) - Maximum tension in the I^{th} mooring part.

TMAX (I) - Maximum tension in the I^{th} mooring part.

TPL (I) - Transient peak load experienced by I^{th} mooring part or elastic modulus for non synthetic ropes.

TSTRA - Total strain in a segment.

TYPE (J) - Name of J^{th} instrument.

U (IC) - Current in IC direction.

UN (IC) - Normal component of current in IC direction.

UPL (N) - Array holding x_1 - currents acting on mooring line, segment by segment.

UT (IC) - Tangential component of current in IC direction.

V (I, J) - Velocity in I^{th} direction for J^{th} vector or surface velocity.

VPL (N) - Array holding x_2 - currents acting on mooring line, segment by segment.

VTEM - Magnitude of the surface current.

WIT - Total weight of instruments.

WN - Normal weight of the segment.

WT - Tangential weight of the segment.

WWL (I) - Weight per unit length of I^{th} mooring part.

X (IC) - Coordinates of a point on mooring line.

XPL (N) - Array holding x_1 - excursions of mooring line, segment by segment.

YPL (N) - Array holding x_2 - excursions of mooring line, segment by segment.

Z - Variable used in changing surface tension magnitude.

ZPL (N) - Array holding x_3 - values of mooring line, segment by segment.

```
C*****COMPLETE PROGRAM LISTING FOR FORTRAN FILE SS3.FORT****************
C*****PROGRAM FOR STATIC ANALYSIS OF SINGLE POINT SURFACE MOORING LINES*
      REAL*8 TYPE(50),MOOR(10),BUOY
      DIMENSION XPL(250),YPL(250),ZPL(250),HPL(250),UPL(250),VPL(250),PI
     1(50),ET(10),DIAL(10),SLL(10),WWL(10),RBSL(10),CDN(10),CDT(10),TPL(
     110),CO1(10),CO2(10),PO1(10),PO2(10),AO(10),NM(10),SL(10),SW(10),CD
     1IA(10),TMAX(10),STRMAX(10),SF(10),PL(10),TLO(10),DN(3),DT(3),WN(3)
     1,THETAT(3)
      COMMON F(3,50),PLT(3,50),V(3,10),SI(50),CDIN(50),CDIT(50),D(10),NV
     1P(3),HO(3),POW(3),CONS(3),U(3),X(3),THETA(3),CS(3),SN(3),DD(3),UN(
     13),UT(3),T,H2,DEPTH,S2,S,J,INDEX
C*****BEGINING OF FORMAT STATEMENTS*************************************
  101 FORMAT(7F8.0,A8)
  102 FORMAT(11I5)
  103 FORMAT(3F10.0,A8)
  104 FORMAT(7F10.0)
  105 FORMAT(5F10.0,A8)
  106 FORMAT(I5)
  107 FORMAT(1H1,9X,'OCEANOGRAPHIC BUOY SYSTEM-SURFACE'/10X,'RUN NUMBER'
     1,I3//15X,'INPUT:   BUOY IS',A8,' NO.',I3/24X,'OCEAN DEPTH=',F6.1,
     1' METERS   MOORING SCOPE=',F5.3//5X,'VEL. PROFILE INFO.:'/5X,'DIRE
     1C. PROF. NO. DEPTHS/VELS. OR TOP VEL. & 3 CONSTANTS')
  108 FORMAT(//15X,'OUTPUT:      ANALYSIS'//35X,'ITERATION PROCEDURE'//5X
     1,'ESTIM. TENSION TOP ANGLE1 TOP ANGLE2 DEPTH REACHED DEPTH ERROR C
     1OMMENTS')
  109 FORMAT(I10,3X,5F8.2,2F5.2,2F6.2,I5)
  110 FORMAT(8X,F7.1,1X,2F11.2,2F13.1,'   TRIAL RUN')
  111 FORMAT(8X,F7.1,1X,2F11.2,2F13.1,'  CONVERGENT RUN')
  112 FORMAT(15X,I2,2X,A8,F11.2,F16.2,F16.3)
  113 FORMAT(//5X,'RESULTS:  BUOY XEXCURSION=',F8.2,' METERS   BUOY YEXC
     1URSION=',F8.2,' METERS'//15X,'-------------------------MOORING PAR
     1TS DATA--------------------'/15X,'NO.   TYPE   MAXIMUM TENSION  SA
     1FTEY FACTOR  MAXIMUM ELONGATION'/33X,'(LBS)',25X,'(% 200 D SQ.)'/)
  114 FORMAT(//35X,'MOORING CONFIGURATION'//5X,'SEG. NO. STR.LEN. XEXCUR
     1. YEXCUR.  DEPTH TENSION XANG YANG XVEL. YVEL. M.P. NO.')
  115 FORMAT(//5X,'MAXIMUM EXPECTED ERROR-ASSUMING VELOCITY PROFILE IS C
     1ORRECT AND'/5X,'IF:TOP ANGLES ARE OFF BY ONE DEGREE AND DRAG COEFF
     1S.'/5X,'AND SYNTHETIC STRETCH OFF 10 PERCENT'/)
  116 FORMAT(5X,'MOORING PART NO.=',I3,'  MAXIMUM TENSION OFF IN LBS=',F
     110.3)
  117 FORMAT(20X,'THE TENSION OR DEPTH IS GETTING LESS THAN 0 AT SEGMENT
     1',I4)
  118 FORMAT(//5X,' THE REST OF THE CABLE OF LENGTH ',F8.2,' METERS IS
     1LYING ON THE FLOOR ')
  119 FORMAT(I7,1X,A8,F13.1,F9.3,F7.3,F9.2,F9.3,F10.1,F7.3)
  120 FORMAT(6X,I2,5X,I1,7X,4F10.2)
  121 FORMAT(/25X,'CABLE BREAKS AT SURFACE CURRENT OF',F8.2,'CM/SEC')
  122 FORMAT(6X,I2,5X,I1,2X,F6.1,F8.3,4(F7.1,F8.3))
  123 FORMAT(/5X,'----------------------------MOORING PARTS DATA--------
     1----------------------'/5X,'NO.  TYPE  LAUNCH TRAN PEAK DRAG COEFFS
     1. SLACK LEN. DIAMETER R.B.S.  WEIGHT'/16X,'LOAD OR E.MODUL. NORM.
     1 TANG.  (METERS)  (INCHES)  (LBS) (LBS/M)'/)
```

```
C*****BEGINING OF THE MAIN PROGRAM*****************************************
      READ(5,106)NSY
C*****LOOP FOR DIFFERENT SYSTEMS(MOORING CONFIGURATIONS)*****************
      DO 48 IK=1,NSY
      READ(5,102)NI,NP,NS,IKK,JMAX,NPO,NB,IFPL,(NVP(I),I=1,3)
      SIT=0.0
      WIT=0.0
      IF(NI.EQ.0)GO TO 2
C*****READ IN THE INSTRUMENT(CONCENTRATED FORCE) SPECIFICATIONS*********
      READ(5,101)(PI(J),SI(J),F(1,J),F(2,J),F(3,J),CDIN(J),CDIT(J),TYPE(
     1J),J=1,NI)
      DO 1 J=1,NI
      SIT=SIT+SI(J)
      IF(F(3,J).GT.0.)GO TO 1
      WIT=WIT-F(3,J)
    1 CONTINUE
    2 READ(5,103)DB,DEPTH,ER,BUOY
C*****READ IN THE PARAMETERS FOR DIFFERENT MOORING PARTS*****************
      READ(5,105)(DIAL(I),SLL(I),WWL(I),RBSL(I),TPL(I),MOOR(I),I=1,NP)
      READ(5,104)(CO1(I),PO1(I),CO2(I),PO2(I),AO(I),CDN(I),CDT(I),I=1,NP
     1)
C*****LOOP FOR DIFFERENT INPUTED VELOCITY PROFILES**********************
      DO 48 IJ=1,JMAX
      DO 3 IZ=1,3
      IF(NVP(IZ).GT.2)GO TO 3
      READ(5,104)(D(I),I=1,IKK)
      GO TO 4
    3 CONTINUE
    4 DO 5 J=1,3
      IF(NVP(J).LE.2)READ(5,104)(V(J,I),I=1,IKK)
      V(J,IKK+1)=0.
    5 IF(NVP(J).GT.2)READ(5,104)V(J,1),HO(J),POW(J),CONS(J)
      D(IKK+1)=DEPTH
      SLT=0.0
      DO 6 I=1,NP
      TMAX(I)=0.0
    6 SLT=SLT+SLL(I)
      SCOPE=(SLT+SIT)/DEPTH
      WRITE(6,107)IJ,BUOY,NB,DEPTH,SCOPE
      DO 7 I=1,3
      IF(NVP(I).LE.2)WRITE(6,122)I,NVP(I),(D(J),V(I,J),J=1,IKK)
    7 IF(NVP(I).GT.2)WRITE(6,120)I,NVP(I),V(I,1),HO(I),POW(I),CONS(I)
      WRITE(6,123)
      WRITE(6,119)(I,MOOR(I),TPL(I),CDN(I),CDT(I),SLL(I),DIAL(I),RBSL(I)
     1,WWL(I),I=1,NP)
C*****SEGMENTATION OF THE MOORING LINE IN NPT SEGMENTS******************
      NPT=1
      DO 8 I=1,NP
      NM(I)=(SLL(I)/SLT)*NS+0.5
      IF(WWL(I).GT.20.)NM(I)=SLL(I)/2.
      IF(NM(I).EQ.0)NM(I)=1
      NPT=NPT+NM(I)
      SL(I)=SLL(I)/NM(I)
      SW(I)=WWL(I)*SL(I)
    8 CDIA(I)=SL(I)*(DIAL(I)**2)
```

```
      IFLAG=0
      INDEX=2
      Z=-300.
      I=0
      IF=1
      IZ=1
      XPL(1)=0.
      YPL(1)=0.
      ZPL(1)=0.
      ITER=1
      VTEM=SQRT(V(1,1)**2+V(2,1)**2)
      IF(VTEM.LE.25.0.OR.(VTEM.LE.50.0.AND.SCOPE.GE.1.))ITER=2
C*****INITIAL ESTIMATE FOR STATIC TENSION IN FIRST SEGMENT**************
      TENS=WIT
      DO 9 I=1,NP
      IF(WWL(I).LT.0.0)GO TO 10
    9 TENS=TENS+WWL(I)*SLL(I)
   10 IF(ITER.EQ.2)TENS=TENS/2.
      IF(VTEM.GT.150.)TENS=TENS*2.5
      IF(TENS.GT.10000.)TENS=10000.
C*****BEGINING OF MOORING LINE CALLCULATIONS*****************************
      WRITE(6,108)
   11 IF(TENS.LE.0.)TENS=50.
      S2=0.0
      K=1
      S=0.0
      X(1)=0.0
      X(2)=0.0
      X(3)=0.0
      N2=0.0
      J=1
      T=TENS
C*****DETERMINING ORIENTATION OF FIRST SEGMENT***************************
      CALL ANGLE(NB,V,TENS,DB,THETAT,VTEM)
      IF(IE.NE.2)GO TO 13
      DO 12 JA=1,2
      IF(THETAT(JA).GT.1.570796)THETAT(JA)=THETAT(JA)+.01745
   12 IF(THETAT(JA).LE.1.570796)THETAT(JA)=THETAT(JA)-.01745
   13 THETAT(3)=ARCOS(SQRT(1.-COS(THETAT(1))**2-COS(THETAT(2))**2))
      DO 14 MZ=1,3
   14 THETA(MZ)=THETAT(MZ)
      DO 24 I=1,NP
      SWW=2.*SW(I)
      SWL=2.*SL(I)
      IF(SWL.LE.50.)SWL=50.
      TMAX(I)=T
      STRMAX(I)=0.0
      PL(I)=TPL(I)
      NK=NM(I)+K-1
      DO 23 N=K,NK
      IF(T.GT.PL(I))PL(I)=T
```

```
C*****CHECK FOR ANY INSTRUMENTS OR CONCENTRATED FORCES******************
      IF(J.GT.NI)GO TO 16
   15 IF((S2+SL(I)*0.5).GE.PI(J))CALL FORCES(TYPE)
      IF(ABS(T*COS(THETA(3))).LE.SWW.AND.ABS(DEPTH-X(3)).LE.SWL)GO TO 42
      IF(T.LE.0.0.OR.H2.LT.0.0)GO TO 40
      IF(J.GT.NI)GO TO 16
      IF((S2+SL(I)*0.5).GE.PI(J))GO TO 15
C*****STRESS-STRAIN CALCULATIONS FOR MOORING SEGMENT********************
   16 IF(PO1(I).EQ.0.0)GO TO 18
C*****SYNTHETIC ROPES**************************************************
      STR=T/(DIAL(I)**2)
      IF(STR.LE.200.0)GO TO 17
      PSTRA=((PL(I)/(DIAL(I)**2)-200.0)/CO1(I))**(1.0/PO1(I))
      TSTRA=PSTRA+((STR-200.0)/CO2(I))**(1.0/PO2(I))
      IF(IE.EQ.2)TSTRA=0.9*TSTRA
      S1=AO(I)*SL(I)*(1.0+TSTRA/100.0)
      GO TO 19
   17 TSTRA=0.0
      S1=SL(I)*(1.0+(AO(I)-1.0)*STR/200.0)
      GO TO 19
C*****WIRE ROPES-PL IS ELASTIC MODULUS AND CO1 IS JACKET DIA*************
   18 TSTRA=T/(0.7854*PL(I)*(DIAL(I)-CO1(I))**2)
      S1=SL(I)*(1.0+TSTRA)
   19 IF(TSTRA.GT.STRMAX(I))STRMAX(I)=TSTRA
C*****BEGINING OF THE NUMERICAL INTEGRATION PROCEDURE*******************
      S2=S2+SL(I)
      S=S+S1
      DO 20 IC=1,3
      SN(IC)=SIN(THETA(IC))
      CS(IC)=COS(THETA(IC))
   20 X(IC)=X(IC)+S1*CS(IC)
      IF(SN(3).EQ.0.)SN(3)=0.000001
      DIA=SQRT(CDIA(I)/S1)
      WNN=SW(I)*SN(3)
      WT=SW(I)*CS(3)
      H2=X(3)-((S1*CS(3))/2.0)
      IF(H2.LE.0.0)GO TO 40
      CALL SPEED
      DO 21 IC=1,3
      II=IC+1
      III=IC+2
      IF(II.GT.3) II=II-3
      IF (III.GT.3) III=III-3
      UN(IC)=U(IC)*SN(IC)**2-U(II)*CS(IC)*CS(II)-U(III)*CS(IC)*CS(III)
      UT(IC)=U(IC)*CS(IC)
   21 WN(IC)=-WNN*CS(IC)*CS(3)/SN(3)
      WN(3)=WN(3)+WNN/SN(3)
      VNM=SQRT(UN(1)**2+UN(2)**2+UN(3)**2)
      UTT=UT(1)+UT(2)+UT(3)
      IF (T.GT.TMAX(I)) TMAX(I)=T
      DO 22 IC=1,3
      DN(IC)=(2.94E-4)*CDN(I)*S1*DIA*VNM*UN(IC)-WN(IC)
   22 THETA(IC)=THETA(IC)-DN(IC)/(T*SN(IC))
```

```
      T=T-WT+(2.94E-4)*CDT(I)*S1*DIA*ABS(UTT)*UTT
      IF(INDEX.EQ.3)WRITE(6,109)M,S,X(1),X(2),X(3),T,THETA(1),THETA(2),
     1U(1),U(2),I
      IF(ABS(T*CS(3)).LE.SWW.AND.ABS(DEPTH-X(3)).LE.SWL)GO TO 42
      IF(T.LE.0.0)GO TO 40
      IF(T.GT.TMAX(I))TMAX(I)=T
      XPL(M+1)=X(1)
      YPL(M+1)=X(2)
      ZPL(M+1)=X(3)
      UPL(M)=U(1)
      VPL(M)=U(2)
      WPL(M)=W2
   23 CONTINUE
      K=NK+1
   24 CONTINUE
C*****CHECK FOR ANY INSTRUMENT(CONCENTRATED FORCE) BEFORE ANCHOR********
   25 IF(J.GT.NI)GO TO 26
      CALL FORCES(TYPE)
      IF(ABS(T*CS(3)).LE.SWW.AND.ABS(DEPTH-X(3)).LE.SWL)GO TO 42
      IF(T.LE.0.0.OR.W2.LE.0.0)GO TO 40
      GO TO 25
C*****BEGINING OF THE ITERATION PROCEDURE*******************************
   26 IF(INDEX.EQ.1.AND.ITER.EQ.2)GO TO 30
      IF(INDEX.EQ.1)GO TO 27
      IF(INDEX.EQ.3)GO TO 35
C*****CALCULATE AND CHECK MAGNITUDE OF DEPTH ERROR**********************
      E=DEPTH-X(3)
      EEE=ABS(E)
      EE=E/EEE
      IF(EEE.LT.ER)GO TO 33
      INDEX=1
      IF(IE.EQ.1)WRITE(6,110)TENS,THETAT(1),THETAT(2),X(3),E
      IF(ITER.EQ.2)GO TO 28
C*****ITERATION PROCEDURE NO. 1 ****************************************
      L=L+1
      IF(L.EQ.10)GO TO 48
      TENS=TENS+50.*EE
      GO TO 11
C*****FIND CHANGE-ERROR/CHANGE-TENSION AND ADJUST TENSION***************
   27 E1=DEPTH-X(3)
      DE=E-E1
      TENS=TENS-50.*EE+50.*EEE/DE
      INDEX=2
      GO TO 11
C*****ITERATION PROCEDURE NO. 2 ****************************************
   28 Z=300.*EE
   29 TENS=TENS+Z
      GO TO 11
   30 E1=DEPTH-X(3)
```

```
      IF(ABS(E1).LE.ER)GO TO 33
      IF(IE.EQ.1)WRITE(6,110)TENS,THETAT(1),THETAT(2),X(3),E1
      L=L+1
      IF(L.EQ.20)GO TO 48
      IF(ABS(E1).GT.ABS(E))GO TO 31
      IF((E.GE.0..AND.E1.GE.0.).OR.(E.LT.0..AND.E1.LT.0.))GO TO 32
   31 Z=-Z/3.0
   32 E=E1
      GO TO 29
C*****CALCULATE AND WRITE FINAL RESULTS****************************************
   33 IF(IE.EQ.2)GO TO 38
      IF(ABS(E).LT.ER)E1=E
      WRITE(6,111)TENS,THETAT(1),THETAT(2),X(3),E1
      WRITE(6,113)X(1),X(2)
      DO 34 I=1,NP
      SF(I)=RBSL(I)/TMAX(I)
      TLO(I)=TMAX(I)
      WRITE(6,112)I,MOOR(I),TMAX(I),SF(I),STRMAX(I)
      IF(SF(I).LT.1.0)WRITE(6,121)VTEM
   34 CONTINUE
C*****RECALCULATE AND WRITE OUT CONFIGURATION IF REQUIRED***************
      IF(IJ.GT.NPO)GO TO 35
      WRITE(6,114)
      INDEX=3
      GO TO 11
C*****RECALCULATE TO DETERMINE THE ERROR BOUNDS*************************
   35 IF(IFLAG.EQ.1)GO TO 43
      IF(IFPL.EQ.0)GO TO 36
      CALL PLT1(NPT,XPL,YPL,ZPL,UPL,VPL,WPL,DEPTH,IFPL,IFK,V,PLT,NI,NVP)
   36 IF(ITER.EQ.2)GO TO 48
      IE=2
      INDEX=2
      DO 37 K=1,NP
      CDN(K)=1.1*CDN(K)
   37 CDT(K)=1.1*CDT(K)
      GO TO 11
C*****CALCULATE AND WRITE POSSIBLE ERROR BOUNDS*************************
   38 WRITE(6,115)
      DO 39 I=1,NP
      CDN(I)=CDN(I)/1.1
      CDT(I)=CDT(I)/1.1
      ET(I)=ABS(TLO(I)-TMAX(I))
      WRITE(6,116)I,ET(I)
   39 CONTINUE
      GO TO 48
```

```
C*****TOP T CHANGED WHEN T OR X(3) NEGATIVE DURING INTEGRATION**********
   40 IF(IZ.EQ.25)GO TO 47
      IZ=IZ+1
      IF(DEPTH.LT.H2.AND.ITER.EQ.2)GO TO 41
      Z=Z/2.0
      IF(ITER.EQ.1)TENS=TENS+300.
      IF(ITER.EQ.2)TENS=TENS-Z
      GO TO 11
   41 TENS=TENS+Z
      GO TO 11
C*****EXCESS MOORING LINE PILE UP AT OCEAN BOTTOM************************
   42 IF(INDEX.EQ.3)GO TO 43
      IFLAG=1
      F1=DEPTH-X(3)
      GO TO 33
   43 SLLF=SLT+SIT-S2
      WRITE(6,118)SLLF
      IF(IFPLO.EQ.0)GO TO 48
      DO 45 KZ=1,NP
      DO 44 NZ=N,NK
      XPL(NZ+1)=XPL(NZ)+SL(KZ)
      YPL(NZ+1)=YPL(NZ)+SL(KZ)
      ZPL(NZ+1)=X(3)
      HPL(NZ)=H2
      UPL(NZ)=0.
   44 VPL(NZ)=0.
      N=NK+1
   45 NK=NM(I)+N-1
      DO 46 KZ=J,NI
      DO 46 IC=1,3
   46 PLT(IC,KZ)=X(IC)
      CALL PLT1(NPT,XPL,YPL,ZPL,UPL,VPL,HPL,DEPTH,IFPL,IKK,V,PLT,NI,NVP)
      GO TO 36
   47 WRITE(6,117)N
   48 CONTINUE
      CALL WHERE(X1,Y1,-3)
      CALL PLOT(X1,Y1,999)
      CALL EXIT
      END
```

```
      SUBROUTINE ANGLE(NB,V,TENS,DB,THETA,VTEM)
      DIMENSION V(1,1),THETA(1)
      DO 5 J=1,2
      IF(NB.EQ.1)GO TO 1
      IF(NB-3)2,3,4
C*****BUOY NO. 1--WHEN DRAG CONSTANT DB(DRAG=DB*V/V/) IS GIVEN**********
    1 THETA(J)=ARCOS(DB*(V(J,1)/929.03)*VTEM/TENS)
      GO TO 5
C*****BUOY NO. 2--TOROID OF DIAMETER DB***********************************
    2 THETA(J)=1.570796-((2.583E-4)*(V(J,1)*VTEM/DB)*(TENS/(.0924
     1*DB**3))**(-.587))
      GO TO 5
C*****BUOY NO. 3--DISK OF DIAMETER DB WITH FEET***************************
    3 THETA(J)=1.570796-((1.98E-4)*(V(J,1)*VTEM/DB)*(TENS/(.0725
     1*DB**3))**(-.583))
      GO TO 5
C*****BUOY NO. 4--DISK OF DIAMETER DB WITHOUT FEET************************
    4 THETA(J)=1.570796-((7.474E-5)*(V(J,1)*VTEM/DB)*(TENS/(.0725
     1*DB**3))**(-.482))
    5 CONTINUE
      RETURN
      END
```

```
      SUBROUTINE FORCES(TYPE)
      REAL*8 TYPE(1)
      COMMON F(3,50),PLT(3,50),V(3,10),SI(50),CDIN(50),CDIT(50),D(10),MV
     1P(3),MO(3),POW(3),CONS(3),U(3),X(3),THETA(3),CS(3),SN(3),DD(3),UN(
     13),UT(3),T,M2,DEPTH,S2,S,J,INDEX
  101 FORMAT(5X,A8,5F8.2,2F5.2,2F6.2,1X,A8)
C*****NUMERICAL INTEGRATION PROCEDURE***********************************
      S2=S2+SI(J)
      S=S+SI(J)
      DO 1 IC=1,3
      SN(IC)=SIN(THETA(IC))
      CS(IC)=COS(THETA(IC))
      X(IC)=X(IC)+SI(J)*CS(IC)
      IF(INDEX.EQ.3)PLT(IC,J)=X(IC)
    1 CONTINUE
      M2=X(3)-SI(J)*CS(3)/2.
      CALL SPEED
      IF (SI(J).NE.0.) GO TO 3
      VNM=SQRT(U(1)**2+U(2)**2+U(3)**2)
      DO 2 IC=1,3
    2 DD(IC)=T*CS(IC)+CDIN(J)*VNM*U(IC)/929.03+F(IC,J)
      GO TO 6
    3 DO 4 IC=1,3
      II=IC+1
      III=IC+2
      IF (II.GT.3) II=II-3
      IF (III.GT.3) III=III-3
      UN(IC)=U(IC)*SN(IC)**2-U(II)*CS(IC)*CS(II)-U(III)*CS(IC)*CS(III)
    4 UT(IC)=U(IC)*CS(IC)
      VNM=SQRT(UN(1)**2+UN(2)**2+UN(3)**2)
      UTT=UT(1)+UT(2)+UT(3)
      DTT=CDIT(J)*ABS(UTT)*UTT/929.03
      DO 5 IC=1,3
    5 DD(IC)=(T+DTT)*CS(IC)+CDIN(J)*VNM*UN(IC)/929.03+F(IC,J)
    6 T=SQRT(DD(1)**2+DD(2)**2+DD(3)**2)
      DO 7 IC=1,3
    7 THETA(IC)=ARCOS(DD(IC)/T)
      IF(INDEX.EQ.3)WRITE(6,101)TYPE(J),S,X(1),X(2),X(3),T,THETA(1),THET
     1A(2),U(1),U(2),TYPE(J)
      J=J+1
      RETURN
      END
```

```
      SUBROUTINE SPEED
      COMMON F(3,50),PLT(3,50),V(3,10),SI(50),CDIN(50),CDIT(50),D(10),NV
     1P(3),HO(3),POW(3),CONS(3),U(3),X(3),THETA(3),CS(3),SN(3),DP(3),UN(
     13),UT(3),T,H2,DEPTH,S2,S,J,INDEX
      M=1
      DO 22 JJ=1,3
      IF(NVP(JJ)-4)10,4,11
   10 IF(NVP(JJ)-2)1,2,3
   11 IF(NVP(JJ)-6)5,6,6
C*****PROFILE NO. 1*****************************************************
    1 IF(H2.LE.D(1))GO TO 20
      IF(H2.GE.DEPTH)GO TO 21
   12 IF(H2.GT.D(M).AND.H2.LE.D(M+1)) GO TO  13
       M=M+1
      GO TO 12
   13 U(JJ)=V(JJ,M)-((V(JJ,M)-V(JJ,M+1))*(H2-D(M)))/(D(M+1)-D(M))
      GO TO 22
C*****PROFILE NO.2******************************************************
    2 IF(H2.LE.D(1))GO TO 20
      IF(H2.GE.DEPTH)GO TO 21
   14 IF(H2.GT.D(M).AND.H2.LE.D(M+1))GO TO 15
      M=M+1
      GO TO 14
   15 TEM=(D(M)+D(M+1))/2.
      IF(H2.GE.TEM)U(JJ)=V(JJ,M+1)
      IF(H2.LT.TEM)U(JJ)=V(JJ,M)
      GO TO 22
C*****PROFILE NO. 3*****************************************************
    3 IF(H2.LE.HO(JJ))GO TO 20
      U(JJ)=V(JJ,1)*(HO(JJ)/H2)**POW(JJ)
      GO TO 22
C*****PROFILE NO. 4*****************************************************
    4 IF(H2.LE.HO(JJ))GO TO 20
      U(JJ)=V(JJ,1)-V(JJ,1)*((H2-HO(JJ))/(DEPTH*CONS(JJ)-HO(JJ)))**POW(J
     1J)
      GO TO 22
C*****PROFILE NO. 5*****************************************************
    5 IF(H2.LE.HO(JJ))GO TO 20
      U(JJ)=POW(JJ)+(V(JJ,1)-POW(JJ))*((H2+CONS(JJ)-DEPTH)/(HC(JJ)+CONS(
     1JJ)-DEPTH))**2
      GO TO 22
C*****PROFILE NO. 6*****************************************************
    6 DEP1=HO(JJ)/2.
      DEP2=DEPTH-HO(JJ)
      [illegible]
      IF(H2-DEP1)17,17,16
   16 IF(H2-HO(JJ))18,18,19
   17 U(JJ)=V(JJ,1)*COS(6.28319*H2/DEP)
      GO TO 22
   18 U(JJ)=-POW(JJ)*COS(6.28319*H2/DEP)
      GO TO 22
   19 U(JJ)=CONS(JJ)*SIN(3.14159*(H2-HO(JJ))/DEP2)
      GO TO 22
  20  U(JJ)=V(JJ,1)
      GO TO 22
   21 U(JJ)=0.
   22 CONTINUE
      RETURN
      END
```

```
 SUBROUTINE PLT1(NPTS,XPL,YPL,ZPL,UPL,VPL,HPL,DEPTH,IFPL,IKK,V,
1PLT,NI,NVP)
 DIMENSION BUFFER(250),XPL(1),YPL(1),ZPL(1),HPL(1),UPL(1),VPL(1)
 DIMENSION V(1,1),PLT(3,1),NVP(1)
 XFR=3.
 XORG=100.
 DU=XORG/XFR
 DY=DEPTH/6.
 XRG=ABS(XPL(NPTS))
 YRG=ABS(YPL(NPTS))
 XFRM=XRG/DY
 YFRM=YRG/DY
 XLEN=2.*XFRM
 YLEN=2.*YFRM
 UPL(NPTS)=0.
 VPL(NPTS)=0.
 HPL(NPTS)=DEPTH
 XPL(NPTS+1)=-XRG
 YPL(NPTS+1)=-YRG
 UPL(NPTS+1)=XORG
 VPL(NPTS+1)=XORG
 ZPL(NPTS+1)=DEPTH
 HPL(NPTS+1)=DEPTH
 XPL(NPTS+2)=DY
 ZPL(NPTS+2)=-DY
 YPL(NPTS+2)=DY
 UPL(NPTS+2)=-DU
 VPL(NPTS+2)=-DU
 HPL(NPTS+2)=-DY
 NTEM=NPTS+2
 DO 9 I=1,IFPL
 CALL PLOTS(BUFFER,NTEM)
 CALL PLOT(0.,0.,-3)
```

```
  IF(I-2)1,2,3
1 CALL AXIS(0.,6.,'XEXCURSION (METERS)',19,XLEN,0.,-XRG,DY,10.)
  CALL AXIS(XFRM,0.,'DEPTH (METERS)',14,6.,90.,DEPTH,-DY,10.)
  CALL LINE(XPL,ZPL,NPTS,1,0,0)
  GO TO 7
2 CALL AXIS(0.,6.,'YEXCURSION (METERS)',19,YLEN,0.,-YRG,DY,10.)
  CALL AXIS(YFRM,0.,'DEPTH (METERS)',14,6.,90.,DEPTH,-DY,10.)
  CALL LINE(YPL,ZPL,NPTS,1,0,0)
  GO TO 7
3 IF(I-4)4,5,6
4 CALL AXIS(0.,6.,'XVELOCITY (CM/SEC)',18,6.,0.,XORG,-DU,10.)
  CALL AXIS(XFR,0.,'DEPTH (METERS)',14,6.,90.,DEPTH,-DY,10.)
  CALL LINE(UPL,HPL,NPTS,1,0,0)
  GO TO 9
5 CALL AXIS(0.,6.,'YVELOCITY (CM/SEC)',18,6.,0.,XORG,-DU,10.)
  CALL AXIS(XFR,0.,'DEPTH (METERS)',14,6.,90.,DEPTH,-DY,10.)
  CALL LINE(VPL,HPL,NPTS,1,0,0)
  GO TO 9
6 CALL AXIS(0.,YFRM,'XEXCURSION (METERS)',19,XLEN,0.,-XRG,DY,10.)
  CALL AXIS(XFRM,0.,'YEXCURSION (METERS)',19,YLEN,90.,-YRG,DY,10.)
  CALL LINE(XPL,YPL,NPTS,1,0,0)
  GO TO 9
7 DO 8 K=1,NI
  IF(I.EQ.1)X=PLT(1,K)/DY+XFRM
  IF(I.EQ.2)X=PLT(2,K)/DY+YFRM
  Y=6.-PLT(3,K)/DY
8 CALL SYMBOL(X,Y,0.035,0,90.,-1)
9 CONTINUE
  RETURN
  END
```

APPENDIX B

Subroutine Speed

As explained in section 4.5, six different types of velocity profiles in the form of analytic expressions have been incorporated in the computer program. These are included as a subroutine called 'SUBROUTINE SPEED'. Variables are defined in Appendix A.

Profile number 1 is described by the expressions:

$$U(J) = \left[\begin{array}{l} V(J,1);\ \text{---}\ H2 \leq D(1) \\ V(J,M) - [V(J,M) - V(J,M+1)] \times [H2 - D(M)] \div [D(M+1) - D(M)]; \\ \text{----------------------------}\ D(M) < H2 \leq D(M+1)\ \&\ 1 \leq M \leq IKK \\ V(J,M) - V(J,M) \times [H2 - D(M)] \div [Depth - D(M)];\ \text{----} \\ \text{--------------------------------------}\ D(IKK) < H2 \leq Depth \end{array}\right] \qquad (1)$$

Here J refers to the directions x_1, x_2, and x_3 and M refers to the number of IKK velocity vectors which are inputed.

Profile number 2 is described by the expressions:

$$U(J) = \left[\begin{array}{l} V(J,1);\text{-----------------------------------}\ H2 \leq (D(1) + D(2))/2 \\ V(J,M); - (D(M-1) + D(M))/2 \leq H2 \leq (D(M) + D(M+1))/2\ \&\ 1 < M < IKK \\ V(J,IKK); - (D(IKK-1) + D(IKK))/2 \leq H2 \leq (D(IKK) + Depth)/2; M = IKK \\ 0 \qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad H2 \geq (D(IKK) + Depth)/2 \end{array}\right] \quad (2)$$

Here J refers to the directions x_1, x_2, x_3 and M refers to the number of IKK velocity vectors which are inputed.

Profile number 3 is described by the expressions:

$$U(J) = \left[\begin{array}{l} V(J,1)\ \text{---------------}\ H2 \leq HO(J) \\ V(J,1) \times (HO(J)/H2)^{\alpha(J)}\text{--}\ H2 > HO(J) \end{array}\right] \qquad (3)$$

Here current speed is expected to decrease as $(H2)^{-\alpha(J)}$. The relationship is therefore of the form:

$$U(J) = C1 \times V(J,1) \times (H2)^{-\alpha(J)} \qquad (3.1)$$

where C1 is a multiplying constant. The expression becomes invalid at the surface where H2 = 0. If the top HO(J) meters of water are moving with the surface current speed we have U(J) = V(J, 1) for H2 $\leq$ HO(J).

Therefore, $V(J,1) = C1 \times V(J,1) \times (HO(J))^{-\alpha(J)}$ (3.2)

or, $C1 = (HO(J))^{\alpha(J)}$ (3.3)

That is, $U(J) = V(J,1) \times (HO(J)/H2)^{\alpha(J)}$ (3.4)

The profile is valid from HO(J) meters below the surface down to any depth.

<u>Profile number 4</u> is described by the expressions:

$$U(J) = \begin{bmatrix} V(J,1); \text{ - } H2 \leq HO(J) \\ V(J,1) - V(J,1) \left\{ \dfrac{H2 - HO(J)}{\beta(J) \times \text{Depth} - HO(J)} \right\}^{\alpha(J)}; \text{ - -} H2 > HO(J) \end{bmatrix} \tag{4}$$

Here, the first HO(J) meters of water are moving with the surface current speed and the profile changes direction at a depth C1 where C1/Depth = β(J), which is inputed as CONS(J).

<u>Profile number 5</u> is described by the expressions:

$$U(J) = \begin{bmatrix} V(J,1); \text{- } H2 \leq HO(J) \\ \alpha(J) + [V(J,1) - \alpha(J)] \left\{ \dfrac{H2 + \beta(J) - \text{Depth}}{HO(J) + \beta(J) - \text{Depth}} \right\}^2; \text{- -} H2 > HO(J) \end{bmatrix} \tag{5}$$

This was derived with the current reversing directions more than once or increasing in magnitude after having decreased in magnitude for some depth. The relationship is of the type:

$U(J) = \alpha(J) + K(H2 + \beta(J) - \text{Depth})^2$ (5.1)

which represents a parabola; at $H2 = HO(J)$, $U(J) = V(J,1)$

Therefore, $V(J,1) = \alpha(J) + K(HO(J) + \beta(J) - \text{Depth})^2$ (5.2)

or, $K = \dfrac{V(J,1) - \alpha(J)}{(HO(J) + \beta(J) - \text{Depth})^2}$ (5.3)

Which gives expression (5). Here α(J), inputed as POW(J) equals the algebraic minimum current as shown in Fig. 23. β(J), inputed as CONS(J) equals the height from bottom where this minimum occurs.

Profile number 6 is described by the expressions:

$$U(J) = \begin{bmatrix} V(J,1) * \cos(1.5\pi H2/HO(J); \text{ ----------- } H2 \leq HO(J)/3 \\ -\alpha(J) * \cos(1.5\pi H2/HO(J)); \text{---} HO(J)/3 < H2 \leq HO(J) \\ \beta(J) * \sin(\pi \dfrac{H2 - HO(J)}{Depth - HO(J)}); \text{ ----------- } H2 > HO(J) \end{bmatrix} \qquad (6)$$

Here, HO(J), $\alpha(J)$ and $\beta(J)$ are as shown in Fig. 24. J refers to th directions x_1, x_2, and x_3.

APPENDIX C

Subroutine Angle

The results of buoy model tests performed on three buoy shapes (Ref. 6) along with an analytic expression relating inclination with tension magnitude (for known drag constant) have been incorporated into the computer program as 'SUBROUTINE ANGLE'. These are explained briefly here. Integer 'NB' refers to the number of the buoy and varies from 1 to 4. For NB = 1, the relationship is described by the expressions:

$$\Theta(J) = \cos^{-1}\left[DB \times \left(\frac{V(J,1)}{30.48^2}\right) \times VNM \Big/ Tens \right] \quad J = 1, 2 \tag{1.1}$$

and,

$$\Theta(3) = \cos^{-1}\left[\sqrt{1 - \cos^2\Theta(1) - \cos^2\Theta(2)} \right] \tag{1.2}$$

where, $VNM = \sqrt{V(1,1)^2 + V(2,1)^2}$

Here, DB is the drag constant in normal direction, defined by:

$$\overline{Drag} = DB\left(\frac{V(J,1)}{30.48^2}\right) \times VNM \tag{1.3}$$

$V(J,1)$ is in cm/sec and all other units are in F.P.S. system.

For NB = 2, 3, and 4, experimental expression were derived (Ref. 6) as listed below. (Here drag force is assumed proportional to square of the velocity.)

NB = 2 (Toroid)

$$\Theta(J) = \frac{\pi}{2} - \left\{ 2.58\text{x}10^{-4}\, \frac{V(J,1) \times VNM}{DB} \left(\frac{Tens}{0.0924\text{x}DB^3}\right)^{-0.587} \right\} \tag{2.1}$$

NB = 3 (Disk - with - Feet)

$$\Theta(J) = \frac{\pi}{2} - \left\{ 1.98\text{x}10^{-4}\, \frac{V(J,1) \times VNM}{DB} \left(\frac{Tens}{0.0725\text{x}DB^3}\right)^{-0.583} \right\} \tag{3.1}$$

NB = 4 (Disk - without - feet)

$$\Theta(J) = \frac{\pi}{2} - \left\{ 7.474\text{x}10^{-5}\, \frac{V(J,1) \times VNM}{DB} \left(\frac{Tens}{0.072\text{x}DB^3}\right)^{-0.482} \right\} \tag{4.1}$$

where, J = 1, 2, and DB represents the diameter of the buoy.

$\Theta(3)$ in all cases is given by:

$$\Theta(3) = \cos^{-1}\left[\sqrt{1 - \cos^2\Theta(1) - \cos^2\Theta(2)}\right] \tag{4.2}$$

Again,

V(J, 1) is in cm/sec and all other units are in F. P. S. system.

PART II

SUBSURFACE MOORING LINES

ABSTRACT

Part II of this report deals mainly with the static case of a single point subsurface mooring line, and presents a computer solution to provide, with reasonable accuracy, the system's steady-state configuration with regard to geometry and line tension.

The work reported here is an extension of work presented in reference 2, and presents a three-dimensional solution to the general three-dimensional buoy system.

The computer program presented is written in FORTRAN. A complete listing and detailed instructions for its use are included.

On IBM 360/75 typical central processor time to complete this computation for a line divided into 50 segments including I/O and plotting calculations is 3 seconds. Computation time for one integration cycle alone (from top to bottom of the line) for the same system is 0.08 seconds.

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1.0 General

1.1 Introduction

Static analysis of a Single Point Subsurface Mooring Line is not much different from a Surface Mooring Line which is dealt with in Part I. One major difference lies in the boundary conditions. In the case of a Subsurface System, the top of the system is free to move in the vertical direction with changing velocity fields. Thus we no longer have a fixed vertical depth for the system as in the case of a Surface Mooring System. But, as the buoyancy and drag characteristics of a submerged body are known to the desired accuracy we no longer have an unknown top tension. This leads to a solvable problem with known top tension and iterating on the top buoy depth.

Subsurface mooring systems are being used more frequently for reasons of logistics, being much cheaper than the surface mooring systems, lesser average motion and a better knowledge of drag characteristics for fully submerged bodies. On the other hand subsurface mooring systems cannot measure oceanic environment very near the surface, telemetry is difficult to achieve and cannot be sighted by radar.

This report is Part II of a four part report and deals with the static case of a single point subsurface mooring line. Computer simulation very much similar to the one for surface mooring lines is performed. A typical mooring line is shown in Fig. 1.

1.2 Assumptions, Limitations and Suggestions for Further Study

The mooring system is limited to a single line, connecting the top buoy with the anchor, made up of different materials and components. The connecting line may also support any number of buoys along its length.

In its present form no allowance for shrinkage or creep of the synthetic ropes is taken into account. Elongations due to rotation of non-torque balanced cables is also not considered.

An important area which may be a cause of errors in the present computer solution is the input information required for the solution. Drag coefficients for mooring components may not be known accurately enough and need further investigation. Elastic and plastic properties of different mooring materials under the deep ocean environment need further investigation. The computer program can be extended to solve mooring systems with multiple legs.

2.0 Theoretical Analysis

2.1 Analysis of Forces - Static or Steady-State

The forces applied to a subsurface system are similar to that of a surface system with the absence of the surface buoy.

2.2 Stress-Strain Relations

This section remains the same as in Part I.

2.3 Mooring System Analysis-Static

This section remains the same as in Part I.

2.3.1 Mooring Line Equilibrium Equations

This section remains the same as in Part I.

2.3.2 Top Buoy Equilibrium Equations

Consider the free body diagram of the top buoy of a subsurface mooring system (Fig. 2). The steady state forces acting on it are the drag and buoyancy forces.

Equilibrium requires vectorially,

$$\overline{T}_1 = \overline{B}_B + \overline{D_{WB}} + \overline{W}_B \tag{1}$$

$\overline{B}_B$, the buoyancy is a function of water displaced by the top buoy and its weight in air. $\overline{D_{WB}}$ is a function of drag coefficients (CD), the velocity field relative to the buoy $\overline{U}$, and the characteristic area of the buoy (A). Hence,

$$\overline{D_{WB}} = f(CD, \overline{U}, A)$$

3.0 Method of Solution

This section remains the same as in Part I.

3.1 Program Logic

This section remains the same as in Part I.

3.1.1 Segmentation of the Mooring Line

This section remains the same as in Part I.

3.1.2 Initialization of Integration Procedure

a. Analysis

To begin the solution procedure an estimate of the top buoy depth has to be made. This estimate has been left as an input and can be estimated by knowing the depth of water, length of mooring components and a little knowledge about the velocity fields and elongation characteristics of the mooring components. In order to find tension and orientation of the first segment buoy equilibrium equation (1) is used. The drag force acting on the top buoy $\overline{D}_{WB}$ can be calculated knowing the flow past the buoy at that depth. $\overline{B}_B$, the buoyancy of buoy is known and $\overline{T}_1$ is the tension in the first segment having Θ_1, Θ_2, and Θ_3, the three angles with respect to the orthogonal axes x_1, x_2, and x_3 .

b. Design

The computer program has a provision by which the length of one mooring part and the positioning of all the instruments can be designed to fit the given depths of top buoy and all the instruments. When this is the case, top buoy depth is fixed and hence the initial condition is known. The tension force $\overline{T}_1$ is calculated as in 'a' .

3.1.3 Integration Procedure

This section remains the same as in Part I.

3.1.4 Iteration Procedure

a. Analysis

After having completed the integration procedure through all the mooring line segments, instruments and concentrated forces, the anchor is met. The depth of anchor will probably not agree with the actual depth as it depends on the estimate of the top buoy depth. Hence the estimate of the top buoy depth has to be modified to get a better value for the depth of anchor and this results in an iterative solution.

At the end of the first computation (Integration Procedure) the depth error E, the difference in anchor depth reached and actual depth, is computed. If this error lies within acceptable error, which is an input, the problem is solved. If not E/α is subtracted from the top buoy depth and the integration is repeated. Here α is a constant which was taken as 1.1 in the program and can be varied. Thus the error in depth reached gets smaller. The iterations are repeated till a valid solution is obtained. The procedure is shown in Fig. 3a.

b. Design

The computer program has a provision to design a subsurface system by giving value to an index, NDES, which is an input. The value equals the number of the mooring part which has to be varied in length to get a valid solution with a fixed top buoy depth for given velocity profiles, i.e., it may be required to keep the top buoy at a certain depth for a certain velocity field in three directions. Hence an estimated value for the slack length of the mooring part being designed is inputed. The iterations to reduce the depth error defined in the previous section for 'analysis' is now done on this slack length instead of the top buoy depth which in this case is given. The factor α is kept the same as 1.1. Hence the slack length is increased or decreased in successive iterations by the current value of E/α.

While designing the system, the program can also calculate the slack length positioning of all the instruments to reach certain inputed values of depths for the specified velocity fields. The inputed slack length positioning of instruments is based on the estimated slack length of the mooring part being designed. The positioning is then changed during successive iterations as the slack length of mooring part changes. This iteration procedure is shown in Fig. 3b.

3.2 Control Parameters

In the computer program, solution procedure is controlled by certain indexing procedures. These are described below.

a. Index:

This variable takes values 2 and 3 and controls the iteration and printing procedures. An initial value of 2 is given to this variable when normal integration and iterations are done. When Index = 3 a valid solution has been found and the system is being recomputed to print the required output.

b. L:

This index controls the number of iterative cycles allowed for each solution. It is indexed one unit for each cycle and control is shifted to the next system if convergence is not achieved in the allowed number of cycles. This index is not allowed to exceed a value of ten.

c. NPO:

This variable is used to restrict detailed output printing for a specified number of solutions for different velocity profiles in a buoy system. It has a value equal to the number of solutions for which detailed output is required. IJ is a dummy index for the inner control loop which is indexed one unit for each complete solution. When IJ exceeds NPO, control is no longer shifted to Index 3 mode, which makes detailed output printing. These control parameters are shown in Fig. 4.

4.0 Physical Parameters as Input Information

4.1 Top Buoy

The subsurface mooring system could have a buoy or other buoyant material at the uppermost point to hold the top end afloat. Hence the integration usually starts with a buoyant instrument at the top unless the first segment is buoyant. If a buoy is provided at the top its drag characteristics and buoyancy are inputed similar to the ones inputed for instrumentation along the line. The position and length of the buoy are zero. The drag characteristics can be inputed as forces acting on the buoy which along with the buoyancy give rise to the tension vector in the first segment.

4.2 Instrumentation, Discrete Buoyancy and Concentrated Forces

Instrumentation and discrete buoyancy can be inserted anywhere in the mooring system. These are considered as concentrated forces having a specified length. Other concentrated forces with zero length can also be specified. Certain physical parameters like the position, length, components of force, drag constants and the name are to be inputed for each, or a group of instruments, discrete buoyancy or concentrated forces . The instrument or concentrated force position refers to its position in the mooring line based on slack lengths measured from the top of the system to its centreline.

In the case of instruments whose drag constants are not known but their hydrodynamic resistance is known this can be inputed as a concentrated force. The length, weight and drag of an instrument are integrated into the mooring line as a segment. No elongation is allowed in an instrument. Lengths of chain could be considered as mooring parts or instruments at user's discretion. Various instruments, used commonly in present day oceanographic research, are listed with their characteristics in Fig. 8 of Part I.

4.3 Elastic Response of Mooring Line Materials

This section remains the same as in Part I.

4.3.1 Loads Experienced by a Mooring

In most cases a mooring line experiences the maximum loading during its launch. This launching load is usually equal to the net resultant of gravitational and hydrodynamic forces below any point, including the submerged weight of the anchor. For subsurface moorings this is usually the highest load they ever experience. This maximum load which a mooring line experiences during its previous life history is critical in determining its total elongation. The launching transient peak load is an input to the computer program and is inputed for each mooring part. A typical mooring line, under tension, stretches by an amount which is partly elastic elongation and partly permanent or semipermanent set which in the case of steel wire mooring lines may be due to the wires and strands becoming more tightly interlocked. In the case of fibre ropes it is due to the unrecoverable stretch of the individual fibres and due to a tighter interlock of strands. This permanent set can be determined and depends on the maximum load a mooring line has experienced in its previous life history.

4.3.2 Experimental Results for Fibre Ropes

This section remains the same as in Part I.

4.4 Hydrodynamic Drag Coefficients

This section remains the same as in Part I.

4.5 Current Profile Formulation

This section remains the same as in Part I.

5.0 Computer Program Instructions and Details

A main program with three subroutines constitute the complete solution program. The computer program has been described adequately by the help of comment statements placed in the program listing and by the variable definitions both of which are included in Appendix A.

Any user wanting to use the computer program will have to provide the input data cards of his own, written as specified in section 5.3. A sample input data set is provided as a reference. Some instructions and details are given in this section to help the user understand the program more critically. The program is made adequately general to solve most of the mooring lines being used presently.

Segmentation of the mooring line and start of the integration procedure were explained in Section 3.1 under Program Logic.

5.1 Specification of Top Buoy Depth

During analysis an estimate has to be made of the approximate depth the top buoy would be at the given velocity profiles. This estimate is inputed while reading in the instrument specifications, as the top buoy in a subsurface system is included in the number of instruments. The value goes into the same array; namely, H3(J) which holds the values for required depths of instruments while in the designing mode. H3(1), which is the top buoy depth must be inputed both while analysis and design. While design its value is not changed but during analysis this value is the value taken for first iteration.

5.2 Positioning of Instrumentation

For certain experiments it is desirable to maintain instruments at a certain constant depth, or in a narrow range of depth, for most of the experiment. This is made possible in the program by inputing the desired depths of the instruments for a particular mean expected flow and the output of the program tells where to position the instruments in the mooring line to obtain those depths. While designing, input values for instrument positions are based on the estimate of their actual positions and the estimate of the slack length of the mooring part being varied in length in the subsequent iterations. Hence position of the instruments and the length of the mooring part being designed should be inputed as the estimated values.

5.3 Data Input Required by Computer Program

The user must provide the input data for the mooring systems he wishes to study. The instructions for writing the input data are similar to the ones described in Part I with minor modifications. Only the modifications will be detailed here.

b. This card includes information about:

(i) NDES - Mooring part number to be designed (zero for analysis)
(ii) ER - Acceptable depth error
(iii) Depth - Ocean depth

in addition to what was contained in Part I. Format (11I5, 2F8.0)

c. The additional information in these NI cards is:

H3(J) - Desired design depth of J^th instrument. If no particular depth required, enter zero.
For analysis; H3(1) equals expected depth of top buoy.
Format (8F8.0, A8)

d. This card is not required for subsurface mooring systems.

5.4 Computer Program Capabilities and Limitations

The computer program was written to be a very general program which could be used effectively for any sensitivity analysis. It can design and/or analyze any number of mooring configurations in one computer run. Elongation is permitted in all components of the mooring line except the instruments. The mooring configuration can consist of any number of instruments and concentrated forces and be made of any number of mooring materials. Stress-strain characteristics of plaited nylon, single braided nylon, and braided dacron have been presented in this report. Instruments and concentrated forces can be located anywhere along the mooring line including next to the top buoy and the anchor. Chain may be considered as a mooring part or an instrument. The program prints out, when designing, where to place the various instruments in slack length positions, to acquire a certain depth for the given design velocity profiles. Results can be plotted by the computer, if desired. The plots will give mooring configurations with velocity profiles used. Six types of velocity profiles are included in the computer program which can be invoked by their respective numbers.

Some of the principle outputs other than the plots are:

1. Maximum tension and safety factor for each mooring part.
2. Maximum elongations in each mooring part as percentage of slack length or $200D^2$ length.
3. Position of the top buoy with respect to the anchor.
4. If required, the segment number, stretched length, coordinates of end point, tension, inclination, speed values in x_1 and x_2 directions and mooring part number can be printed out at each segment including the instruments. This allows a graphic presentation of mooring configuration.

The solution is a purely steady-state solution making no allowance for dynamic effects.

6.0 Case Study

Case study of a subsurface mooring line which was actually deployed is presented here to illustrate the use of the computer program and the type of results obtained. The system is highly instrumented and motion of one point on this mooring line was acoustically tracked by four bottom transponders. Results of that Mooring Motion Experiment are to be presented in Reference 3. The results of computer program presented in this Part are compared to experimental data in Reference 3. Fig. 5 shows the mooring system being studied and input data is shown in Fig. 6. Results for designing the system are shown in Fig. 7, while results of analysis are shown in Fig. 8. Detailed results for other runs are shown in graphical form in Figs. 9 through 14.

7.0 References

This section remains the same as in Part I.

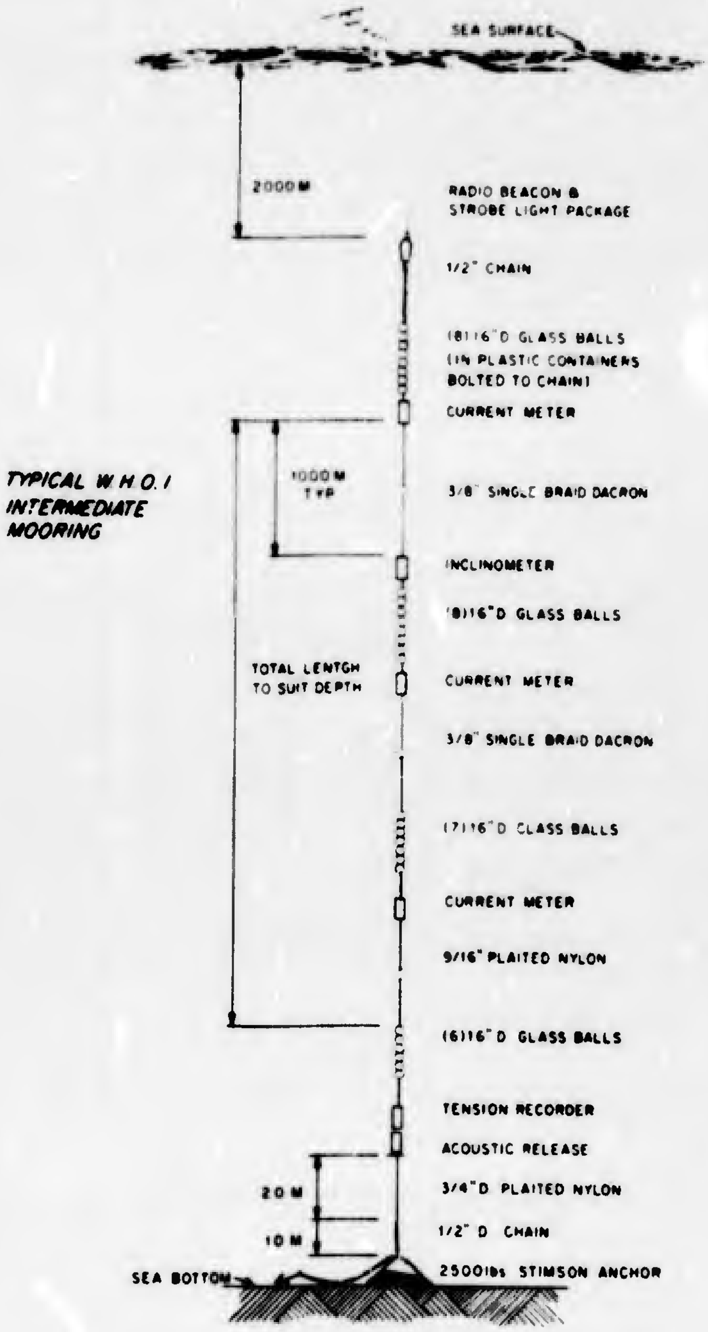


Figure 1. Typical W.H.O.I. Intermediate Mooring
(From Reference 2)

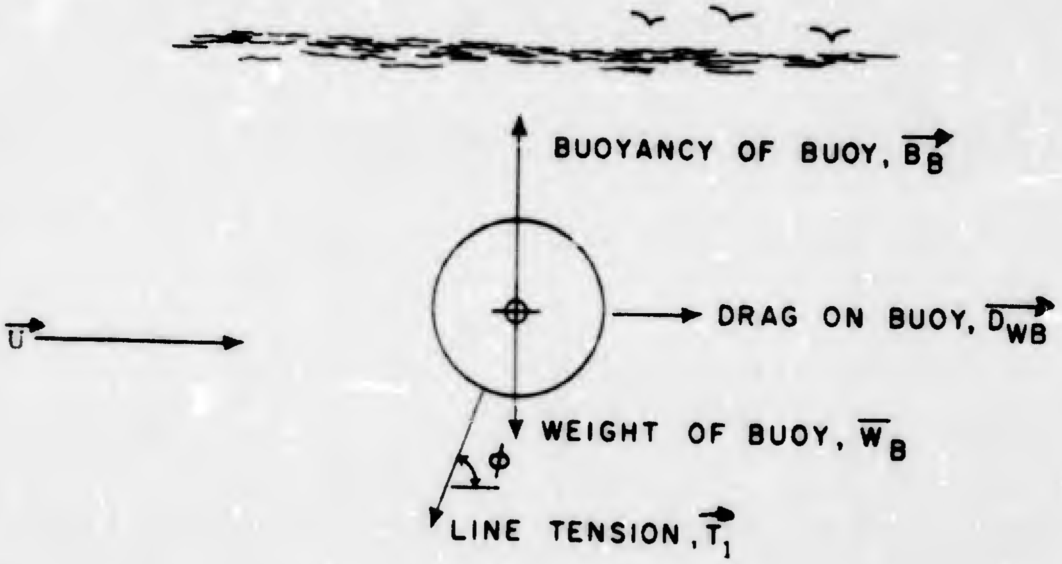
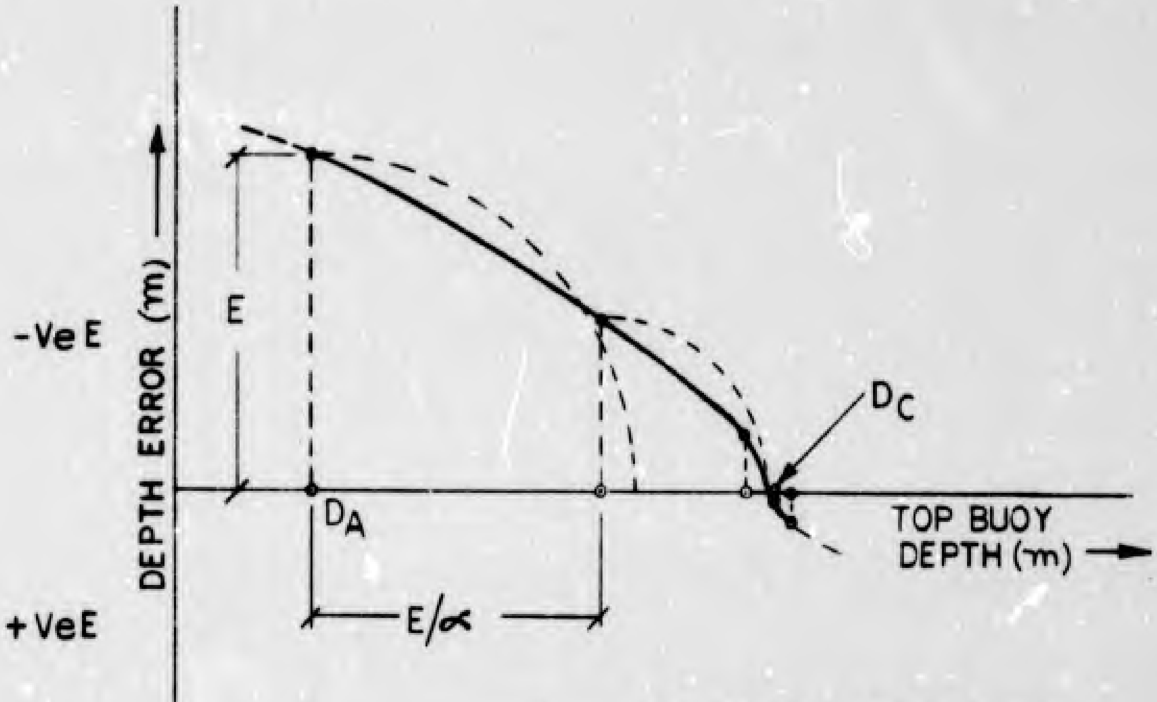


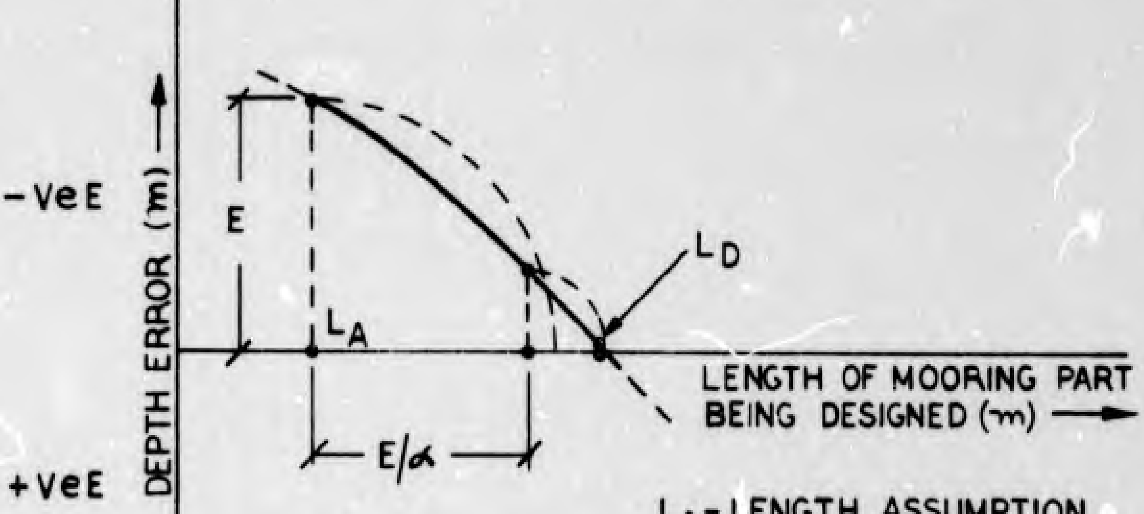
Figure 2. Forces on a Subsurface Buoy



D_A = DEPTH ASSUMPTION

D_C = DEPTH CALCULATED

FIG. 3a. ITERATION PROCEDURE (ANALYSIS)



L_A = LENGTH ASSUMPTION

L_D = LENGTH DESIGNED

FIG. 3b. ITERATION PROCEDURE (DESIGN)

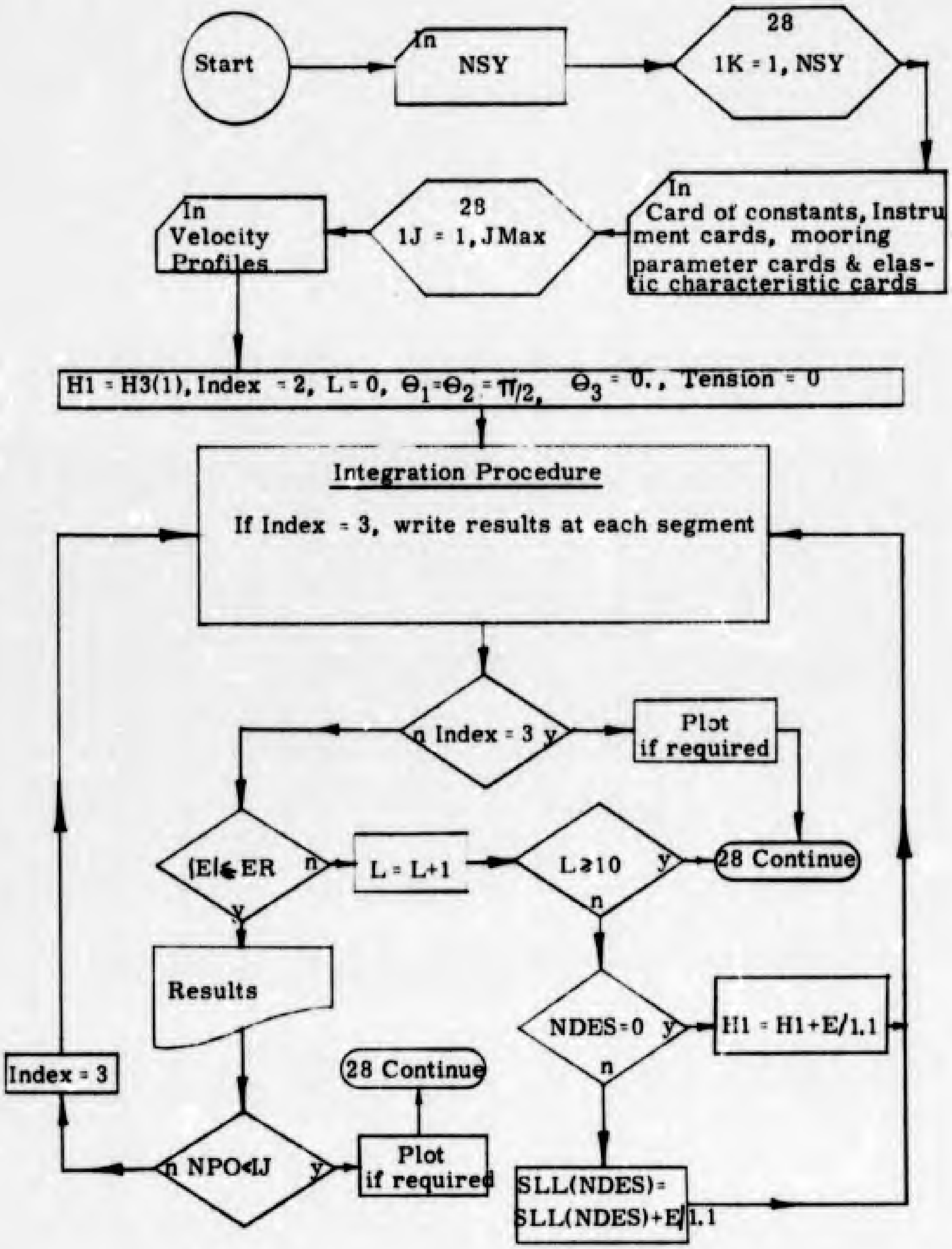


Figure 4. CONTROL PARAMETERS

Figure 5. Case Study - Subsurface Buoy System

```
SB33.DATA
00010     1
00020    12    10    50    0     2     2     1     1     1     5     5     3.   5450.
00030  0.       0.       0.       0.       43.5    1.75    0.      470.5  TOP BUOY
00040  15.     30.      0.       0.       572.     50.06   1.14    485.5  VACM TDR
00050  531.5  7.       0.       0.       177.     12.0    0.24    1000.  VACM&CPS
00060  1037.5 7.       0.       0.       120.     11.3    0.24    1500.  VACM&CPS
00070  1542.  4.       0.       0.       -65.     2.4     0.06    2000.  TDR INCL
00080  1974.5 7.       0.       0.       120.     11.3    0.24    2500.  VACM&CPS
00090  2922.  12.      0.       0.       60.      17.40   0.20    3500.  VACM TDR
00100  3497.5 1.       0.       0.       -32.     1.5     0.05    4100.  INCLINOM
00110  4718.  16.      0.       0.       449.     13.10   0.12    5376.  T&D C
00120  4740.  8.       0.       0.       150.     9.70    0.17    5398.  ACO R
00130  4776.  2.       0.       0.       -99.     4.0     0.13    5432.  ACO RELS
00140  4799.5 3.       0.       0.       -30.     1.00    0.03    5457.5 .5 CHAIN
00150  0.259       498.     0.154     4000.     10000000. 3/16WIRE
00160  0.259       499.     0.154     4000.     10000000. 3/16WIRE
00170  0.259       499.     0.154     4000.     10000000. 3/16WIRE
00180  0.375       427.     0.0375    5000.     1145.     3/8  DAC
00190  0.375       944.     0.0375    5000.     1455.     3/8 DAC.
00200  0.375       563.     0.0375    5000.     1720.     3/8 DAC.
00210  0.375       1210.    0.0375    5000.     1870.     3/8 DAC.
00220  0.50       10.       0.0667    14000.    2535.     1/2  DAC
00230  0.75       31.       0.0457    14200.    2735.     3/4  NYL
00240  0.75       21.       0.0457    14200.    2640.     3/4  NYL
00250  0.0625     0.        0.        0.        1.0       1.4         0.028
00260  0.0625     0.        0.        0.        1.0       1.4         0.028
00270  0.0625     0.        0.        0.        1.0       1.4         0.028
00280  1250.      1.8       1350.     1.6       1.0       1.4         0.028
00290  1250.      1.8       1350.     1.6       1.0       1.4         0.028
00300  1250.      1.8       1350.     1.6       1.0       1.4         0.028
00310  1250.      1.8       1350.     1.6       1.0       1.4         0.028
00320  1250.      1.8       1350.     1.6       1.0       1.4         0.028
00330  88.        1.94      74.8      1.87      1.0       1.4         0.028
00340  88.        1.94      74.8      1.87      1.0       1.4         0.028
00350   490.5       1008.       1515.5      2474.      3478.
00360   28.28       -21.91      -16.95      27.35      49.56
00370   28.28       -21.91      -16.95      13.67      24.78
00380   0.          0.          0.          0.         0.
00390   490.5       1008.       1515.5      2474.      3478.
00400   2.83        -2.19       -1.70       2.74       4.96
00410   2.83        -2.19       -1.70       1.37       2.48
00420   0.          0.          0.          0.         0.
READY
```

Figure 6. Input Data - Subsurface Buoy System (Analysis)

```
          OCEANOGRAPHIC BUOY SYSTEM-SUBSURFACE
          RUN NUMBER  1

               INPUT:  OCEAN DEPTH=5459.0 METERS
     VEL. PROFILE INFO:
     DIREC. PROF. NO. DEPTHS/VELS. OR TOP VEL.&3CONSTANTS
       1      1  490.5    0.0  1008.0    0.0  1515.5    0.0  2474.0    0.0  3478.0    0.0
       2      1  490.5    0.0  1008.0    0.0  1515.5    0.0  2474.0    0.0  3478.0    0.0
       3      1  490.5    0.0  1008.0    0.0  1515.5    0.0  2474.0    0.0  3478.0    0.0

     ----------------------------MOORING PARTS DATA-----------------------------
     NO.  TYPE  LAUNCH TRAN PEAK DRAG COEFFS. SLACK LEN. DIAMETER R.B.S.  WEIGHT
                LOAD OR E.MODUL. NORM.  TANG.  (METERS)  (INCHES)  (LBS) (LBS/M)

      1 3/16WIRE   10000000.0      1.400  0.028   498.00     0.259    4000.0  0.154
      2 3/16WIRE   10000000.0      1.400  0.028   499.00     0.259    4000.0  0.154
      3 3/16WIRE   10000000.0      1.400  0.028   499.00     0.259    4000.0  0.154
      4 3/8  DAC       1145.0      1.400  0.028   427.00     0.375    5000.0  0.037
      5 3/8 DAC.       1455.0      1.400  0.028   944.00     0.375    5000.0  0.037
      6 3/8 DAC.       1720.0      1.400  0.028   563.00     0.375    5000.0  0.037
      7 3/8 DAC.       1870.0      1.400  0.028  1200.00     0.375    5000.0  0.037
      8 1/2  DAC       2535.0      1.400  0.028    10.00     0.500   14000.0  0.067
      9 3/4  NYL       2735.0      1.400  0.028    31.00     0.750   14200.0  0.046
     10 3/4  NYL       2640.0      1.400  0.028    21.00     0.750   14200.0  0.046

             OUTPUT:     DESIGN FOR MOORING PART NO.  7

                                  ITERATION PROCEDURE

                 PART LENGTH  DEPTH REACHED  DEPTH ERROR  COMMENTS

                   1200.00       5445.92        13.0820   TRIAL RUN
                   1211.89       5458.50         0.5039  CONVERGENT RUN

     RESULTS:  BUOY XEXCURSION=    0.00 METERS   BUOY YEXCURSION=    0.00 METERS

               ------------------------MOORING PARTS DATA-------------------
               NO.    TYPE   MAXIMUM TENSION  SAFTEY FACTOR  MAXIMUM ELONGATION
                                  (LBS)                         (% 200 D SQ.)
                1   3/16WIRE     615.50             6.50           0.002
                2   3/16WIRE     715.81             5.59           0.002
                3   3/16WIRE     767.96             5.21           0.003
                4   3/8   DAC    691.11             7.23           4.842
                5   3/8 DAC.     739.1[illegible]             6.7[illegible]           5.[illegible]
                6   3/8 DAC.     772.70             6.47           5.868
                7   3/8 DAC.     751.59             6.65           5.931
                8   1/2   DAC    674.14            20.77           4.633
                9   3/4   NYL   1278.47            11.11          13.648
               10   3/4   NYL   1277.06            11.12          13.224
 EADY
```

Figure 7. Detailed Output (Design)

```
                          MOORING CONFIGURATION

SEC. NO. STR.LEN. XEXCUR. YEXCUR.  DEPTH TENSION XANG YANG XVEL. YVEL. M.P. NO.
TOP BUOY    0.0      0.0      0.0   470.50   43.50 1.57 1.57  0.0   0.0  TOP BUOY
THE INST. SHOULD BE PLACED AT     0.0 M. SLACK LEN. TO OBTAIN DEPTH OF  470.5 M.
VACM T&D   30.00     0.00     0.00  500.50  615.50 1.57 1.57  0.0   0.0  VACM T&D
THE INST. SHOULD BE PLACED AT    15.0 M. SLACK LEN. TO OBTAIN DEPTH OF  485.5 M.
    1     129.80     0.00     0.00  600.30  600.16 1.57 1.57  0.0   0.0     1
    2     229.60     0.00     0.00  700.10  584.82 1.57 1.57  0.0   0.0     1
    3     329.39     0.00     0.00  799.89  569.48 1.57 1.57  0.0   0.0     1
    4     429.18     0.00     0.00  899.68  554.15 1.57 1.57  0.0   0.0     1
    5     528.96     0.00     0.00  999.46  538.81 1.57 1.57  0.0   0.0     1
VACM&GRS  535.96     0.00     0.00 1006.46  715.81 1.57 1.57  0.0   0.0  VACM&GRS
THE INST. SHOULD BE PLACED AT   528.5 M. SLACK LEN. TO OBTAIN DEPTH OF 1000.0 M.
    6     636.00     0.00     0.00 1106.50  700.44 1.57 1.57  0.0   0.0     2
    7     736.03     0.00     0.00 1206.53  685.07 1.57 1.57  0.0   0.0     2
    8     836.05     0.00     0.00 1306.55  669.70 1.57 1.57  0.0   0.0     2
    9     936.07     0.00     0.00 1406.57  654.33 1.57 1.57  0.0   0.0     2
   10    1036.09     0.00     0.00 1506.59  639.96 1.57 1.57  0.0   0.0     2
VACM&GRS 10[illegible]   [illegible]   [illegible] 15[illegible]  7[illegible] [illegible] 1.57  0.0   0.0  VACM&GRS
THE INST. SHOULD BE PLACED AT 1027.4 M. SLACK LEN. TO OBTAIN DEPTH OF 1500.0 M.
   11    1143.14     0.00     0.00 1613.64  752.59 1.57 1.57  0.0   0.0     3
   12    1243.19     0.00     0.00 1713.69  737.22 1.57 1.57  0.0   0.0     3
   13    1343.23     0.00     0.00 1813.73  721.85 1.57 1.57  0.0   0.0     3
   14    1443.27     0.00     0.00 1913.77  706.48 1.57 1.57  0.0   0.0     3
   15    1543.30     0.00     0.00 2013.80  691.11 1.57 1.57  0.0   0.0     3
T&D INCL 1547.30     0.00     0.00 2017.80  626.11 1.57 1.57  0.0   0.0  T&D INCL
THE INST. SHOULD BE PLACED AT 1526.2 M. SLACK LEN. TO OBTAIN DEPTH OF 2000.0 M.
   16    1636.83     0.00     0.00 2107.33  622.91 1.57 1.57  0.0   0.0     4
   17    1726.36     0.00     0.00 2196.86  619.71 1.57 1.57  0.0   0.0     4
   18    1815.88     0.00     0.00 2286.38  616.51 1.57 1.57  0.0   0.0     4
   19    1905.40     0.00     0.00 2375.90  613.30 1.57 1.57  0.0   0.0     4
   20    1994.91     0.00     0.00 2465.41  610.10 1.57 1.57  0.0   0.0     4
VACM&GRS 2001.91     0.00     0.00 2472.41  739.10 1.57 1.57  0.0   0.0  VACM&GRS
THE INST. SHOULD BE PLACED AT 2004.2 M. SLACK LEN. TO OBTAIN DEPTH OF 2500.0 M.
   21    2101.49     0.00     0.00 2571.99  735.56 1.57 1.57  0.0   0.0     5
   22    2201.06     0.00     0.00 2671.56  732.02 1.57 1.57  0.0   0.0     5
   23    2300.62     0.00     0.00 2771.12  728.48 1.57 1.57  0.0   0.0     5
   24    2400.18     0.00     0.00 2870.68  724.94 1.57 1.57  0.0   0.0     5
   25    2499.73     0.00     0.00 2970.23  721.40 1.57 1.57  0.0   0.0     5
   26    2599.27     0.00     0.00 3069.77  717.86 1.57 1.57  0.0   0.0     5
   27    2698.80     0.00     0.00 3169.30  714.32 1.57 1.57  0.0   0.0     5
   28    2798.33     0.00     0.00 3268.83  710.78 1.57 1.57  0.0   0.0     5
   29    2897.85     0.00     0.00 3368.35  707.24 1.57 1.57  0.0   0.0     5
   30    2997.37     0.00     0.00 3467.87  703.70 1.57 1.57  0.0   0.0     5
VACM T&D 3009.37     0.00     0.00 3479.87  772.70 1.57 1.57  0.0   0.0  VACM T&D
THE INST. SHOULD BE PLACED AT 2952.8 M. SLACK LEN. TO OBTAIN DEPTH OF 3500.0 M.
   31    3108.71     0.00     0.00 3579.21  769.18 1.57 1.57  0.0   0.0     6
   32    3208.04     0.00     0.00 3678.54  765.66 1.57 1.57  0.0   0.0     6
   33    3307.37     0.00     0.00 3777.87  762.14 1.57 1.57  0.0   0.0     6
   34    3406.69     0.00     0.00 3877.18  758.62 1.57 1.57  0.0   0.0     6
   35    3506.00     0.00     0.00 3976.50  755.11 1.57 1.57  0.0   0.0     6
   36    3605.30     0.00     0.00 4075.80  751.59 1.57 1.57  0.0   0.0     6
INCLINOM 3606.30     0.00     0.00 4076.80  719.59 1.57 1.57  0.0   0.0  INCLINOM
THE INST. SHOULD BE PLACED AT 3519.9 M. SLACK LEN. TO OBTAIN DEPTH OF 4100.0 M.
   37    3705.06     0.00     0.00 4175.55  716.09 1.57 1.57  0.0   0.0     7
   38    3803.80     0.00     0.00 4274.30  712.59 1.57 1.57  0.0   0.0     7
   39    3902.54     0.00     0.00 4373.04  709.10 1.57 1.57  0.0   0.0     7
   40    4001.27     0.00     0.00 4471.77  705.60 1.57 1.57  0.0   0.0     7
```

Figure 7. Detailed Output (Design)
(Cont.)

```
     41     4100.00      0.00     0.00 4570.49  702.11 1.57 1.57  0.0    0.0      7
     42     4198.71      0.00     0.00 4669.20  698.61 1.57 1.57  0.0    0.0      7
     43     4297.42      0.00     0.00 4767.91  695.12 1.57 1.57  0.0    0.0      7
     44     4396.13      0.00     0.00 4866.62  691.62 1.57 1.57  0.0    0.0      7
     45     4494.82      0.00     0.00 4965.31  688.12 1.57 1.57  0.0    0.0      7
     46     4593.51      0.00     0.00 5064.00  684.63 1.57 1.57  0.0    0.0      7
     47     4692.20      0.00     0.00 5162.69  681.13 1.57 1.57  0.0    0.0      7
     48     4790.87      0.00     0.00 5261.36  677.64 1.57 1.57  0.0    0.0      7
     49     4889.54      0.00     0.00 5360.03  674.14 1.57 1.57  0.0    0.0      7
     50     4900.00      0.00     0.00 5370.49  673.47 1.57 1.57  0.0    0.0      8
  T&D GBS   4916.00      0.00     0.00 5386.49 1122.47 1.57 1.57  0.0    0.0  T&D GBS
  THE INST. SHOULD BE PLACED AT 4719.7 M. SLACK LEN. TO OBTAIN DEPTH OF 5370.0 M.
  ACO RELS 4924.00       0.00     0.00 5394.49 1278.47 1.57 1.57  0.0    0.0  ACO RELS
  THE INST. SHOULD BE PLACED AT 4742.3 M. SLACK LEN. TO OBTAIN DEPTH OF 5393.0 M.
     51     4959.23      0.00     0.00 5429.72 1277.06 1.57 1.57  0.0    0.0      9
  ACO RELS 4961.23       0.00     0.00 5431.72 1178.06 1.57 1.57  0.0    0.0  ACO RELS
  THE INST. SHOULD BE PLACED AT 4777.0 M. SLACK LEN. TO OBTAIN DEPTH OF 5432.0 M.
     52     4985.00      0.00     0.00 5455.50 1177.10 1.57 1.57  0.0    0.0     10
  .5 CHAIN 4988.00       0.00     0.00 5458.50 1147.10 1.57 1.57  0.0    0.0  .5 CHAIN
  THE INST. SHOULD BE PLACED AT 4799.8 M. SLACK LEN. TO OBTAIN DEPTH OF 5457.5 M.
\DY
```

Figure 7. Detailed Output (Design)
(Cont.)

```
     OCEANOGRAPHIC BUOY SYSTEM-SUBSURFACE
     RUN NUMBER  1

          INPUT:  OCEAN CEPTH=5459.0 METERS
VEL. PROFILE INFO:
DIREC. PROF. NO. DEPTHS/VELS. OR TUP VEL.&3CONSTANTS
  1      1  490.5  28.28 1008.C -21.91 1515.5 -16.95 2474.0  27.35 3478.0  49.58
  2      1  490.5  28.28 1008.0 -21.91 1515.5 -16.95 2474.0  13.67 3478.0  24.79
  3      1  490.5   0.0  1008.0   0.0  1515.5   0.0  2474.0   0.0  3478.0   0.0

---------------------------MOORING PARTS DATA-----------------------------
NC.  TYPE  LAUNCH TRAN PEAK CRAG COEFFS. SLACK LEN. DIAMETER R.B.S.  WEIGHT
           LOAD OR E.MODUL. NCRM.  TANG.  (METERS)  (INCHES)  (LBS) (LBS/M)

 1 3/16WIRE   10000000.0      1.400  0.028    498.00     0.259    4000.0  0.154
 2 3/16WIRE   10000000.0      1.400  0.028    499.00     0.259    4000.0  0.154
 3 3/16WIRE   10000000.0      1.400  0.028    499.00     0.259    4000.0  0.154
 4 3/8  DAC       1145.0      1.400  0.028    427.00     0.375    5000.0  0.037
 5 3/8 DAC.       1455.0      1.400  0.028    944.00     0.375    5000.0  0.037
 6 3/8 DAC.       1720.0      1.400  0.028    563.00     0.375    5000.0  0.037
 7 3/8 DAC.       1870.0      1.400  0.028   1212.00     0.375    5000.0  0.037
 8 1/2  DAC       2535.0      1.400  0.028     10.00     0.500   14000.0  0.067
 9 3/4  NYL       2735.0      1.400  0.028     31.00     0.750   14200.0  0.046
10 3/4  NYL       2640.0      1.400  0.028     21.00     0.750   14200.0  0.046

          OUTPUT:     ANALYSIS

                         ITERATION PROCEDURE

             BUOY DEPTH  DEPTH REACHED  DEPTH ERROR  COMMENTS

               470.50       4899.87       559.1289   TRIAL RUN
               978.80       5482.51       -23.5078   TRIAL RUN
               957.43       5455.84         3.1602   TRIAL RUN
               960.30       5459.39        -0.3867  CONVERGENT RUN

RESULTS:  BUOY XEXCURSION= 1235.15 METERS   BUOY YEXCURSION=  392.98 METERS

          -----------------------MOORING PARTS DATA-------------------
          NO.    TYPE   MAXIMUM TENSION  SAFTEY FACTOR  MAXIMUM ELONGATION
                             (LBS)                        (% 200 D SQ.)
           1  3/16WIRE     615.84             6.50            0.002
           2  3/16WIRE     714.84             5.60            0.002
           3  3/16WIRE     766.49             5.22            0.003
           4  3/8   DAC    690.26             7.24            4.841
           5  3/8 DAC.     739.56             6.76            5.484
           6  3/8 DAC.     766.83             6.52            5.856
           7  3/8 DAC.     749.77             6.67            5.941
           8  1/2   DAC    690.76            20.27            4.657
           9  3/4   NYL   1203.96            11.79           13.443
          10  3/4   NYL   1202.66            11.81           13.036

                          MOORING CONFIGURATION

SEG. NO. STR.LEN. XEXCUR. YEXCUR.  DEPTH TENSION XANG YANG XVEL. YVEL. M.P. NO.
TOP BUOY    0.0     0.0     0.0   960.30   43.51 1.59 1.59-17.28-17.28 TOP BUOY
VACM T&D   30.00   -0.55   -0.55  990.29  615.84 1.62 1.62-18.74-18.74 VACM T&D
    1     129.80   -5.26   -5.26 1089.87  600.54 1.63 1.63-21.60-21.60    1
    2     229.60  -11.22  -11.22 1189.31  585.25 1.64 1.64-20.62-20.62    1
    3     329.39  -18.38  -18.38 1288.59  570.00 1.65 1.65-19.65-19.65    1
```

Figure 8. Detailed Output (Analysis)

```
    4       429.18   -26.69   -26.69 1387.68   554.77 1.67 1.67-18.68-18.68     1
    5       528.96   -36.13   -36.13 1486.56   539.57 1.68 1.68-17.72-17.72     1
VACM&GBS    535.96   -36.87   -36.87 1493.49   714.84 1.66 1.66-17.20-17.20 VACM&GBS
    6       636.00   -45.57   -45.57 1592.76   699.59 1.66 1.66-15.67-16.07     2
    7       736.03   -54.96   -54.97 1691.91   684.36 1.67 1.67-11.09-12.90     2
    8       836.05   -64.83   -64.90 1790.95   669.14 1.67 1.67  -6.51  -9.73     2
    9       936.07   -75.04   -75.23 1889.91   653.94 1.68 1.68  -1.93  -6.57     2
   10      1036.09   -85.50   -85.86 1988.80   638.74 1.68 1.68   2.64  -3.41     2
VACM&GBS   1043.09   -86.25   -86.63 1995.72   766.49 1.66 1.66   5.09  -1.72 VACM&GBS
   11      1143.14   -95.11   -95.73 2094.96   751.24 1.66 1.66   7.54  -0.02     3
   12      1243.19  -104.07  -105.02 2194.17   736.00 1.66 1.67  12.12   3.15     3
   13      1343.23  -113.00  -114.44 2293.37   720.76 1.66 1.67  16.71   6.32     3
   14      1443.26  -121.69  -123.89 2392.58   705.51 1.65 1.66  21.29   9.48     3
   15      1543.30  -129.85  -133.23 2491.84   690.26 1.64 1.66  25.88  12.65     3
T&D,INCL   1547.30  -130.14  -133.59 2495.81   625.73 1.65 1.67  27.79  13.89 T&D INCL
   16      1636.83  -136.95  -142.33 2584.66   622.55 1.63 1.66  28.82  14.40     4
   17      1726.36  -142.04  -150.25 2673.70   619.36 1.61 1.65  30.79  15.39     4
   18      1815.88  -145.11  -157.20 2762.91   616.17 1.58 1.64  32.76  16.38     4
   19      1905.40  -145.87  -163.03 2852.26   612.97 1.55 1.62  34.74  17.36     4
   20      1994.91  -143.99  -167.57 2941.69   609.77 1.52 1.61  36.72  18.35     4
VACM&GBS   2001.91  -143.61  -167.81 2948.69   739.56 1.50 1.59  37.78  18.89 VACM&GBS
   21      2101.49  -136.55  -169.33 3048.00   736.03 1.47 1.57  38.96  19.48     5
   22      2201.06  -126.06  -169.15 3147.05   732.51 1.43 1.55  41.16  20.58     5
   23      2300.62  -111.75  -167.06 3245.60   729.02 1.38 1.53  43.34  21.67     5
   24      2400.18   -93.26  -162.85 3343.38   725.57 1.34 1.51  45.52  22.76     5
   25      2499.73   -70.23  -156.35 3440.06   722.18 1.29 1.48  47.67  23.83     5
   26      2599.27   -42.36  -147.37 3535.27   718.87 1.23 1.45  49.34  24.67     5
   27      2698.81    -9.52  -135.82 3628.59   715.65 1.19 1.43  46.98  23.49     5
   28      2798.34    27.61  -122.04 3719.97   712.52 1.15 1.41  44.67  22.33     5
   29      2897.86    68.43  -106.34 3809.45   709.46 1.11 1.40  42.40  21.20     5
   30      2997.38   112.43   -88.96 3897.09   706.48 1.08 1.38  40.19  20.09     5
VACM T&D   3009.38   118.07   -86.70 3907.45   766.83 1.10 1.38  38.96  19.48 VACM T&D
   31      3108.71   163.07   -68.32 3994.07   763.89 1.08 1.37  37.75  18.87     6
   32      3208.03   210.25   -48.80 4079.27   760.99 1.05 1.36  35.60  17.80     6
   33      3307.35   259.32   -28.29 4163.15   758.14 1.03 1.35  33.48  16.74     6
   34      3406.66   310.03    -6.92 4245.84   755.32 1.02 1.35  31.40  15.70     6
   35      3505.97   362.14    15.18 4327.44   752.54 1.00 1.34  29.34  14.67     6
   36      3605.27   415.48    37.92 4408.07   749.77 0.99 1.33  27.31  13.66     6
INCLINOM   3606.27   416.03    38.15 4408.87   724.47 0.97 1.33  26.29  13.15 INCLINOM
   37      3705.04   472.12    62.19 4486.53   721.81 0.96 1.32  25.31  12.66     7
   38      3803.80   529.11    86.67 4563.39   719.17 0.95 1.32  23.38  11.69     7
   39      3902.56   586.89   111.51 4639.52   716.55 0.94 1.31  21.46  10.73     7
   40      4001.32   645.34   136.83 4715.00   713.93 0.93 1.31  19.57   9.78     7
   41      4100.07   704.40   162.38 4789.91   711.33 0.92 1.31  17.68   8.84     7
   42      4198.81   763.97   188.20 4864.31   708.73 0.92 1.30  15.81   7.91     7
   43      4297.55   824.01   214.24 4938.25   706.15 0.91 1.30  13.96   6.98     7
   44      4396.28   884.45   240.49 5011.79   703.57 0.91 1.30  12.11   6.06     7
   45      4495.01   945.24   266.90 5084.96   700.99 0.90 1.30  10.28   5.14     7
   46      4593.73  1006.36   293.47 5157.81   698.42 0.90 1.30   8.45   4.22     7
   47      4692.45  1067.76   320.17 5230.36   695.86 0.90 1.30   6.63   3.32     7
   48      4791.16  1129.42   346.99 5302.64   693.31 0.89 1.29   4.82   2.41     7
   49      4889.87  1191.33   373.91 5374.66   690.76 0.89 1.29   3.01   1.51     7
   50      4900.34  1197.92   376.78 5382.27   690.27 0.89 1.29   2.02   1.01     8
T&D GBS    4916.34  1208.00   381.16 5393.89  1062.35 1.15 1.39   1.78   0.89 T&D GBS
ACO RELS   4924.34  1211.27   382.59 5401.05  1203.96 1.20 1.41   1.54   0.77 ACO RELS
   51      4959.50  1223.98   388.11 5433.37  1202.66 1.20 1.41   1.05   0.52     9
ACO RELS   4961.50  1224.70   388.43 5435.21  1112.36 1.17 1.40   0.62   0.31 ACO RELS
   52      4985.23  1233.98   392.47 5456.68  1111.50 1.17 1.40   0.33   0.16    10
.5 CHAIN   4988.23  1235.15   392.98 5459.39  1084.44 1.16 1.40   0.02   0.01 .5 CHAIN
```

Figure 8. Detailed Output (Analysis)

(Cont.)

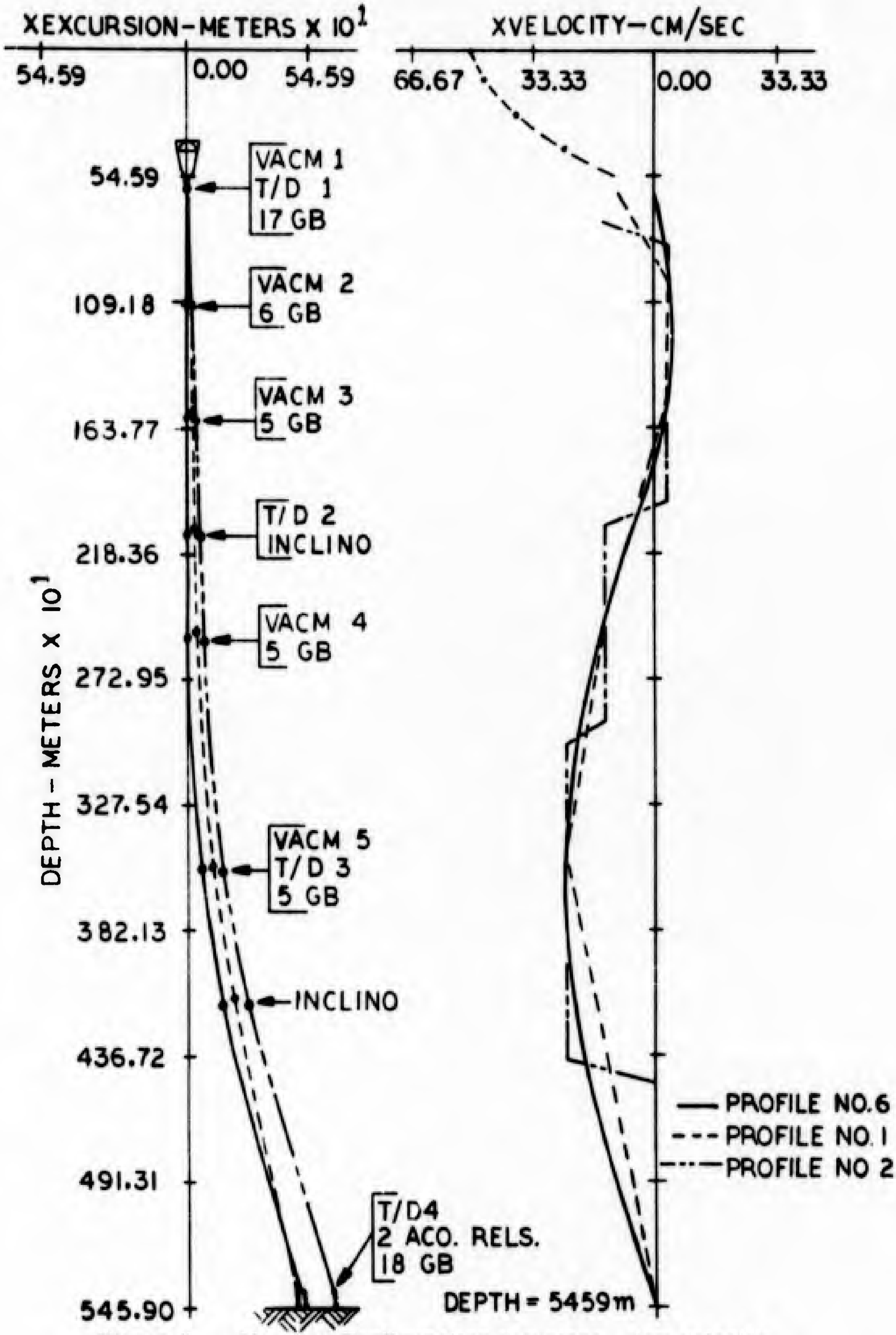


Figure 9. Mooring Configuration x-y plane - low velocity (Three profiles through five fixed vectors)

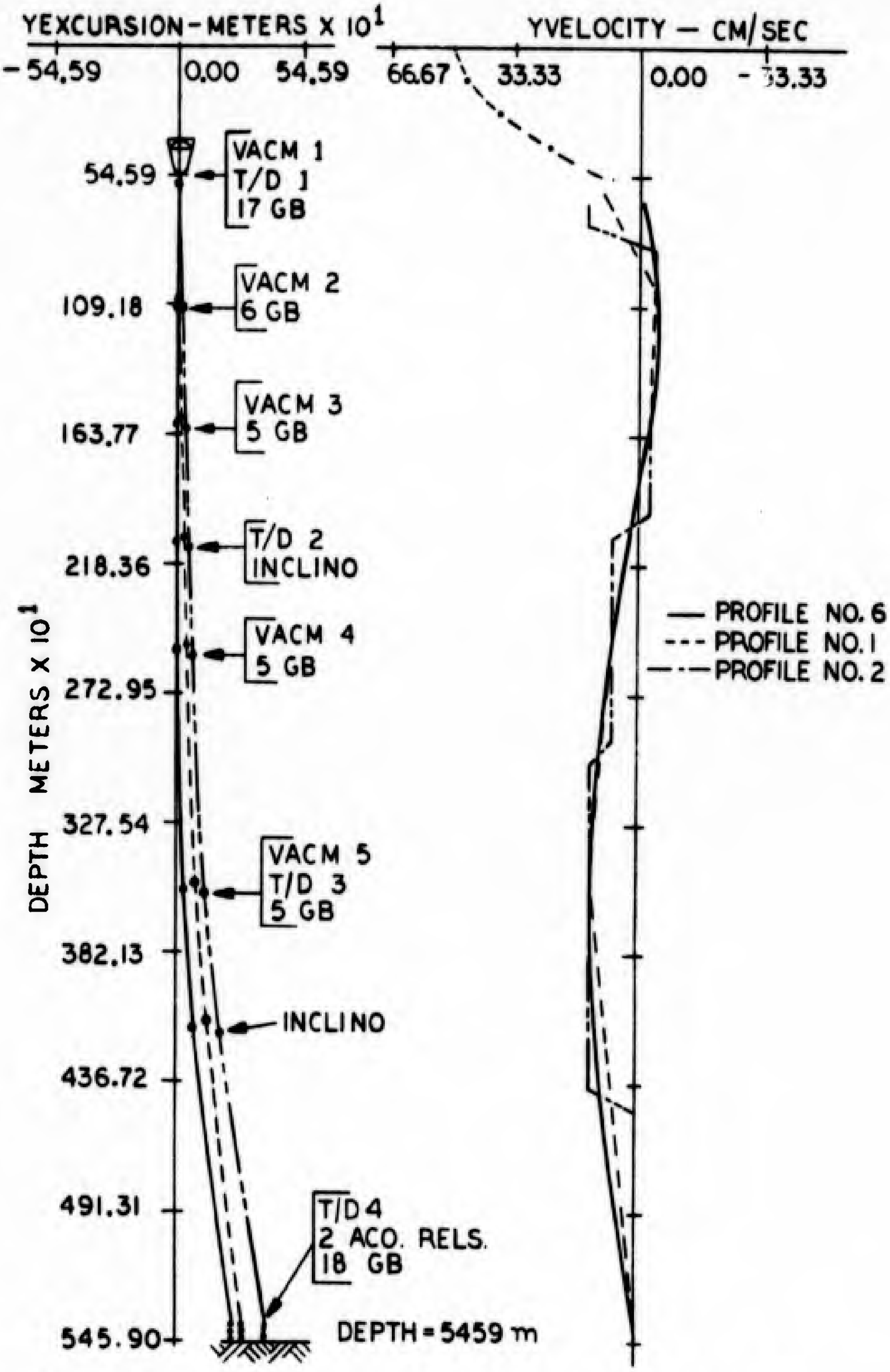


Figure 10. Mooring Configuration in y-z plane - low velocity

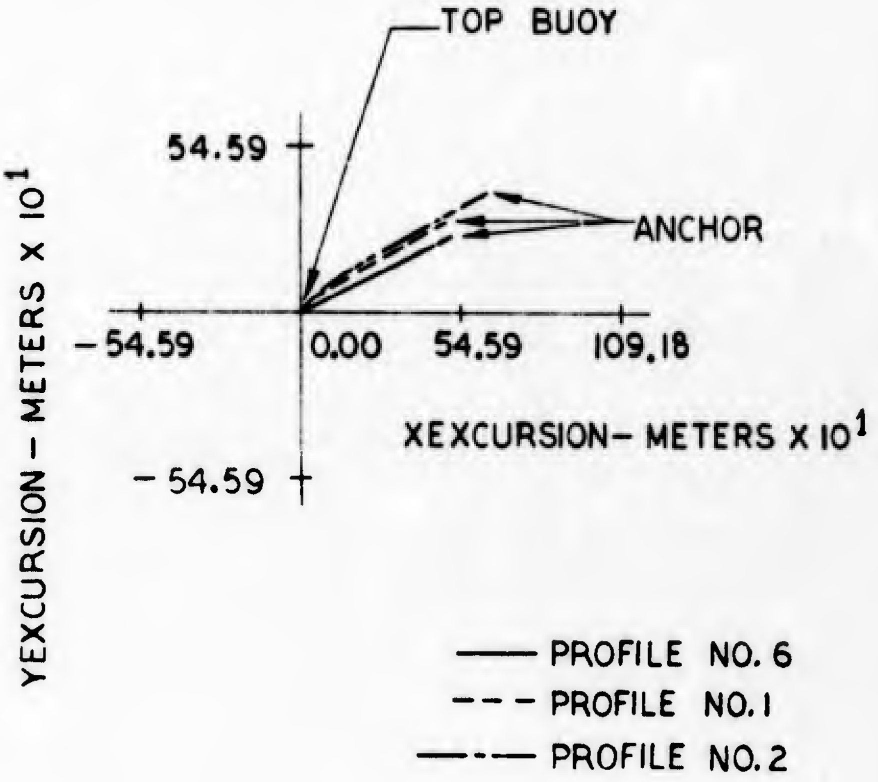


Figure 11. Mooring Configuration in x-y plane - low velocity

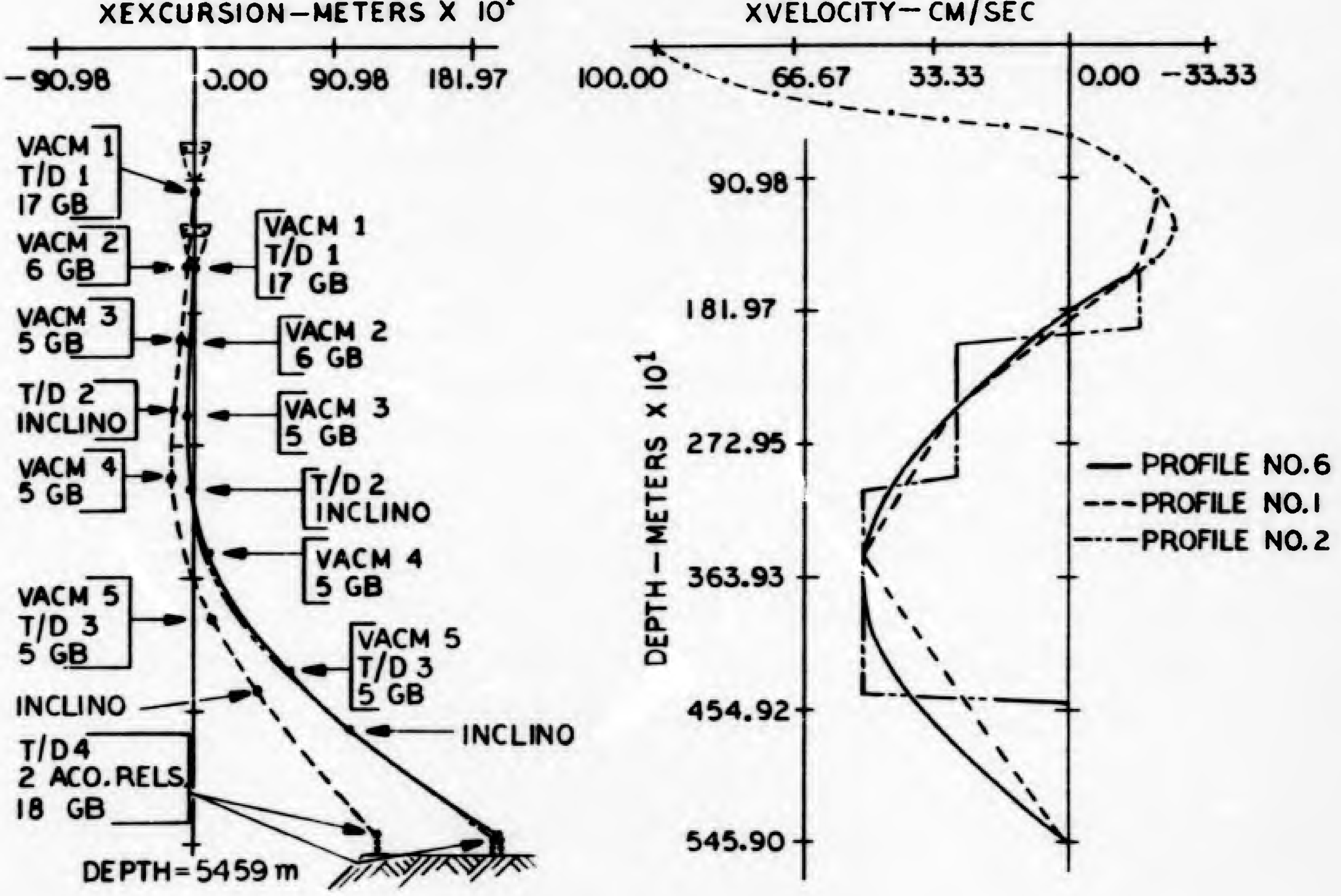


Figure 12. Mooring Configuration in x-z Plane - High Velocity

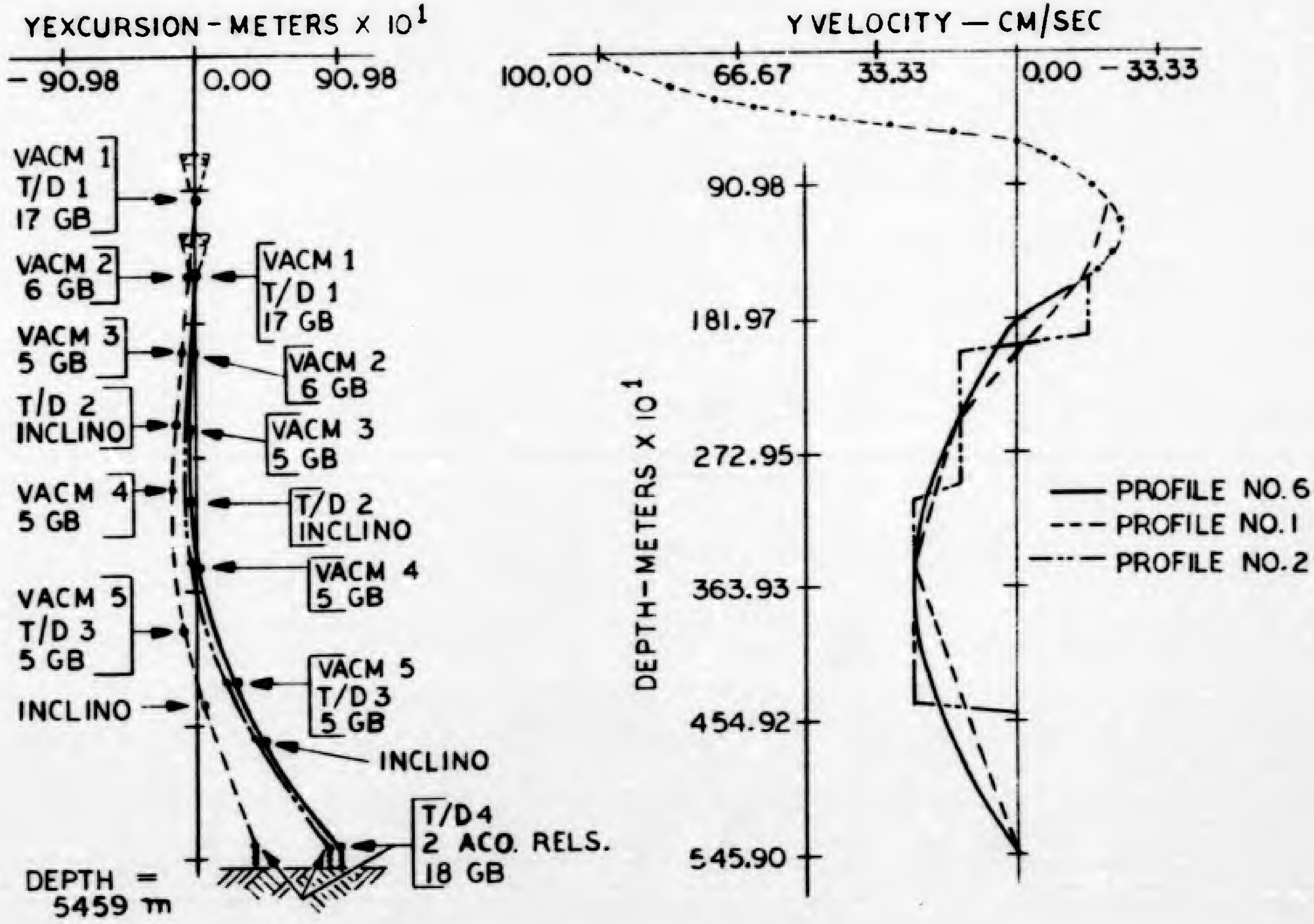


Figure 13. Mooring Configuration in y-z Plane - High Velocity

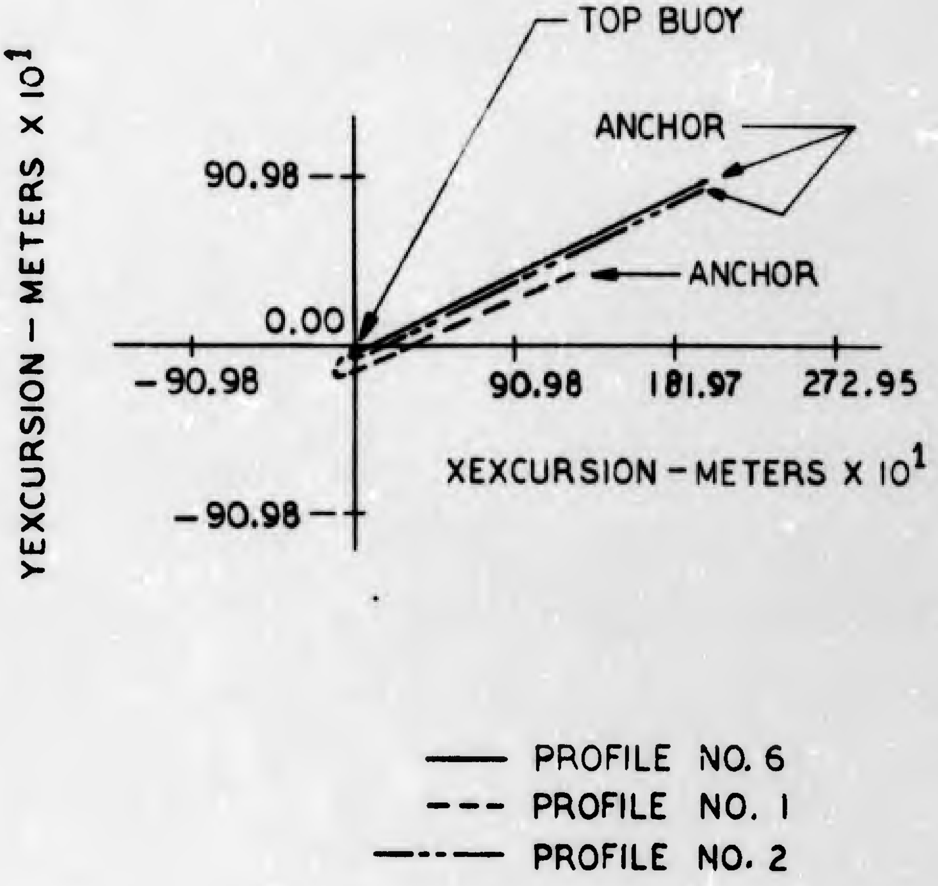


Figure 14. Mooring configuration in x-y plane - high velocity

APPENDIX A

Variable Definitions and Program Listing

Only those variables which were not defined in Part I will be outlined.

H1 - Estimated depth of top buoy.

H3(J) - Design depth of Jth instrument or estimated depth of top buoy.

H4 - Discrepancy in depth inputed and depth desired of an instrument.

NDES - Mooring part number, being designed.

S3 - Total slack length from top buoy to mooring part being designed.

S4 - Slack length position (designed) of an instrument.

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C*****COMPLETE PROGRAM LISTING FOR FORTRAN FILE SP3.FORT*****************
C*****PROGRAM TO COMPUTE CONFIGURATION OF INTERMEDIATE MOORINGS*********
      REAL*8 TYPE(25),MOOR(10)
      DIMENSION XPL(150),YPL(150),[illegible],[illegible],[illegible],[illegible],PI
     1(25),DIAL(10),SLL(10),WWL(10),RBSL(10),CDN(10),CDT(10),TPL(10),CO1
     1(10),CO2(10),PO1(10),PO2(10),MN(10),SW(10),SM(10),[illegible](10),TMAX(10
     1),STRMAX(10),SF(10),DN(3),WN(3)
      COMMON F(3,25),PLT(3,25),V(3,10),SI(25),CDIN(25),CDIT(25),H3(25),A
     1O(10),D(10),NVP(3),VO(3),POW(3),CONS(3),H(3),X(3),THETA(3),CS(3),S
     1N(3),DD(3),WN(3),UT(3),J,INDEX,NDES,DEPTH,TOTRA,I,S2,S,T,N2
C*****BEGINING OF FORMAT STATEMENTS*************************************
  101 FORMAT(11I5,2F8.0)
  102 FORMAT(8F8.0,A8)
  103 FORMAT(7F10.0)
  104 FORMAT(5F10.0,A8)
  105 FORMAT(1H1,9X,'OCEANOGRAPHIC BUOY SYSTEM-SUBSURFACE'/10X,'RUN NUMB
     1ER',I3//15X,'INPUT:  OCEAN DEPTH=',F6.1,' METERS'/5X,'VEL. PROFILE
     2 INFO:'/5X,'DIREC. PROF. NO. DEPTHS/VELS. OR TOP VEL.&3CONSTANTS')
  106 FORMAT(/5X,'------------------------------MOORING PARTS DATA--------
     1---------------------'/5X,'NO.  TYPE  LAUNCH TRAN BREAK ELAS COEFFS
     1. SLACK LEN. DIAMETER R.B.S.  WEIGHT'/16X,'LOAD OR E.MODUL. NORM.
     1 TANG.  (METERS)  (INCHES)  (LBS) (LBS/M)'/)
  107 FORMAT(I10,3X,5F8.2,2F5.2,2F6.2,I5)
  108 FORMAT(14X,F12.2,F14.2,F15.4,'  CONVERGENT RUN')
  109 FORMAT(14X,F12.2,F14.2,F15.4,'   TRIAL RUN')
  110 FORMAT (15X,I2,2X,A8,F11.2,F16.2,F16.3)
  111 FORMAT(//5X,'RESULTS:  BUOY XEXCURSION=',F8.2,' METERS   BUOY YEXC
     1URSION=',F8.2,' METERS'//15X,'--------------------------MOORING PAR
     2TS DATA--------------------'/15X,'NO.   TYPE   MAXIMUM TENSION  SA
     3FTEY FACTOR  MAXIMUM ELONGATION'/33X,'(LBS)',25X,'(% 200 D SP.)')
  112 FORMAT(//15X,'OUTPUT:',5X,'ANALYSIS'//35X,'ITERATION PROCEDURE'//1
     10X,'BUOY DEPTH  DEPTH REACHED  DEPTH ERROR  COMMENTS'/)
  113 FORMAT (I5)
  114 FORMAT(//15X,'OUTPUT:',5X,'DESIGN FOR MOORING PART NO.',I3,//35X,'
     1ITERATION PROCEDURE'//18X,'PART LENGTH  DEPTH REACHED  DEPTH ERROR
     2  COMMENTS'/)
  115 FORMAT(6X,I2,5X,I1,5(F7.1,F7.2))
  116 FORMAT(I7,1X,A8,F13.1,F9.3,F7.3,F9.2,F9.3,F10.1,F7.3)
  117 FORMAT(//35X,'MOORING CONFIGURATION'//5X,'SEC. NO. STR.LEN. XEXCUR
     1. YEXCUR.  DEPTH TENSION YANG YANG XVEL. YVEL. M.P. NO.')
  118 FORMAT (6X,I2,4X,I2,7X,4F10.2)
C*****BEGINING OF THE MAIN PROGRAM***************************************
      READ(5,113)NSY
C*****LOOP FOR DIFFERENT SYSTEMS(MOORING CONFIGURATIONS)*****************
      DO 28 IK=1,NSY
      READ(5,101)NI,NP,NS,NDES,JMAX,NPO,(NVP(I),I=1,3),IKK,IFPL,FN,DEPTH
      IF(NI.EQ.0)GO TO 1
C*****READ IN THE INSTRUMENT(CONCENTRATED FORCE) SPECIFICATIONS*********
      READ(5,102)(PI(J),SI(J),F(1,J),F(2,J),F(3,J),CDIN(J),CDIT(J),H3(J)
     1,TYPE(J),J=1,NI)
C*****READ IN THE PARAMETERS FOR DIFFERENT MOORING PARTS****************
    1 READ(5,104)(DIAL(I),SLL(I),WWL(I),RBSL(I),TPL(I),MOOR(I),I=1,NP)
      READ(5,103)(CO1(I),PO1(I),CO2(I),PO2(I),AO(I),CDN(I),CDT(I),I=1,NP
     1)
```

```
C*****LOOP FOR DIFFERENT INPUTED VELOCITY PROFILES*************************
      DO 28 IJ=1,JMAX
      DO 2 J=1,3
      IF(NVP(J).GT.2)GO TO 2
      READ(5,103)(D(I),I=1,IKK)
      GO TO 3
  2   CONTINUE
   3  DO 4 J=1,3
      IF(NVP(J).LE.2)READ(5,103)(V(J,I),I=1,IKK)
      V(J,IKK+1)=0.
   4  IF(NVP(J).GT.2)READ(5,103)V(J,1),HO(J),POW(J),CONS(J)
      D(IKK+1)=DEPTH
      WRITE(6,105)IJ,DEPTH
      DO 5 I=1,3
      IF(NVP(I).LE.2)WRITE(6,115)I,NVP(I),(D(J),V(I,J),J=1,IKK)
  5   IF(NVP(I).GT.2)WRITE(6,118)I,NVP(I),V(I,1),HO(I),POW(I),CONS(I)
      IF(IJ.EQ.1)WRITE(6,106)
      IF(IJ.EQ.1)WRITE(6,116)(I,MOOR(I),TPL(I),CDN(I),CDT(I),SLL(I),DIAL
     1(I),RBSL(I),WWL(I),I=1,NP)
      IF(NDES.EQ.0)WRITE(6,112)
      IF(NDES.GT.0)WRITE(6,114)NDES
      TSTRA=0.0
      N1=N3(1)
      INDEX=2
      L=0
      E=0.0
      XPL(1)=0.
      YPL(1)=0.
C*****SEGMENTATION OF THE MOORING MOOR IN NPTS SEGMENTS*****************
    6 SLT=0.0
      NPTS=1
      DO 7 I=1,NP
      TMAX(I)=0.0
    7 SLT=SLT+SLL(I)
      DO 8 I=1,NP
      NM(I)=(SLL(I)/SLT)*NS+0.5
      IF(NM(I).EQ.0)NM(I)=1
      SL(I)=SLL(I)/NM(I)
      SW(I)=WWL(I)*SL(I)
      CDIA(I)=SL(I)*(DIAL(I)**2)
    8 NPTS=NPTS+NM(I)
C*****CHANGING POSITION OF INSTRUMENTS IF SYSTEM BEING DESIGNED*********
      S3=0.0
      NM1=NDES-1
      DO 9 IL=1,NM1
    9 S3=S3+SLL(IL)
      DO 11 JL=1,NI
      S3=S3+SI(JL)
      IF(PI(JL)-S3)11,11,10
   10 PI(JL)=PI(JL)+E/1.1
   11 CONTINUE
```

```
C*****BEGINNING OF MOORING MOOR CALCULATIONS********************************
   12 S2=0.0
      X(3)=H1
      K=1
      X(1)=0.
      X(2)=0.
      S=0.0
      ZPL(1)=H1
      J=1
      T=0.0
      THETA(1)=1.570796
      THETA(2)=1.570796
      THETA(3)=0.
      IF(INDEX.EQ.3)WRITE(6,117)
      DO 22 I=1,NP
      STRMAX(I)=0.0
      TMAX(I)=T
      NK=NN(I)+K-1
      DO 21 M=K,NK
C*****CHECK FOR ANY INSTRUMENTS OR CONCENTRATED FORCES*******************
      IF(J.GT.NI)GO TO 14
   13 IF((S2+SL(I)*0.5).GE.PI(J))CALL FORCES(TYPE)
      IF(J.GT.NI)GO TO 14
      IF((S2+SL(I)*0.5).GE.PI(J))GO TO 13
C*****STRESS-STRAIN CALCULATIONS FOR MOORING SEGMENT*********************
   14 IF(PO1(I).EQ.0.0)GO TO 16
C*****SYNTHETIC ROPES******************************************************
      STR=T/(DIAL(I)**2)
      IF(STR.LE.200.0)GO TO 15
      PSTRA=((TPL(I)/(DIAL(I)**2)-200.0)/CO1(I))**(1.0/PO1(I))
      TSTRA=PSTRA+((STR-200.0)/CO2(I))**(1.0/PO2(I))
      S1=AO(I)*SL(I)*(1.0+TSTRA/100.0)
      GO TO 17
   15 TSTRA=0.
      S1=SL(I)*(1.0+(AO(I)-1.0)*STR/200.0)
      GO TO 17
C*****WIRE ROPES-TPL IS ELASTIC MODULUS AND CO1 IS JACKET DIA************
   16 TSTRA=T/(.7854*TPL(I)*(DIAL(I)-CO1(I))**2)
      S1=SL(I)*(1.0+TSTRA)
   17 IF(TSTRA.GT.STRMAX(I))STRMAX(I)=TSTRA
C*****BEGINNING OF THE NUMERICAL INTEGRATION PROCEDURE*******************
      S2=S2+SL(I)
      S=S+S1
      DO 18 IC=1,3
      SN(IC)=SIN(THETA(IC))
      CS(IC)=COS(THETA(IC))
   18 X(IC)=X(IC)+S1*CS(IC)
      IF(SN(3).EQ.0.)SN(3)=0.000001
      DIA=SQRT(CDIA(I)/S1)
      WNN=SW(I)*SN(3)
      WT=SW(I)*CS(3)
      H2=X(3)-S1*CS(3)/2.
      CALL SPEED
```

```
      DO 10 IC=1,3
      II=IC+1
      III=IC+2
      IF(II.GT.3)II=II-3
      IF(III.GT.3)III=III-3
      UN(IC)=U(IC)*SN(IC)**2-U(II)*CS(IC)*CS(II)-U(III)*CS(IC)*CS(III)
      UT(IC)=U(IC)*CS(IC)
   10 UN(IC)=-UNN*CS(IC)*CS(3)/SN(3)
      UN(3)=UN(3)+UNN/SN(3)
      VNN=SQRT(UN(1)**2+UN(2)**2+UN(3)**2)
      UTT=UT(1)+UT(2)+UT(3)
      IF(T.GT.TMAX(I))TMAX(I)=T
      DO 20 IC=1,3
      DN(IC)=(2.04E-4)*CDN(I)*S1*DIA*VNN*UN(IC)-WN(IC)
   20 THETA(IC)=THETA(IC)-DN(IC)/(T*SN(IC))
      T=T-WT+(2.04E-4)*CDT(I)*S1*DIA*ABS(UTT)*UTT
      IF(INDEX.EQ.3)WRITE(6,107)N,S,X(1),X(2),X(3),T,THETA(1),THETA(2),U
     1(1),U(2),I
      XPL(N+1)=X(1)
      YPL(N+1)=X(2)
      ZPL(N+1)=X(3)
      UPL(N)=U(1)
      VPL(N)=U(2)
      WPL(N)=W2
   21 CONTINUE
      N=NK+1
   22 CONTINUE
C*****CHECK FOR ANY INSTRUMENT(CONCENTRATED FORCE) BEFORE ANCHOR********
   23 IF(J.GT.NI)GO TO 24
      CALL FORCES(TYPE)
      GO TO 23
C*****BEGINNING OF THE ITERATION PROCEDURE*******************************
   24 IF(INDEX.EQ.3)GO TO 27
      E=DEPTH-X(3)
      IF(ABS(E).LE.ER)GO TO 25
      IF(NDES.EQ.0)WRITE(6,109)W1,X(3),E
      IF(NDES.GT.0)WRITE(6,109)SLL(NDES),X(3),E
      L=L+1
      IF(L.GE.10)GO TO 28
      IF(NDES.EQ.0)W1=W1+E/1.1
      IF(NDES.EQ.0)GO TO 12
      IF(NDES.GT.0)SLL(NDES)=SLL(NDES)+E/1.1
      IF(NDES.GT.0)GO TO 6
   25 IF(NDES.EQ.0)WRITE(6,108)W1,X(3),E
      IF(NDES.GT.0)WRITE(6,108)SLL(NDES),X(3),E
C*****CALCULATE AND WRITE FINAL RESULTS*********************************
      WRITE(6,111)X(1),X(2)
      DO 26 I=1,NP
      SF(I)=BBSL(I)/TMAX(I)
   26 WRITE(6,110)I,MOOR(I),TMAX(I),SF(I),STRMAX(I)
      IF(NPO.LT.IJ)GO TO 27
      INDEX=3
      GO TO 12
   27 IF(IFPL.GT.0)CALL PLT1(NPTS,XPL,YPL,ZPL,UPL,VPL,WPL,DEPTH,IFPL,INK
     1,V,PLT,W1)
   28 CONTINUE
      CALL WHERE(X,Y,-3)
      CALL PLOT(X,Y,999)
      CALL EXIT
      END
```

```
      SUBROUTINE FORCES(TYPE)
      REAL*8 TYPE(1)
      COMMON F(3,25),PLT(3,25),V(3,10),SI(25),CDIN(25),CDIT(25),H3( ),
     [illegible]( ), ( ),[illegible](3),[illegible](3),[illegible](3),CONS(3),U(3),X(3),THETA(3),CS(3),S
     1 (3),DD(3),UN(3),UT(3),J,INDEX,NDES,DEPTH,TSTRA,I,S2,S,T,H2
  101 FORMAT(5X,A8,5F8.2,2F5.2,2F6.2,1X,A8)
  102 FORMAT(5X,'THE INST. SHOULD BE PLACED AT',F7.1,' M. SLACK LEN. TO
     1OBTAIN DEPTH OF',F7.1,' M.')
C*****NUMERICAL INTEGRATION PROCEDURE*************************************
      S2=S2+SI(J)
      S=S+SI(J)
      DO 1 IC=1,3
      SN(IC)=SIN(THETA(IC))
      CS(IC)=COS(THETA(IC))
      X(IC)=X(IC)+SI(J)*CS(IC)
      IF (INDEX.EQ.3) PLT(IC,J)=X(IC)
    1 CONTINUE
      IF(SN(3).EQ.0.)SN(3)=.000001
      H2=X(3)-SI(J)*CS(3)/2.
      CALL SPEED
      IF (SI(J).NE.0.) GO TO 3
      VNN=SQRT(U(1)**2+U(2)**2+U(3)**2)
      DO 2 IC=1,3
    2 DD(IC)=T*CS(IC)+CDIN(J)*VNN*U(IC)/920.03+F(IC,J)
      GO TO 6
   3  DO 4 IC=1,3
      II=IC+1
      III=IC+2
      IF(II.GT.3)II=II-3
      IF(III.GT.3)III=III-3
      UN(IC)=U(IC)*SN(IC)**2-U(II)*CS(IC)*CS(II)-U(III)*CS(IC)*CS(III)
    4 UT(IC)=U(IC)*CS(IC)
      VNN=SQRT(UN(1)**2+UN(2)**2+UN(3)**2)
      UTT=UT(1)+UT(2)+UT(3)
      DTT=CDIT(J)*ABS(UTT)*UTT/920.03
      DO 5 IC=1,3
    5 DD(IC)=(T+DTT)*CS(IC)+CDIN(J)*VNN*UN(IC)/920.03+F(IC,J)
    6 T=SQRT(DD(1)**2+DD(2)**2+DD(3)**2)
      DO 7 IC=1,3
   7  THETA(IC)=ARCOS(DD(IC)/T)
      IF(INDEX.EQ.3)WRITE(6,101)TYPE(J),S,X(1),X(2),X(3),T,THETA(1),THET
     1A(2),U(1),U(2),TYPE(J)
      IF(INDEX.EQ.3.AND.NDES.GT.0.AND.H3(J).GT.0.0)GO TO 8
      GO TO 9
    8 H4=H2-H3(J)
      S4=S2-H4/(A0(I)*(1.0+TSTRA/100.0)*SN(1))-SI(J)/2.0
      WRITE(6,102)S4,H3(J)
    9 J=J+1
      RETURN
      END
```

```
      SUBROUTINE SPEED
      COMMON F(3,25),PLT(3,25),V(3,10),SI(25),CDIN(25),CDIT(25),H3(25),A
     10(10),D(10),NVP(3),HO(3),POW(3),CONS(3),U(3),X(3),THETA(3),CS(3),S
     1N(3),DD(3),UN(3),UT(3),J,INDEX,NDES,DEPTH,TSTRA,I,S2,S,T,H2
      M=1
      DO 22 JJ=1,3
      IF(NVP(JJ)-4)10,4,11
   10 IF(NVP(JJ)-2)1,2,3
   11 IF(NVP(JJ)-6)5,6,6
C*****PROFILE NO. 1*****************************************************
    1 IF(H2.LE.D(1))GO TO 20
      IF(H2.GE.DEPTH)GO TO 21
   12 IF(H2.GT.D(M).AND.H2.LE.D(M+1))GO TO 13
      M=M+1
      GO TO 12
   13 U(JJ)=V(JJ,M)-((V(JJ,M)-V(JJ,M+1))*(H2-D(M)))/(D(M+1)-D(M))
      GO TO 22
C*****PROFILE NO. 2*****************************************************
    2 IF(H2.LE.D(1))GO TO 20
      IF(H2.GE.DEPTH)GO TO 21
   14 IF(H2.GT.D(M).AND.H2.LE.D(M+1))GO TO 15
      M=M+1
      GO TO 14
   15 TEM=(D(M)+D(M+1))/2.
      IF(H2.GE.TEM)U(JJ)=V(JJ,M+1)
      IF(H2.LT.TEM)U(JJ)=V(JJ,M)
      GO TO 22
C*****PROFILE NO. 3*****************************************************
    3 IF(H2.LE.HO(JJ))GO TO 20
      U(JJ)=V(JJ,1)*(HO(JJ)/H2)**POW(JJ)
      GO TO 22
C*****PROFILE NO. 4*****************************************************
    4 IF(H2.LE.HO(JJ))GO TO 20
      U(JJ)=V(JJ,1)-V(JJ,1)*((H2-HO(JJ))/(DEPTH*CONS(JJ)-HO(JJ)))**POW(J
     1J)
      GO TO 22
C*****PROFILE NO. 5*****************************************************
    5 IF(H2.LE.HO(JJ))GO TO 20
      U(JJ)=POW(JJ)+(V(JJ,1)-POW(JJ))*((H2+CONS(JJ)-DEPTH)/(HO(JJ)+CONS(
     1JJ)-DEPTH))**2
      GO TO 22
C*****PROFILE NO. 6*****************************************************
    6 DEP1=HO(JJ)/3.
      DEP2=DEPTH-HO(JJ)
      DEP=4.*DEP1
      IF(H2-DEP1)17,17,16
   16 IF(H2-HO(JJ))18,18,19
   17 U(JJ)=V(JJ,1)*COS(6.28319*H2/DEP)
      GO TO 22
   18 U(JJ)=-POW(JJ)*COS(6.28319*H2/DEP)
      GO TO 22
   19 U(JJ)=CONS(JJ)*SIN(3.14159*(H2-HO(JJ))/DEP2)
      GO TO 22
   20 U(JJ)=V(JJ,1)
      GO TO 22
   21 U(JJ)=0.
   22 CONTINUE
      RETURN
      END
```

```
      SUBROUTINE PLT1(NPTS,XPL,YPL,ZPL,UPL,VPL,WPL,DEPTH,IFPL,IKK,V,
     1PLT,NI,NVP)
      DIMENSION BUFFER(250),XPL(1),YPL(1),ZPL(1),WPL(1),UPL(1),VPL(1)
      DIMENSION V(1,1),PLT(3,1),NVP(1)
      XFR=3.
      XORG=100.
      DU=XORG/XFR
      DY=DEPTH/10.
      XRG=ABS(XPL(NPTS))
      YRG=ABS(YPL(NPTS))
      XFRM=XRG/DY
      YFRM=YRG/DY
      XLEN=2.*XFRM
      YLEN=2.*YFRM
      UPL(NPTS)=0.
      VPL(NPTS)=0.
      WPL(NPTS)=DEPTH
      XPL(NPTS+1)=-XRG
      YPL(NPTS+1)=-YRG
      UPL(NPTS+1)=XORG
      VPL(NPTS+1)=XORG
      ZPL(NPTS+1)=DEPTH
      WPL(NPTS+1)=DEPTH
      XPL(NPTS+2)=DY
      ZPL(NPTS+2)=-DY
      YPL(NPTS+2)=DY
      UPL(NPTS+2)=-DU
      VPL(NPTS+2)=-DU
      WPL(NPTS+2)=-DY
      NTEM=NPTS+2
      DO 9 I=1,IFPL
      CALL PLOTS(BUFFER,NTEM)
      CALL PLOT(0.,0.,-3)
```

```
      IF(I-2)1,2,3
    1 CALL AXIS(0.,10.,'XEXCURSION (METERS)',19,XLEN,0.,-XRC,DY,10.)
      CALL AXIS(YERM,0.,'DEPTH (METERS)',14,10.,90.,DEPTH,-DY,10.)
      CALL LINE(YPL,ZPL,NPTS,1,0,0)
      GO TO 7
    2 CALL AXIS(0.,10.,'YEXCURSION (METERS)',19,YLEN,0.,-YRC,DY,10.)
      CALL AXIS(YERM,0.,'DEPTH (METERS)',14,10.,90.,DEPTH,-DY,10.)
      CALL LINE(YPL,ZPL,NPTS,1,0,0)
      GO TO 7
    3 IF(I-4)4,5,6
    4 CALL AXIS(0.,10.,'XVELOCITY (CM/SEC)',18,6.,0.,XORG,-DU,10.)
      CALL AXIS(XER,0.,'DEPTH (METERS)',14,10.,90.,DEPTH,-DY,10.)
      CALL LINE(UPL,WPL,NPTS,1,0,0)
      GO TO 9
    5 CALL AXIS(0.,10.,'YVELOCITY (CM/SEC)',18,6.,0.,XORG,-DU,10.)
      CALL AXIS(XER,0.,'DEPTH (METERS)',14,10.,90.,DEPTH,-DY,10.)
      CALL LINE(VPL,WPL,NPTS,1,0,0)
      GO TO 9
    6 CALL AXIS(0.,YERM,'XEXCURSION (METERS)',19,XLEN,0.,-XRC,DY,10.)
      CALL AXIS(YERM,0.,'YEXCURSION (METERS)',19,YLEN,90.,-YRC,DY,10.)
      CALL LINE(XPL,YPL,NPTS,1,0,0)
      GO TO 9
    7 DO 8 K=1,NI
      IF(I.EQ.1)X=PLT(1,K)/DY+YERM
      IF(I.EQ.2)X=PLT(2,K)/DY+YERM
      Y=10.-PLT(3,K)/DY
    8 CALL SYMBOL(X,Y,0.035,0,90.,-1)
    9 CONTINUE
      RETURN
      END
```

APPENDIX B

Subroutine Speed

This appendix is the same as in Part I.