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Silver Spring, Maryland

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NOAA/DOE CWP STRUCTURAL ANALYSIS PACKAGE

SEPTEMBER 1979

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PREPARED FOR:

NOAA OFFICE OF OCEAN ENGINEERING

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ABSTRACT

This report contains the theoretical development and computer code user's manual for analysis of the Ocean Thermal Energy Conversion (OTEC) plant cold water pipe (CWP). The analysis of the CWP includes coupled platform/CWP loadings and dynamic responses. The present report with the exception of the Introduction and Appendix F was originally published as Hydronautics, Inc., Technical Report No. 7825-2 (by Barr, Chang, and Thasanatorn) in November 1978. A detailed theoretical development of the equations describing the coupled platform/CWP system and preliminary validation efforts are described in the main body of the report. The appendices encompass a complete user's manual, describing the inputs, outputs and operation of the four component programs, and detail changes and updates implemented since the original release of the code by Hydronautics. The code itself is available through NOAA's Office of Ocean Technology and Engineering Services.

ABSTRACT

This report contains the theoretical development and computer code user's manual for analysis of the Ocean Thermal Energy Conversion (OTEC) plant cold water pipe (CWP). The analysis of the CWP included coupled platform/CWP loadings and dynamic responses. The main body of the report, originally published by HYDRONAUTICS, Incorporated, contains a detailed theoretical development of the equations describing the coupled platform/CWP system and preliminary validation efforts. The appendices encompass a complete user's manual, describing the inputs, outputs and operation of the four component programs and detailing changes and updates implemented since the original release of the code. The code itself is available through NOAA's Office of Ocean Engineering.

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LIST OF SYMBOLS

a	Amplitude of motion
a_w	Amplitude of surface ocean wave
a_i	Amplitude of internal ocean wave
A	Area or shear area
A_{jk}	Added mass matrix
A_n	Amplitude of response
A_{wp}	Platform waterplane area
b	Exciting moment
b_c	Cosine (in-phase) component of b
b_s	Sin (out-of-phase) component of b
B_{jk}	Hydrodynamic damping matrix
BG	Distance from center of buoyancy to center of gravity
c_h	Damping coefficient
c_h'	Equivalent linearized damping coefficient
c_m	Added mass coefficient
c_m'	Inertia coefficient
C	Damping coefficient for translational motion
C_D	Viscous damping coefficient
C_{jk}	Platform stiffness matrix
C_o	Damping coefficient for rotational motions
C_T	Torsional damping coefficient
C_z	Longitudinal damping coefficient
D_i	CWP inside diameter
D_o	CWP outside diameter

D_p	CWP diameter
E	Modulus of elasticity (Young's modulus)
f	Exciting force
f_c	Cosine (in-phase) component of f
f_s	Sin (out-of-phase) component of f
f_z	Longitudinal exciting force
F	Frequency in Hertz
F_a	Force due to acceleration, force at CWP attachment
F_j	Wave exciting force vector
F_v	Force due to velocity, viscous damping force
F_x	Horizontal force
F_z	Vertical force
g	Acceleration of gravity
G	Shear modulus of elasticity
GM	Metacentric height
H	Shear force
I	Moment of inertia
I_a	Mass polar moment of inertia
I_p	Polar moment of inertia
I_{wp}	Waterplane moment of inertia
k	Roughness height, wave number
$\bar{k}$	Mean mooring stiffness
K	Keulegan-Carpenter Number = 2π a/D, Stiffness matrix
K_s	CWP attachment stiffness
l_m	Mooring length at tension $\bar{T}$
L	CWP length

m_a	Added mass per unit length of CWP
m_i	Mass per unit length of internal flow
m_p	Mass per unit length of CWP
m_z	Added mass of ring stiffness
M	Bending moment
$\bar{M}$	Mass matrix
M_{jk}	Platform mass matrix
N	CWP axial force, number of mooring lines
N_s	Number of ring stiffeners
P	Torsional exciting moment
q	Constant static loading
Q	Exciting force vector
R_{e_d}	Reynolds number based on diameter
R_{e_k}	Reynolds number based on roughness height
S	State variable vector, Strouhal number
t_w	CWP wall thickness
T	Torque, tension
$\bar{T}$	Mean tension
$T_{p_{jk}}$	CWP transfer fuction matrix
U	Transfer matrix
v	CWP deflection, velocity of motion
v_w	Wave orbital velocity
V	Velocity of CWP internal flow
V_c	Current velocity
V_o	Current velocity at deep depth
V_s	Current velocity at water surface

w	Torsional or axial displacement, longitudinal velocity
w_s	Width of ring stiffener
y	Distance from CWP axis
z	Coordinate along CWP axis
α	Horizontal angle of mooring line
Δ	Displacement
∇	Displaced volume
η_h	Platform motion
η_i	Imaginary part of η_j
η_j	Platform motion vector
η_p	CWP motion
η_r	Real part of η_j
σ	CWP shape
ρ	Mass density
ϕ	Angle of twist
$\bar{\phi}$	Mean inclination angle of mooring
ϕ_n	Phase of response, phase of n'th mode
ω	Exciting frequency in radians per second
ω_n	Natural or modal frequency for n'th mode

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1.0 INTRODUCTION

The design of ocean thermal energy conversion (OTEC) plant cold water pipes (CWPs) which are structurally adequate and have acceptable weight and cost is a difficult problem. The Department of Energy (DOE) and its predescessor, ERDA, have provided significant funding since 1975 to study the design and behavior of the CWP. In 1977 the responsibility for development of CWP design technology was transferred by DOE to the Office of Ocean Engineering of the National Oceanic and Atmospheric Administration (NOAA).

HYDRONAUTICS, Incorporated, under Department of Commerce Contract No. 03-78-G03-0504, completed a study concerning the application of existing methods and for the analysis of the dynamic, linear response and stressing of an OTEC plant CWP subject to various environmental and operational loads. The study of CWP hydrodynamic loads completed recently by SAI (1)* provides an important input to this study.

Except for analysis of static CWP loading, all methods used in this study are linear. All dynamic responses are calculated assuming harmonic excitation and response. Responses to random excitations, such as ocean waves, are calculated using methods of Rayleigh statistics. The CWP is treated as a beam having an arbitrary longitudinal distribution of applied bending, shear and tensile loads. Circumferential variations of loads are not considered. Hydroelastic effects are not considered, although some of the unsteady flow induced loadings considered reflect hydroelastic effects. These tasks are described in more detail in Section 2.

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* Numbers in parentheses refer to References at the end of this report.

HYDRONAUTICS, Incorporated's deliverable to NOAA's Office of Ocean Engineering is incorporated into this report. Sections 2 through 12 contain the theoretical analysis of dynamic loads and stresses of the OTEC plant CWP. Appendices A through E present the documentation and user's manual for the CWP computer code that HYDRONAUTICS, Incorporated developed and coupled to existing frequency domain platform computer programs for slender hulls and axisymmetric hulls.

These sections describe all work carried out under this study including:

- o CWP structural analysis methods.
- o Analysis of CWP static and dynamic loads and responses.
- o Analysis of coupled CWP/platform responses.
- o Description of computer programs.
- o Illustrative examples.
- o Preliminary Validation.
- o Computer program user's manuals.

This study consisted of five basic tasks:

- o Development of existing methods and computer programs for CWPs.
- o Coupling of these CWP programs to existing platform programs.
- o Validation of these programs and conduct of representative sample calculations.
- o Preparation of final reports, program user's manuals and validated computer program source decks.
- o Operational Application and Code Upgrading.

This work is based primarily on earlier OTEC work carried out by HYDRONAUTICS for the Department of Energy (DOE). In particular the CWP analysis methods are essentially those developed and described by Chang (2) and the platform and platform/CWP coupling analysis methods are primarily those developed and described by Barr, et al, (3) and (4). Validation is based largely on comparisons with earlier HYDRONAUTICS calculated results (3) and model test data for OTEC-1 (5).

ORI, Inc., under contract to NOAA, received HYDRONAUTICS, Incorporated's computer code in January 1979 and began reviewing and exercising the code. ORI has found it necessary to implement several updates and revisions to improve the operational efficiency of the existing code (referred to as the NOAA/DOE Code). These changes were originally issued as CWP Notes #1-4 from January through June, 1979 and are incorporated into this report as Appendix F.

ORI, Inc. has made changes to the NOAA/DOE Code to improve the operational efficienty only, and has made no evaluations of the accuracy of the theoretical analysis or the correctness of the code beyond those changes specified in Appendix F.

2.0 SCOPE OF WORK

This study consisted of four basic tasks. These tasks are:

1. Development of existing methods and computer programs, as described in Reference 2, to provide linear, frequency-domain and random statistical analysis methods for rigid CWPs with joints, compliant CWPs, stockade CWPs and bottom mounted buoyant CWPs. These methods permit calculation of:

- CWP static and dynamic responses.
- CWP stress distributions.
- CWP failure modes.

for the following sources of loading:

- Steady current.
- Unsteady (harmonic) current induced flows.
- Harmonic and random ocean waves.
- Motions of the platform.
- Unsteady loads inside the CWP.
- End loads.
- Moorings attached to the CWP.

2. Coupling of CWP analysis computer programs of Task 1 to existing frequency-domain platform computer programs to permit calculation of coupled platform/CWP responses to the loads of Task 1. The particular programs for which coupling has been carried out are the HYDRONAUTICS programs for slender hulls and axi-symmetric hulls described by Barr, et al. (7).

3. Validations of these CWP methods and programs and the coupled CWP/platform programs using (a) calculated results from HYDRONAUTICS existing methods, Reference 3, (b) calculated results from Paulling's method, Reference 9 and (c) model test results from tests of the OTEC-1, Sheldon, et al. (5). Illustration of the use of these methods through representative calculations for two examples of interest:

- The APL 10/20 MW grazing barge platform with concrete CWP.
- The MINI OTEC plant with polyethelene CWP.

4. Preparation of a final report describing all work carried out and provision of computer program user's manuals and validated computer source decks for CWP and platform programs.

3.0 DESCRIPTION OF CWP STRUCTURAL ANALYSIS METHOD

The methods used here for the CWP structural analysis have been discussed in detail by Chang (2). The CWP is treated as a general, nonprismatic, stepped beam. In order to take into consideration all properties of such a complex beam, the line solution method is used to solve the general first-order simultaneous equations which are more complete and accurate than a single fourth-order beam equation.

No attempt is made here to fully describe the methodology, since this is done in Reference 2, which is generally available. Rather, an extended summary of the method is provided so that the reader can understand the basic approach, techniques, capabilities and limitations of the methods. For further details the reader is referred to References 2 and 13.

3.1 Basic Assumptions in Formulating Problem

The analytical method and the computer program are based on the following assumptions:

1. The CWP deflections are sufficiently small so that linear beam theory is valid and the principle of linear superposition is applicable.

Based on calculated results for several very flexible cold water pipes it seems that most or all practical CWPs will fall within this limit of applicability.

2. The interaction of the bending, torsional, and axial deformation can be neglected.

These interactions have been shown to be negligible by Chang (2).

3. The terms which arise from the fact that damping and inertia forces are not proportional when CWP diameter is not constant can be neglected.

This has been shown to be the case in similar problems such as that of a pipe conveying fluid, as discussed by Chang (2).

3.2 General Method of Approach

The behavior of a general beam section can be expressed by a set of four first-order simultaneous partial differential equations. This set of four equations can be reduced to two second-order simultaneous partial differential equations or to one fourth-order partial differential equation by neglecting some of the terms when these terms are not important.

The fourth-order equation has been used in Reference 2 for illustration of the method and for parameter study. For numerical computation, however, the first-order equations are more convenient and more accurate than the fourth-order equation.

This set of first-order equations is solved explicitly by the approach of transfer matrices. The general mathematical procedure for the solution is discussed in detail in Reference 13. A representative transfer matrix used for the CWP is included in Appendix A.

An individual transfer matrix is formulated and used for each different section and different CWP attachment or support. The responses, specifically the state variables of the CWP, are obtained by solving the global simultaneous equations by the line solution approach of Reference 13. This approach is much simpler than the Gauss' elimination scheme even for problems with narrow-banded coefficient matrices. The reduction of the number of mathematical operations makes this methos both more economical in terms of computer time and more accurate.

3.3 Formulation of the CWP Bending Problem

The general differential equations for CWP beam bending are adapted directly from Reference 2 with some modification in the generalized forcing function to facilitate computer programming of the method.

3.3.1 Static Behavior - Eliminating the terms associated with inertia and damping forces, the equations governing the CWP static behavior are obtained.

$$\begin{cases} \dfrac{\partial v}{\partial z} = -\theta + \dfrac{H}{GA} \\[2ex] \dfrac{\partial \theta}{\partial z} = \dfrac{M}{EI} \\[2ex] \dfrac{\partial M}{\partial z} = H + (N - m_i V^2)\theta - b \\[2ex] \dfrac{\partial H}{\partial z} = -f \end{cases} \qquad [1]$$

3.3.2 Dynamic Behavior - For dynamic response in the frequency domain the beam bending equations are given by:

$$\begin{aligned} \frac{\partial v}{\partial z} &= -\theta + \frac{H}{GA} \\ \frac{\partial \theta}{\partial z} &= \frac{M}{EI} \\ \frac{\partial M}{\partial z} &= H + (N - m_i V^2)\theta + C_o \frac{\partial \theta}{\partial t} + I_o \frac{\partial^2 \theta}{\partial t^2} - b_c \cos \omega t - b_s \sin \omega t \\ \frac{\partial H}{\partial z} &= (m_p + m_i + m_a)\frac{\partial^2 v}{\partial t^2} - 2m_i V \frac{\partial \theta}{\partial t} + C \frac{\partial v}{\partial t} - f_c \cos \omega - f_s \sin \omega t \end{aligned} \qquad [2]$$

This equation can be written in matrix form as

$$S' = KS + \overline{M}\ddot{S} + D\dot{S} + Q \qquad [3]$$

where

$S = \{v, \theta, M, H\}$ is the state variable matrix

$$\dot{S} = \frac{\partial S}{\partial t}, \quad S' = \frac{\partial S}{\partial z}, \quad \ddot{S} = \frac{\partial^2 S}{\partial t^2}$$

$$K = \begin{Bmatrix} 0 & -1 & 0 & \frac{1}{GA} \\ 0 & 0 & \frac{1}{EI} & 0 \\ 0 & N - m_i V^2 & 0 & 1 \\ 0 & 0 & 0 & 0 \end{Bmatrix}$$

$$\overline{M} = \begin{Bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & I_o & 0 & 0 \\ m_p + m_i + m_a & 0 & 0 & 0 \end{Bmatrix}$$

$$D = \begin{Bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ C & -2m_i V & 0 & 0 \end{Bmatrix}$$

$$Q = \{ 0 \quad 0 \quad -b \quad -f \}$$

$$b = b_c(z) \cos \omega t + b_s(z) \sin \omega t$$

$$f = f_c(z) \cos \omega t + f_c(z) \sin \omega t$$

ω is the excitation frequency.

and where

A	shear area of the CWP.
b, b_c, b_s	exciting moment, $b = b_c \cos \omega t + b_s \sin \omega t$.
C_o, C	damping coefficients associated with angular and translational velocities.
f, f_c, f_s	exciting force, $f = f_c \cos \omega t + f_s \sin \omega t$.
H	shear force of CWP.
M	bending moment of CWP.
m_a, m_i, m_p	added mass, the mass of the internal flow, and the mass of the CWP.
I	moment of inertia of CWP.
N	axial force of CWP.
E	modulus of elasticity.
G	shear modulus of elasticity.
θ	slope of CWP.
v	deflection of CWP.
z	coordinate along the CWP axis.
ω	the excitation frequency
ω_n	the natural frequencies of CWP associated with the nth node.
V	velocity of the internal flow.

3.4 Solution of the CWP Bending Problem

3.4.1 Static CWP Behavior - The static beam equation can be expressed as

$$S' = KS + Q \qquad [4]$$

Taking the Laplace transform of Equation [4] yields

$$s\bar{S}(s) = \bar{S}(o) + K\bar{S}(s) + \bar{Q}(s)$$

which upon collection of terms in s becomes

$$\bar{S}(s) = [sI - K]^{-1}[\bar{S}(o) + Q(s)] \qquad [5]$$

where s is the Laplace transform variable. Taking the inverse transform of [5] provides

$$S(z) = \mathcal{L}^{-1}[sI - K]^{-1}[\bar{S}(o) + \bar{Q}(s)] \qquad [6]$$

or

$$S(z) = U(z,o)\, S(o) + F(z) \qquad [7]$$

where

S(z) is state variable vector at z.
S(o) is state variable at z = 0.
F(z) is vector associated with the force.
U(z,o) is transfer matrix between z and o.

Consider, as an example, a simple beam subjected to uniform force with $\frac{H}{GA} = N = V^2 = b = 0$ and $f = q$. In this case Equation [7] can be written:

$$\begin{bmatrix} v \\ \theta \\ M \\ H \end{bmatrix}_z = \begin{bmatrix} 1 & -z & -\frac{z^2}{2EI} & -\frac{z^3}{6EI} \\ 0 & 1 & \frac{z}{EI} & \frac{z^2}{EI} \\ 0 & 0 & 1 & z \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} v \\ \theta \\ M \\ H \end{bmatrix}_o + \begin{bmatrix} \frac{qz^4}{24EI} \\ -\frac{qz^3}{6EI} \\ -\frac{1}{2}qz^2 \\ -qz \end{bmatrix} \qquad [8]$$

Equation [8] can be rewritten in a more convenient form as follows:

$$\begin{bmatrix} v \\ \theta \\ M \\ H \\ 1 \end{bmatrix}_z = \begin{bmatrix} 1 & -z & -\frac{z}{2EI} & -\frac{z}{6EI} & -\frac{qz^4}{24EI} \\ 0 & 1 & \frac{z}{EI} & \frac{z}{2EI} & -\frac{qz^3}{6EI} \\ 0 & 0 & 1 & z & -\frac{1}{2}qz^2 \\ 0 & 0 & 0 & 0 & -qz \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix}_o \begin{bmatrix} v \\ \theta \\ M \\ H \\ 1 \end{bmatrix} \qquad [9]$$

This five by five matrix is called the extended transfer matrix and the vector is called the extended state variable vector. In matrix form Equation [9] is

$$S(z) = U(z,o)S(o) \qquad [10]$$

In the following discussion in this report, the symbols S and U are used for the extended state variable vector and extended transfer matrix of the types defined in Equation [10].

For a cold water pipe with n sections the relation of equation can be expressed as follows:

$$\begin{aligned} S(z_1) &= U(z_1, o)S(o) \\ S(z_2) &= U(z_2, z_1)S(z_1) = U(z_2, z_1)U(z,o)S(o) \\ &\text{----------} \\ S(z_n) &= U_n U_{n-1} \ldots U_1 S(o) \end{aligned} \qquad [11]$$

or

$$S_n = \bar{U} S_o$$

where

$$S_n = S(z_n), \quad S_o = S(o)$$

$$\bar{U} = U_n U_{n-1} \ldots U_1$$

$$U_n = U(z_n, z_{n-1})$$

$$Si = U_i U_{i-1} \ldots U_1 S(o), \quad i=1,\ldots,n$$

$\bar{U}$ is called the global transfer matrix and U_n is called the transfer matrix between station n and n-1.

From these equations it can be seen that the unknown variables at stations 2 to n-1 have been eliminated by the products of the transfer matrices.

The above procedure can be illustrated by an example in which a uniform CWP is subjected to uniform force due to the slow motions of the OTEC platform. If CWP deflections are small and thus the effects of CWP weight can be neglected, Equation [9] can be used directly. The global matrix is independent of the number of CWP sections due to the absence of variable axial load. If the upper end of the CWP is assumed to be clamped and the lower end is assumed to be free:

$$v(o) = \theta(o) = 0$$

$$M(L) = H(L) = 0$$

From Equation [9] :

$$\begin{bmatrix} M(L) \\ M(L) \end{bmatrix} = \begin{bmatrix} 1 & L & -\frac{1}{2}qL^2 \\ 0 & 1 & -qL \end{bmatrix} \begin{bmatrix} M(o) \\ M(1) \\ 1 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix}$$

or

$$\begin{bmatrix} 1 & L \\ 0 & 1 \end{bmatrix} \begin{bmatrix} M(o) \\ H(o) \end{bmatrix} = \begin{bmatrix} \frac{1}{2}qL^2 \\ qL \end{bmatrix}$$

$$M(o) = -\tfrac{1}{2}qL^2$$
$$H(o) = qL$$

Substitute v(o), θ(o), M(o), H(o) into [9] we have

$$\begin{cases} v(z) = \frac{qL^2}{4EI}z^2 - \frac{qL}{6EI}z^3 + \frac{qz^4}{24EI} \\ \theta(z) = -\frac{qL^2}{2EI}z + \frac{qL}{2EI}z^2 - \frac{qz^3}{6EI} \\ M(z) = -\tfrac{1}{2}qL^2 + qLz - \tfrac{1}{2}qz^2 \\ H(z) = q(L - z) \end{cases} \qquad [12]$$

In general the weight of the cold water pipe is quite important and cannot be neglected. In such cases the global matrix is quite complicated and cannot be expressed in simple terms. For such problems computer program must be used for the prediction of the CWP response.

3.4.2 Dynamic CWP Behavior - The solution for dynamic behavior is much more complicated than the static solution. A general solution of Equation [2] for each section of the cold water pipe is necessary. Such a solution cannot be expressed in one transfer matrix. Rather a set of 12 transfer matrices depending on the properties of the CWP are required. Those matrices are given in Reference 13. Note that the beam element stiffness matrix required in the finite element analysis can be obtained from the transfer matrix. In most general purpose finite element computer programs only one stiffness matrix is given for the beam element. The line solution approach is theoretically

more accurate than such a finite element approach.

The dynamic solution can be described in terms of the type of excitation. Three cases are discussed below, although only two, free vibrations and forced, harmonic vibrations are considered in detail.

3.4.2.1 Free Vibration - Omitting the damping and excitation force terms in Equation [3] produces the equation for undamped vibrations.

$$S' = KS + \overline{M}\ddot{S} \qquad [13]$$

Assuming harmonic vibrations of frequency ω and thus that

$$S = S \sin \omega t$$

Equation [13] becomes:

$$\overline{S} = (K - \overline{M}\omega^2)S \qquad [14]$$

Solution of Equation [14] provides an infinite set of eigenvalues and eigenvectors, ω_n and S_n which satisfy the given boundary conditions and the conditions:

$$S_n = (K - \overline{M}\omega_n{}^2)S_n \qquad [15]$$

Where ω_n and $S_n(z)$ are the natural frequency and modeshape for the n mode and for the given boundary conditions. For typical CWPs, which are lightly damped in all modes, the actual natural frequencies are the same, although motion amplitudes are different and maximum response will not occur at the natural frequency.

3.4.2.2 Forced Vibration - Assuming a solution of the form

$$S(z,t) = \sum A_n S_n(z) \cos(\omega t - \phi_n) \qquad [16]$$

substituting Equation [16] into [3] and using the relation of Equation [15] yields:

$$\sum A_n \left\{ (\omega_n{}^2 - \omega^2)\overline{M}S_n \cos(\omega t - \phi_n) \right. - \sum A_n \omega D S_n \sin(\omega t - \phi_n) = Q_c \cos \omega t + Q_s \sin \omega t \qquad [17]$$

where

$$Q_c = \left\{ 0,\ 0,\ b_c,\ f_c \right\}$$
$$Q_s = \left\{ 0,\ 0,\ b_s,\ f_s \right\}$$

Equation [17] represents a set of four simultaneous equations. Multiply the third equation of [17] by θ_m and the fourth equation of [17] by v_m and integrate over the whole length of the cold water pipe yields:

$$\sum A_n \left[(\omega_n{}^2 - \omega^2) N_{mn} \cos(\omega t - \phi_n) - \omega D_{mn} \sin(\omega t - \phi_n) \right] = F_m \qquad [18]$$

$$N_{mn} = \int_o^L \left[I_o \theta_n \theta_m + (m_i + m_p + m_a) v_n v_m \right] dz$$

$$D_{mn} = \int_o^L \left[C_o \theta_n \theta_m + C v_n v_m - 2 m_i V v_n \theta_m \right] dz$$

$$F_m = F_{cm} \cos \omega t + F_{sm} \sin \omega t$$

$$F_{cm} = \int_o^L (b_c \theta_m + f_c v_m) dz$$

$$F_{sm} = \int_o^L (b_s \theta_m + f_s v_m) dz$$

In Equation [18] the values of A_n for various modes are coupled by the terms associated with the damping. The coupling terms are usually neglected because the ratio of damping to total mass is usually nearly constant of the CWP length and hence their effect is quite small, as has been discussed in Reference 2. Note that if the damping is everywhere proportional to mass, all the coupled terms are zero except those associated with the internal flow. It is more practical to consider the actual damping as predicted by the hydrodynamic theory and to neglect the coupled terms than to assume proportional damping. In this case

$$A_n(\omega^2 - \omega_n^2)N_{nm} \cos(\omega - \phi_n) - \omega D_{nm} \sin(\omega - \phi_n)$$

$$= F_{cm} \cos \omega t + F_{sn} \sin \omega t \qquad [19]$$

Collecting the terms associated with cos ωt and sin ωt provides two equations with two unknowns, A_n and ϕ_n. Solving for A_n and ϕ_n yields

$$\phi_n = \tan^{-1} \frac{\mu_n \omega f_{nc} + (\omega_n^2 - \omega^2) f_{ns}}{(\omega_n^2 - \omega^2) f_{nc} - \mu_n \omega f_{ns}} \qquad [20]$$

$$A_n = \frac{\sqrt{f_{nc}^2 + f_{ns}^2}}{\sqrt{(\omega_n^2 - \omega^2)^2 + \mu_n^2 \omega^2}} \qquad [21]$$

where

$$f_{ns} = \frac{F_{cn}}{N_{nm}}, \quad f_{ns} = \frac{F_{sn}}{N_{nm}}$$

$$\mu_n = \frac{D_{nn}}{N_{nm}}$$

Substituting Equation [21] into Equation [16]

$$S(z,t) = \sum \frac{\sqrt{f_{nc}^2 + f_{ns}^2}\cos(\omega t - \phi_n)}{\sqrt{(\omega_n^2 - \omega^2)^2 + \mu_n^2\omega^2}} S_n(z) \qquad [22]$$

3.4.2.3 Transient or Non-Harmonic Vibration - For non-harmonic vibrations which must be analyzed in the time domain the above procedure can also be used, except that a more general, non-harmonic modeshape must be used. Such a modeshape can be defined by:

$$S(z,t) = \sum A_n(t) S_n(z) \qquad [23]$$

Substituting this expression into Equation [3] provides

$$\sum \left\{ \bar{M}\omega_n^2 A_n(t) + D\dot{A}_n(t) + \bar{M}\ddot{A}_n(t) \right\} S_n(z) = F(z,t)$$

This expression can be used together with the result:

$$F\ (t) = \frac{\int_0^L F(z,t)V_n(z)dz}{N_{nm}}$$

To provide a solution for the modal response of the CWP:

$$\ddot{A}_n(t) + \mu_n\dot{A}_n(t) + \omega_n^2 A_n(t) = F_n(t) \qquad [24]$$

Equation [24] can be solved explicitly. Substituting $A_n(t)$ back to Equation [23] the CWP responses can be obtained. The present study does not include this solution however. It can be seen from this brief analysis that it is not difficult to extend the present methods and computer program to time domain solutions of the CWP responses.

3.5 Solution of CWP Torsion and Extension Problems

The solutions of CWP torsion and extension (longitudinal motions) problems is similar to but simpler than bending problems. In general the damping force due to twisting and extension is quite small. For this reason only the undamped solution is considered in the computer programs.

3.5.1 CWP Differential Equations

Torsion of the Cold Water Pipe:

$$\frac{\partial \phi}{\partial z} = \frac{T}{GI_p}$$

$$\frac{\partial T}{\partial} = I_a \frac{\partial^2 \phi}{\partial t} + C_T \frac{\partial \phi}{\partial t} - P(z,t) \qquad [25]$$

Extension of Cold Water Pipes:

$$\frac{\partial w}{\partial z} = \frac{N}{AE}$$

$$\frac{\partial N}{\partial z} = (m_p + m_z) \frac{\partial^2 w}{\partial t^2} + C_z \frac{\partial w}{\partial t} - mg - f_z \qquad [26]$$

where

ϕ is twisting angle.
T is torque.
G is shear modulus of elasticity.
I_p is polar moment of inertia of CWP.
I_a is mass polar moment of inertia of CWP.
C_T is torsional damping coefficient.
P is excitation.
w is extension or longitudinal displacement.
N is axial force.

E is modulus of elasticity.
m_p, m_a are mass and added mass of CWP.
A is sectional area.
C_z is vertical damping coefficient.
f_z is excitation force.
mg is buoyant weight of CWP.

Upon examination of these equations it is obvious that Equations [25] and [26] are identical if the following parameters are interchanges:

$$N \longrightarrow T$$
$$E \longrightarrow G$$
$$A \longrightarrow I_p$$
$$m_p + m_z \longrightarrow I_a$$
$$C_z \longrightarrow C_T$$
$$mg - f_z \longrightarrow P(z,t)$$

For this reason only one solution is required for both problems.

3.5.2 <u>The Undamped Solution</u> - Let the excitation and the resulting response be

$$P(z,t) = P(z) \cos \omega t \qquad [27]$$

$$\begin{bmatrix} \phi(z,t) \\ T(z,t) \end{bmatrix} = \begin{bmatrix} \phi(z) \\ T(z) \end{bmatrix} \cos \omega t \qquad [28]$$

Substituting Equations [27] and [38] into [25] yields:

$$\begin{cases} \dfrac{d}{dz} = \dfrac{T}{GI_p} \\ \\ \dfrac{dT}{dz} = -I_a \omega^2 \phi - P \end{cases} \qquad [29]$$

The transfer matrix for this equation is

$$\begin{Bmatrix} \phi \\ T \\ 1 \end{Bmatrix}_z = \begin{bmatrix} \cos \beta z & \frac{\sin \beta z}{GI_p \beta} & F_\phi \\ -I_p G\beta \sin \beta z & \cos \beta z & F_T \\ 0 & 0 & 1 \end{bmatrix} \begin{Bmatrix} \phi \\ T \\ 1 \end{Bmatrix}_o \qquad [30]$$

where

$$F_\phi = -P_o \frac{1 - \cos \beta z}{GI_p \beta^2} - P' \frac{\beta z - \sin \beta z}{GI_p \beta^3}$$

$$F_T = -P_o \frac{\sin \beta z}{\beta} - P' \frac{1 - \cos \beta z}{\beta^2}$$

$$\beta = \frac{\omega^2 I_a}{GI_p}$$

$$P(z) = P_o + P'z$$

With the transfer matrix, the computation procedure follows that of the bending problems as described in Section 3.4.

3.5.2 <u>The Static Solution</u> - Omitting the inertia and damping terms in Equation [25] yields

$$\begin{cases} \frac{d}{dz} = \frac{T}{GI} \\ \frac{dT}{dz} = -P(z) \end{cases} \qquad [31]$$

The transfer matrix for this equation is

$$\begin{Bmatrix} \phi \\ T \\ 1 \end{Bmatrix}_z = \begin{bmatrix} 1 & \frac{z}{GI_p} & F_\phi \\ 0 & 1 & F_T \\ 0 & 0 & 1 \end{bmatrix} \begin{Bmatrix} \phi \\ T \\ 1 \end{Bmatrix}_o \qquad [32]$$

$$F_\phi = -\frac{1}{GI_p}\left(P_o \frac{z^2}{2} + P' \frac{z^2}{6}\right)$$

$$F_T = -\left(P_o z + P' \frac{z^2}{2}\right)$$

$$P(z) = P_o + P'z$$

The computational procedure again follows that outlined for bending in Section 3.4.

4.0 ANALYSIS OF CWP STATIC AND DYNAMIC RESPONSE

The methods described in Section II provide a means for analyzing the response of a CWP of specified structural and hydrodynamic characteristics to specified static and/or dynamic loadings. In order to analyze the responses of a given CWP design, it is necessary to suitably characterize the structural characteristics, hydrodynamic characteristics and loadings of the CWP. Each of these areas is discussed in this section.

4.1 General Types of CWP Considered

The methods developed in this study are applicable to the analysis of four basic CWP types or concepts, defined by NOAA:

- Rigid wall CWP with or without flexible joints.
- Compliant CWP.
- Stockage CWP.
- Bottom mounted buoyant CWP.

These types or concepts are described briefly below.

4.1.1 Rigid Wall CWPs - These are CWPs made of relatively rigid elastic materials such as steel, aluminum, reinforced concrete or glass-reinforced plastic (GRP). The CWP can be prismatic (constant cross-section geometry) or may have stepwise variations in cross-section properties (wall thickness, material elasticity, etc.) and can have flexible joints at a number of arbitrary points along the CWP length. These joints, if used, are assumed to have a specified rotational and/or axial stiffness. Generally the joints will be assumed to have freedom only in rotation. Materials such as reinforced concrete are treated as orthotropic materials having different properties in the longitudinal and circumferential directions.

4.1.2 Compliant CWPs - These are assumed to be CWPs with small bending and axial stiffness. These CWPs are generally made of a very compliant or low modulus of elasticity material such as reinforced elastomers or polyethylene. Because of the low inherent CWP stiffness, it is unlikely that the CWP will have flexible joints. The CWP may, however, have stepwise variations in cross-sectional properties. The CWP material must be assumed to act in as an elastic material, although materials such as polyethylene may have non-linear (plastic) behavior for strains of interest. In such cases, appropriate linear or equivalent linearized material properties must be used.

With composite structures, such as those with reinforced elastomers, a set of equivalent orthotropic properties must be determined. Methods for determining these properties are considered in Section 4.3 but are not incorporated in the computer programs.

4.1.3 Stockade CWPs - The stockade CWP concept is an attempt to simplify CWP construction, Anderson (10). The CWP consists of a large ring of small pipes as shown in Figure 4.1. The diameter of these small pipes is, typically, two to five percent of overall CWP diameter. The individual pipes are rigidly connected, so that the entire structure acts as a thin wall CWP.

The rather specialized structure of the stockade CWP can be represented by a thin wall isotropic pipe having a set of equivalent properties. Assuming that all components are made of the same material and that all longitudinal members are continuous and fully effective, the following equivalent CWP properties can be defined:

$$D_{p_e} = D_c + d_p$$

$$A_e = n(a_p + a_{cc} + a_{ci})$$

$$t_{w_e} = \frac{A_e}{\pi(D_{p_e} - t_{w_e})} \cong \frac{A_e}{\pi D_{p_e}} \qquad [33]$$

$$I_e = \frac{A_e}{8}\left[D_{p_e}^{\,2} - \frac{4}{\pi} A_e\right] \cong \frac{A_e D_{p_e}^{\,2}}{8}$$

$$E_e \cong E \frac{n(a_p + a_{cc})\, D_{p_e}^{\,2}}{8\, I_e}$$

where

D_{p_e} is equivalent CWP outside diameter

A_e is equivalent CWP cross-sectional area

t_{w_e} is equivalent CWP wall thickness

I_e is equivalent CWP moment of inertia

E_e is equivalent CWP modulus of elasticity

D_c is small pipe centerline diameter

d_p is small pipe outside diameter

n is number of small pipes

a_p is small pipe cross-sectional area

a_{cc} is small pipe connection continuous area

a_{ci} is small pipe connection interrupted area

E is material modulus of elasticity.

These equivalent characteristics are used as inputs to the CWP program, in the same way as the equivalent properties for more complex structures discussed in Section 4.3.

4.1.4 Bottom Mounted, Buoyant CWP - These CWPs have an attachment between the ocean floor and the bottom of the CWP which typically places most or all of the buoyant CWP in tension. Typically this attachment will consist of one or several vertical cables under tension, as shown in Figure 4.2a. This attachment will provide both vertical and lateral restraint to the bottom of the CWP. Where the distance from the bottom of the CWP to the ocean floor is small, say a few hundred feet or less, rigid links rather than cables may be used as the attachment.

If a rigid link attachment is used, it is probably appropriate to treat this link as a segment of the CWP having appropriate geometric and structural properties. The lower end of this link would have infinite spring attachment stiffnesses in surge, sway and heave and appropriate stiffnesses in roll and pitch (typically zero). Treatment of cable moorings are discussed in Section 4.4.

4.2 CWP Geometric and Structural Characteristics

In this study certain limitations have been placed on allowable CWP geometric and structural characteristics, including:

1. All CWP cross-sections are circular and remain invariant under CWP loading.
2. The CWP has a continuous, impermeable surface from intake to platform attachment.
3. The CWP material(s) are elastic and are isotropic or orthotropic. For orthotropic materials, one set of properties apply to the axial direction, the other to

the plane of the CWP cross-sections.

4. For complex CWP structures, such as shown in Figure 4.3, an equivalent structure must be defined. This equivalent structure consists of a cylindrical shell having appropriate values of:
   - Diameter
   - Cross-sectional area or wall thickness
   - Cross-sectional moment of inertia
   - Modulus of elasticity
   - Material density
5. Ring stiffness or other circumferential members contribute to buckling and ovalling strength but not to axial or bending strength.
6. The CWP can have changes, at a number of points along its length, in all important geometric and material properties.
7. The CWP can have attached masses, buoyancies and/or spring stiffnesses (moorings) at a number of points along its length.

Methods for treating complex structures are discussed in Section 4.3 and, for the relatively well defined geometry of the stockade CWP, in Section 4.1.3.

The allowable characteristics and treatment of the CWP/platform attachment are discussed in Section 5.3. The characteristics and treatment of CWP bottom moorings or other moorings attached to the CWP are discussed in Section 4.4.

4.3 Definition of Equivalent CWP Properties

Section 4.1.3 provides a methodology for determining the equivalent CWP properties required as input to the CWP structural analysis for a single, rather specialized and well defined CWP type. It is necessary to have methods for determining the required equivalent CWP properties for an arbitrary, complex

CWP design. Such methods are provided in this section. For certain designs other methods or approaches may be more suitable. A general approach to estimating equivalent properties is given in this section.

It is desirable to select the equivalent parameters so that both CWP structural and hydrodynamic characteristics are correct. In general this requires correct specification of all of the following parameters

- Effective outside diameter
- Inside diameter
- Cross-sectional bending moment of inertia
- Cross-sectional area
- Effective CWP material density
- Effective CWP modulus of elasticity

The first two parameters determine CWP hydrodynamic characteristics while the last four parameters determine CWP structural characteristics.

In the following sections emphasis is placed on proper determination of CWP structural characteristics. The effective CWP outside diameter should be equal to the envelope of CWP longitudinal meterial, as shown in Figure 4.3a, since this envelope gives the correct maximum fiber distance and gives the best approximation of CWP hydrodynamic damping and external added mass. The mass of fluid within the CWP will be correctly estimated, however, only if the correct CWP inside diameter is used.

4.3.1 Determination of Equivalent CWP Sectional Properties - For cold water pipe the two most important properties are the cross-sectional moment of inertia and sectional area. If a CWP section is made of n longitudinal pieces of materials the equivalent cross-sectional area A_e and moment of inertia about the CWP centerlinear global neutral axis, I_e, can be determined

from the following equations:

$$A_e = \sum_{i=1}^{n} A_i \frac{E_i}{E_o} \qquad [34]$$

$$I_e = \sum_{i=1}^{n} (I_i + \bar{y}_i^2 A_i) \frac{E_i}{E_o} \qquad [35]$$

where

A_i, E_i are the cross-sectional area and modulus of elasticity of the ith piece of material.

I_i is the moment of inertia of the ith piece of material about an axis parallel to the global neutral axis and through its own center of gravity.

y_i is the distance from the global neutral axis to the center of gravity of the ith piece of material.

E_o is the bending or Young's modulus of elasticity assumed for the complete structure. It will, typically, be the modulus of elasticity of the major piece or pieces of the CWP structure.

Consider as an example a sandwich type of pipe wall such as shown in Figure 4.3b. Let the pipe be made of two concentric steel cylinders or shells separated by GRP. If the outside diameter is D, the thickness of the outer, middle and inner sections are t_1, t_2, t_3 respectively, then:

$$A_e = \frac{\pi}{4} \Big[4Dt_1 - t_1^2 + 4(D - 2t_1 - 2t_2)t_3 - t_3^2 + \{4(D - 2t_1)t_2 - t_2^3\} \frac{E_p}{E_s} \Big]$$

$$I_e = \frac{\pi}{64}\left[8D^3t_1 - 24D^2t_1^2 + 8(D-2t_1-2t_2)^3 t_3 - 24(D-2t_1-2t_2)^2 t_3^2\right]$$
$$+ \{8(D-2t_1)^3 t_2 - 24(D-2t_1)^2 t_2^2\}\frac{E_p}{E_s}$$

where

E_s and E_p are steel and GRP modulii of elasticity,

and the standard modulus of elasticity, E_o, is that of the steel, E_s.

4.3.2 The Continuation and Bond of Different CWP Component Pieces- Equations [34] and [35] are valid only if all the pieces of materials are continuously bonded together for the whole CWP sections length considered, and only if bond strength is greater than the largest shear force occurring between these pieces. For some stockade CWPs where the small pipes are loosely held together or are connected only at some particular points, the above equations are not entirely valid. Using these equivalent properties can lead to underestimation of CWP responses.

For interrupted pieces such as shown in Figure 4.3, the proper treatment is to define one CWP section for each length of piece attachment and for each length of piece interruption. For a large number of pieces and interruptions, it is probably appropriate to neglect the pieces entirely, since bending will be governed by the stiffness of interrupted sections.

4.3.3 Non-Longitudinal CWP Component Pieces - Equations [34] and [35] are valid only for component pieces whose axis is parallel to the CWP global or longitudinal axis. When members are at an angle to this CWP global axis their contribution to A_e and I_e is reduced. The contribution of such members will depend on the exact details of the CWP structure, and no general guidance can be given. As noted earlier, the effect of all circumferential members on A_e and I_e is neglected.

4.4 CWP Moorings and Restraints

Any CWP moorings, restraints or connections to the OTEC platform and for other bodies such as buoys, must be considered in analyzing CWP behavior. Connection of the CWP to the OTEC platform is considered in Section 5.4 In this section the treatment of CWP moorings and connections to bodies other than the platform, are considered.

Figure 4.2 shown three typical cases which may need to be analyzed. In each case the approach is to represent the mooring or connection by vertical and/or horizontal linear springs. Since mooring lines and connections at an angle to the direction of motion generally have non-linear characteristics it is necessary to make some approximations and to use stiffnesses appropriate to typical displacements.

4.4.1 Vertical Bottom Moorings - For the bottom, vertical moorings of Figure 4.2a the appropriate horizontal and vertical spring stiffnesses, k_v and k_h are:

$$k_v = \frac{F_z}{z} \cong \bar{k}$$

$$k_h = \frac{F_x}{x} \cong \frac{\bar{T}}{\ell_m}$$

where

F_x and F_z are horizontal and vertical forces.

x and z are horizontal and vertical displacement of the bottom of the CWP.

$\bar{T}$ is mean tension.

$\bar{k}$ is mean mooring stiffness defined at the mean tension, as shown in Figure 4.4.

ℓ_m is mooring length at mean tension $\bar{T}$, equal to $(1+\varepsilon)$ time unloaded length.

The errors arising from these approximations will be significant only if the motions of the bottom of the CWP are significant (say typically 10 percent or more) compared to mooring length.

4.4.2 Non Vertical Moorings - For non-vertical heavy moorings attached at the bottom or along the sides of the CWP, Figures 4.2b, the approximate spring stiffnesses are

$$k_v \cong \left(\frac{dT}{dz}\right)_{\overline{T}} \cos \overline{\phi}$$

$$k_h \cong \left(\frac{dT}{dx}\right)_{\overline{T}} \sin \overline{\phi}$$

where

$(dT/dz)_{\overline{T}}$ and $(dT/dx)_{\overline{T}}$ are changes in tension due to unit vertical and horizontal displacements of the attachment point at mean tension $\overline{T}$.

$\overline{\phi}$ is mean mooring inclination to the vertical at the CWP.

In general, moorings will consist totally or in part of segments heavier than or lighter than water. Analysis of such moorings requires solution of cable equations. There are a number of methods for calculating the values of $\overline{T}$, $\overline{\phi}$, dT/dz and dT/dx for catenary or buoyant moorings. The method of Cuthill (14) is well known. It can be used for simple or complex moorings with or without current, and is recommended for use in calculating $\overline{T}$, $\overline{\phi}$, dT/dz and dT/dx.

It should be noted that vertical and horizontal motions of the attachment point will produce additional horizontal and vertical forces, respectively. The CWP analysis methods do not, however, treat cross-coupling of vertical and lateral CWP motions and hence these mooring cross-coupling forces must be neglected.

4.4.3 Neutrally Buoyant, Non-Vertical Moorings - For neutrally buoyant moorings attached to the bottom or sides of the CWP, Figure 4.2c, the determination of spring stiffnesses is greatly simplified. The spring stiffnesses are given by the expressions in Section 4.4.2 where the values of dT/dz and dT/dx are determined from purely geometric considerations:

$$\left(\frac{dT}{dz}\right)_{\overline{T}} = \overline{k} \sin \overline{\phi}$$

$$\left(\frac{dT}{dx}\right)_{\overline{T}} = \overline{k} \cos \overline{\phi}$$

and where $\overline{k}$ is determined by the mooring line characteristics at mean tension $\overline{T}$, as defined in Figure 4.4.

4.4.4 Multi-Point Moorings - In some cases multi-point moorings having three or more mooring lines attached at a given depth will be used. Such an arrangement is shown in Figure 4.5. The total effective spring stiffnesses for horizontal motion in a given direction and for vertical motions are:

$$\frac{dT}{dx} \cong \sum_{n=1}^{N} \left(\frac{dT}{dx}\right)_n |\cos \alpha_n|$$

$$\frac{dT}{dz} = \sum_{n=1}^{N} \left(\frac{dT}{dz}\right)_n$$

where

α is angle between horizontal projection of mooring and direction of motion, x, Figure 4.5.

N is number of mooring lines, and

where n denotes the nth mooring line.

4.4.5 Connections to Other Bodies - Attachment of the CWP to bodies other than the platform will effect CWP response. Figure 4.2d shows a typical attachment to a floating buoy, a scheme proposed for several OTEC applications. The characterization of the effect of such attachments will depend on the specific geometry of the attachment. The treatment of a buoy support scheme proposed for use in the MINI-OTEC is discussed in some detail in Section 8.2.

4.5 CWP Hydrodynamic Forces

If the CWP is placed in a moving fluid, the motions of the fluid will induce forces on the CWP and these forces will produce CWP motions. Unsteady forces acting on the CWP will produce displacement, velocity and acceleration of the CWP. The displacement will produce hydrostatic forces while the velocity and acceleration will produce hydrodynamic forces which will tend to resist motions of the CWP.

The CWP hydrodynamic forces are characterized by a damping coefficient and an added mass. These forces are given, for a unit length of CWP by:

$$\frac{d\vec{F}_v}{dZ} = -C_h \vec{V}$$

$$\frac{d\vec{F}_a}{d3} = -m_a \dot{\vec{V}}$$

where

$\vec{F}_v$ and $\vec{F}_a$ are force vectors due to velocity vector $\vec{V}$ and and acceleration vector $\dot{\vec{V}}$.

C_h is damping coefficient.

m_a is added mass.

In this study it is assumed that there is one set of added mass and damping coefficients associated with CWP transverse motions and a second set associated with CWP axial or longitudinal motions.

In this section the determination of appropriate values of added mass and damping coefficient are discussed. The selection of these values is complicated by their dependence on Reynolds number, CWP roughness and the amplitude of motion, as discussed by Hove, et al (1) and Sarpkaya (15). The dependence on amplitude of motion is particularly difficult to define based on

available data.

In this section the following parameters are used:

$$R_{e_d} = \frac{VD}{\nu}$$

$$R_{e_k} = \frac{Vk}{\nu} = R_{e_d}\left(\frac{k}{D}\right)$$

$$K = \frac{2\pi a}{D}$$

where

R_{e_d} is Reynolds number based on diameter, D.
R_{e_k} is Reynolds number based on roughness height k.
K is Keulegan - Carpenter number or amplitude ratio based on amplitude of motion, a.
V is maximum velocity during an oscillation.
ν is kinematic viscosity of water.

4.5.1 <u>CWP Transverse Added Mass</u> - In previous CWP dynamic analyses by HYDRONAUTICS and other, the CWP added mass due to transverse flow around the CWP has been assumed equal to the mass of fluid displaced by the CWP. The mass per unit, m_a, is thus

$$m_a = \rho\pi D_o^2 C_m \equiv \rho\pi D_o^2$$

where

ρ is seawater mass density.
D_o is CWP outside diameter.
C_m is added mass coefficient $\equiv 1.0$.

Calculations such as those of Bai (16) have demonstrated that end effects and the free surface have a negligable effect on added mass for typical CWPs and that the added mass coefficient is essentially one in an ideal fluid. Data for rectilinear

accelerations of circular cylinders in real fluids also indicate that added mass coefficient is essentially one.

The only important CWP accelerations are those due to wave orbital accelerations and to the motions of the CWP induced by the waves. These accelerations, which are assumed to be harmonic, arise from fluid and CWP motions whose amplitudes are comparable to CWP diameter. Available data, such as those of Reference 15, indicate a dependence of inertia coefficient and added mass coefficient on the ratio of motion amplitude to diameter, or on the Keulegan-Carpenter number, K. From the results of Reference 15, inertia coefficients appear to be well defined for smooth cylinders and for rough cylinders with large amplitudes of motion ($K \geq 100$), but not well defined for rough cylinders with smaller motion amplitudes ($K < 100$).

Figures 4.6 and 4.7 show Sarpkaya's results for smooth cylinders and rough cylinders with $K \geq 100$. Figure 4.8 shows a summary and comparison of Sarpkaya's results for rough cylinders with $K \leq 100$. It should be noted that the inertia coefficient, C_m', for an accelerating flow field is related to the added mass coefficient for an accelerating body by

$$C_m = C_m' - 1.0$$

where

C_m is added mass coefficient for an accelerating body.
C_m' is inertia coefficient for an accelerating fluid.

It is difficult to accurately predict added mass coefficients for representative roughnesses ($10^{-5} \leq k/D \leq 10^{-3}$) and amplitudes ($K < 20$). It is perhaps desirable to use a value of 1.8 for C_m' or 0.8 for C_m for all rough and smooth CWPs.

In this study the water within the CWP is assumed to move with the CWP transverse motions and hence to contribute an

additional mass term, m_i, in Equation [2] , which might be considered as an added mass term. The value of m_i is given by

$$m_i = \frac{\pi}{4} D_i^2$$

where D_i is the CWP inside diameter.

4.5.2 CWP Transverse Hydrodynamic Damping - CWP hydrodynamic damping or velocity dependent force arises from the relative velocity between the fluid and CWP. The CWP moves with some velocity in an unsteady fluid velocity field due to ocean current and waves. The CWP and fluid transverse velocities vary with depth and time.

In earlier HYDRONAUTICS studies the hydrodynamic transverse damping was assumed to be linear. This was done both because the analysis methods were linear and because data available in 1975 for oscillating cylinders, Reference 17, indicated that drag was nearly linear for small values of the Keulegan-Carpenter number K. The newer data of Sarpkaya (15) shows that this is primarily true at the low Reynolds numbers of the Keulegan and Carpenter tests (17). At realistic CWP Reynolds numbers ($R_{e_d} > 10^6$) and for roughened cylinders, damping appears to be essentially quadratic and characterized by a drag coefficient C_D, where

$$\frac{dF_v}{dz} = \tfrac{1}{2}\rho V^2 D C_D$$

and where ρ is water mass density.

Figure 4.9 shows measured quadratic drag coefficients, C_D, for smooth circular cylinders from Reference 15. The results for oscillatory flow generally collapse, for Reynolds numbers greater than 10^6, to a drag coefficient of about 0.65. There is some indication, however, that drag coefficients at very high Reynolds numbers may increase somewhat as K is reduced from 40

to typical CWP values of about 5 to 20.

Figure 4.10 shows measured drag coefficients for rough cylinders, as a function of roughness Reynolds number, from Reference 15. These data are all for the most realistic roughness ratio (k/D = 1/800) considered in Reference 15. Data for other roughness generally collapse to the same curve for roughness Reynolds number greater than about five. For roughness Reynolds number greater than about 5000, drag coefficients appear to become independent of Reynolds number and to have values between 1.23 and 1.34. Cross-plots of drag coefficient as a function of k indicate that there may be a rapid rise in drag coefficient as k decreases below 20. Data for these values of k are clearly needed.

It is probably conservative to use the drag curve for k = 20 for most CWP analyses, or to use a drag coefficient of 1.3 for all roughness Reynolds numbers greater than 3000. This drag coefficient is significantly larger than typical drag coefficients for steady flow over rough clyinders (see Section 4.6).

If CWP velocity dependent transverse force is assumed to be proportional to velocity, then:

$$\frac{d\vec{F}_v}{dz} = C_h(\vec{v}_w + \vec{V}_c + \vec{v}) = C_h\vec{v}_w + C_h\vec{V}_c + C_h\vec{v} \qquad [36]$$

where

$\frac{dF_v}{dz}$ is force vector per unit CWP length.

C_h is damping coefficient.

$\vec{v}_w$ is wave velocity

$\vec{V}_c$ is current velocity.

$\vec{v}$ is body velocity.

The first term, $C_h\vec{V}_w$, in Equation [36] is not a damping term, but rather part of the wave exciting force. The second term, $C_h\vec{V}_c$, is a current loading term. Only the last term is a true damping term.

If the CWP velocity dependent force is assumed to be proportional to the square of velocity, then

$$\vec{F}_v = C_h(\vec{v}_w + \vec{V}_c + \vec{v})\,|\,\vec{v}_w + \vec{V}_c + \vec{v}\,| \qquad [37]$$

The damping coefficient, C_h, is related to the quadratic drag coefficient by

$$C_h = \tfrac{1}{2}\rho C_d D$$

If current velocity is assumed to be constant and positive, Equation [37] can be written as

$$F_v = C_h\left[V_c^2 + (\vec{v}_w + \vec{v})|v_w + v| + V_c\vec{v}_w + V_c\vec{v} + V_c|v_w + v|\right] \qquad [38]$$

The first term of Equation [38] is the current load, the second term is a combined wave loading/damping term and the last three terms are interaction terms. The second term can be replaced by an equivalent linearized term [see for example, Minorski(18)]:

$$C_h(\vec{v}_w + \vec{v})|v_w + v| = \frac{8}{3\pi}\,C_h a\omega\vec{v}_w + \frac{8}{3\pi}\,C_h a\omega\vec{v} \qquad [39]$$

where

- a is amplitude of relative motion between the CWP and fluid particles, $a\omega$ is relative velocity of motion.
- ω is wave and body frequency.

The first term of Equation [39] is again part of the wave exciting force while the second term is a damping term. This damping term does depend, through a, on the wave orbital velocity.

The first interaction term of Equation [39] represents an increase in wave exciting force due to current, the second interaction term an added linear damping due to current. The last term is a non-harmonic term. In the present analysis all of these

interaction terms have been neglected, although the term

$$C_h V_c \vec{v}$$

may be considered through a proper choice of an equivalent damping coefficient, C_h'

$$C_h' = C_h(\frac{8}{3\pi} a\omega + V_c)$$

The effect of current velocity on damping is probably small except near the surface or for cases where current surface velocities are much greater than wave surface velocities. It should be noted that the damping coefficients for steady flow and oscillatory flow are different.

4.5.3 CWP Longitudinal Hydrodynamic Forces - The CWP longitudinal hydrodynamic forces are generally much smaller than transverse hydrodynamic forces and can, in many cases, be neglected. Longitudinal added mass and damping will arise primarily from ring stiffeners, discontinuities in CWP outside diameter or attachments to the top, bottom or outside of the CWP. It is not possible to give general methods for estimating these forces.

For CWPs having constant diameter and no exposed external structure, CWP added mass will be due entirely to attachments such as intake screens. For such CWPs damping will be that due to CWP skin friction, which is very small, plus that due to any attachments.

If external exposed structure such as ring stiffeners (see Figure 4.3) are used, the added mass and damping due to this structure may be significant. The added mass of a single ring stiffener can be determined by treating the stiffener as a flat plate:

$$m_z = \frac{\pi^2}{2} w_s^2 D C_{ms}$$

where

m_z is the longitudinal added mass per stiffness.

w_s is the exposed stiffener width.

Stiffener spacing will probably be sufficiently large to avoid hydrodynamic interactions between stiffeners. In the absence of data for added mass coefficients for small amplitude, high Reynolds number oscillatory motions of flat plates, it is proposed that a value of 1.0 be used for C_{ms}.

It is more difficult to estimate the hydrodynamic damping of exposed structure, due to the absence of suitable test data. In the absence of data, it is probably reasonable to assume a quadratic drag coefficient, C_D, of 1.0 based on the horizontal projection of area. The equivalent linearized damping due to CWP longitudinal motion is thus given by:

$$\vec{F}_w = C_h \vec{w} = \frac{4}{3\pi} \rho C_D A_s \, a\omega \vec{w}$$

where

F_w is the force due to one member of horizontal projected area A .

w is CWP longitudinal velocity.

In this study the water within the CWP has been assumed not to respond to CWP longitudinal motions and hence to make no contribution to longitudinal added mass and damping.

4.6 Sources of CWP Loading

The present methods provide the ability to treat a number of sources of CWP loading, including:

- Platform steady motion or grazing.
- Steady, planar ocean currents.
- Unsteady, current induced forces.
- Motions of the CWP/platform attachment point.
- Unsteady flow induced loads within the CWP.

The CWP will be subject to additional loads due to moorings and attachments, but these loads are a direct result of the loadings described above. In this analysis all unsteady loadings are assumed to be harmonic. Response to loadings due to random ocean waves are determined by standard seakeeping statistical methods for linear systems (19). Response to other random loadings could be determined by the same methods.

In the present methods the loadings are divided into three areas which are treated separately. These are:

- Steady loading due to grazing and current.
- Unsteady, harmonic loading distributions due to unsteady flow inside or outside the CWP.
- Unsteady loading due to ocean wave loading on the coupled CWP/platform system.

The treatment of these loadings are discussed in the following sections.

4.7 Steady Loading Due to Current and Grazing

Any steady fluid flow past the CWP or steady motion of the CWP through the water will produce large steady CWP loading due to the CWP drag. The primary sources of such loadings are ocean currents, which generally can be considered steady for CWP behavior, and propulsion of the plant or grazing, a concept advocated by APL. In some cases the plant may be allowed to move or drift with the current. In all of these cases the distribution of relative velocity between CWP and water along the length of the CWP can be determined and used to determine CWP loading.

Steady relative velocities between CWP and water will produce both steady and unsteady forces and loading. The steady loading is discussed in this section. Unsteady loading is discussed in Section 4.8.

Three non-dimensional current velocity-depth profiles from the latest DOE environmental data package were provided for use in this study. These profiles, which are shown in Figures 4.11 - 4.13, are for normal and extreme conditions at the various DOE proposed OTEC sites. The surface current velocities for these sites, from Reference 24, are given in Table 4 - 1.

It was found that the velocity profiles of Figures 4 - 11 to 4 - 13 can be satisfactorily represented by the following analytical expression

$$\frac{V(z)}{V_s} = \frac{V_o}{V_s} + a\ e^{k_1 z} + a_2 z e^{k_2 z} \qquad [40]$$

where

$V(z)$ is velocity at depth of z feet.

V_s is surface current velocity.

V_o is current velocity at the deepest depth known (here 1000 meters or 3280 feet).

TABLE 4 - 1

Surface Current Velocities

Site	Conditions	Velocity-Knots
Keahole Pt., HI	Normal	1.13
	Extreme	2.18
Punta Tuna, P.R.	Normal	1.21
	Extreme	2.76
Offshore, New Orleans, LA	Normal	1.17
	Extreme	2.49
West Coast Florida	Normal	2.5
	Extreme	5.0
Offshore Brazil	Normal	0.5
	Extreme	3.2

The coefficients a_1, a_2, k_1 and k_2 in Equation [40] used to describe these current profiles are given in Table 4 - 2. The resulting curve fits are in good agreement with the actual profiles for all cases, as shown in Figures 4 - 11 to 4 - 13. The use of an analytical expression such as Equation [40] greatly simplifies the specification of velocity profile data.

It has been concluded by Hove, et al (1) that, for typical values of velocity shear gradient, it is appropriate to assume a single drag coefficient, based on Reynolds number at the mean velocity, for the entire CWP. This conclusion certainly appears reasonable for typical CWPs at realistic roughness ($k/D \leq 10^{-5}$). With the assumption of constant drag coefficient, the drag force is proportional to the local product of CWP outside diameter and dynamic pressure.

The mean or steady load at any CWP section or any depth is given by

$$\frac{dF(z)}{dz} = \tfrac{1}{2}\rho V(z)^2 \bar{C}_D D_p(z) \qquad [41]$$

where

$\frac{dF(z)}{dz}$ is force per unit length of CWP.

ρ is fluid mass density.

$\bar{C}_D$ is drag coefficient at mean current velocity, $\bar{V}$

$D_p(z)$ is CWP diameter at depth z.

The drag coefficient is generally dependent on CWP surface roughness and on Reynolds number.

Available data for the high Reynolds numbers associated with the CWP ($Re > 10^6$) are summarized by Hove, et al (1). Reference 1 indicates that at Reynolds numbers greater than about 4×10^5, the drag coefficient of circular cylinders is determined by surface roughness for even slightly rough cylinders

TABLE 4-2

Coefficients for Empirical Fits to Current Velocity Profile Data

Site/Condition	a_1	a_2	k_1	k_2
Non-Florida/Normal	0.9	0.0023	-0.0012	-0.002
Non-Florida/Extreme	0.9	0.0007	-0.0012	-0.003
West Coast Florida/ Normal and Extreme	0.9	0.0007	-0.0012	-0.003

($k/D \geq 10^{-5}$). For a 30 foot diameter CWP, it can therefore be assumed that the drag coefficient will be constant for all portions of the pipe having a current velocity of 0.16 feet per second or more. For the specified velocity profiles the current velocity everywhere exceeds this value and hence the use of a constant drag coefficient is clearly indicated. The value of drag coefficient as a function of roughness ratio is obtained from the data of Reference 1, as reproduced in Figure 4 - 14.

4.8 Unsteady Current and Internal Flow Loading

The flow of a steady velocity over a bluff body, such as a circular cylinder, produces vortex shedding and unsteady forces on the body. Typically, the unsteady forces acting on a circular cylinder are divided into an axial or drag force parallel to current velocity vector and a lateral or lift force normal to the current velocity plane. These forces are generally periodic, with frequency and magnitude which depend on Reynolds number and roughness.

Hove, et al (1) have carried out a detailed study of the unsteady CWP forces induced by steady current velocity. It is not possible to fully discuss the results of Reference 1, but a brief summary is provided. For constant velocity along the CWP length, such as occurs with grazing or propulsion of the platform in still water it is concluded in Reference 1 that:

- The mean or steady drag coefficient for rough and smooth CWPs can be obtained from Figure 4 - 14.
- Unsteady drag forces are small compared to mean drag forces and can be accounted for by increasing mean drag coefficient by 20 percent.

- Unsteady lift forces (forces normal to the direction of flow) are significant, are assumed to be fully correlated (in-phase over the entire CWP length), and should have a narrow-banded energy spectrum for most CWP application.

Figures 4 - 15 and 4 - 16, from Reference 1, show recommended values of Strouhal number and lift coefficient for smooth and rough cylinders in uniform flow. The Strouhal number is:

$$S = \frac{FD}{V} = \frac{\omega}{2\pi}\frac{D}{V}$$

where F is shedding frequency in Hertz. For typical CWP applications lift coefficient and Strouhal number are 0.27 and 0.3 respectively.

The conclusions given above for uniform velocity are also generally applicable to cases with significant velocity shear over the CWP length. With velocity shear it is recommended that mean drag coefficient, lift coefficient and Strouhal frequency be assumed constant and be based on mean velocity, $\overline{V}$:

$$\overline{V} = \frac{1}{L}\int_0^L V(z)\,dz$$

The drag and lift coefficients and Strouhal number are again obtained from Figures 4 - 14 to 4 - 16.

The situation is more complicated when the CWP flexibility is taken into account. If any CWP modal or natural frequency falls within about 50 percent of the Strouhal shedding frequency, the CWP will oscillate in response to the lift forces and hydroelastic effects will become important. A significant amplification of the lift forces results. Reference 1 provides an extensive discussion of the resulting CWP forces and a simplified method, based on calculations for a representative CWP, for

estimating these forces. This method can be summarized as follows.

1. If any modal frequency falls within 50 percent of the Strouhal frequency, the entire CWP will vibrate at this modal frequency with a lift coefficient amplification given by Figure 4 - 17. The forces are assumed to be everywhere in-phase with the CWP displacements.

2. If no modal frequency falls within 50 percent of the Strouhal frequency, the CWP lift coefficient will be that of Figure 4 - 16 and the frequency of the force will vary along the CWP length and be given by:

$$\omega = 2\pi S \int_0^L V^3(z)\,dz \Big/ \int_0^L DV^2(z)\,dz$$

It has been indicated by SAI that if more than one CWP modal frequency falls within 50 percent of Strouhal frequency, each mode should be excited in accord with item 1 above, and the responses to these modal excitations will be superimposed. There do not appear to be any data verifying simultaneous "lock-on" to two or more modal frequencies. A "lock-on" to only the modal frequency closest to the Strouhal frequency seems more likely. It is not possible in the absence of reliant data, to fully justify these or other conclusions about "lock-on," particularly for cases with velocity shear.

The local unsteady lift force is given by:

$$\frac{dF_\ell}{dz} = \tfrac{1}{2}\rho V^2 C_L D_p e^{i\omega t}$$

where

F_ℓ is unsteady lift force.
V is local steady velocity.
C_L is unsteady lift force coefficient.
ω is frequency of unsteady lift force.
D is local CWP diameter.

The force at any point on a CWP is assumed to be proportional to the local velocity and CWP diameter and to have some phase relative to a reference phase; and hence:

$$\frac{dF_\ell(z,t)}{dz} = \tfrac{1}{2}\rho V(z)^2 C_L(z) D(z) e^{i[\omega(z)t - \delta(z)]} \qquad [42]$$

where $\delta(z)$ is lift force phase angle. The variation of δ with z is determined by the correlation length of the vortex shedding, which is considered in detail in Reference 1. It is generally recommended in Reference 1 that the forces are fully correlated and hence are everywhere in phase with CWP motion.

Reference 1 does not consider loadings due to unsteady flow within the CWP in detail, although water hammer loads due to rapid shut-dwon of CWP flow are considered briefly. Water hammer will produce pressure waves which travel within the CWP at the speed of sound in seawater. The wavelength of such waves, for a rigid wall CWP, is four times the CWP length. For a sonic velocity of 4800 feet per second, the effective frequency of excitation is 2.5 radians per second for a 3000 foot long CWP. This frequency will be important only for small diameter, relatively stiff CWPs having relatively high modal or natural frequencies. CWP wall flexibility can significantly reduce this frequency.

Other possible sources of CWP loading due to internal flow include flow swirl or non-uniformity due to motions of the CWP intake. These disturbances will travel through the CWP at the

cold water flow velocity and hence will have an effective wave length of

$$\lambda_d = \frac{2\pi V}{\omega}$$

where

λ_d is disturbance wave length.
V is cold water flow velocity.
ω is frequency of disturbance.

For a typical disturbance frequency of 0.5 radians per second and a typical flow velocity of 8 feet per second, the wave length is about 100 feet. This wavelength is probably too short to produce any significant CWP loading for most CWPs.

4.9 Ocean Wave Loading

For most CWPs, ocean surface waves and wave induced motions of the OTEC platform represent the important source of CWP loading. This is particularly true for larger OTEC plants since wave loading varies as diameter squared while current loading varies as diameter.

Ocean waves are rarely regular or harmonic, but the effect of irregular or random waves on linear systems can be readily determined from the effect of regular waves.

It is essential, in calculating the effects of wave loading, to consider the coupled response of the CWP and platform since the CWP loading due to direct action of the waves and due to wave induced platform motions are comparable in magnitude. In this section direct wave loading of the CWP is considered. CWP loading due to coupling of wave induced platform motions and CWP motions is considered in Section 5.

There are available two approaches to calculation of wave loadings on cylinders. The first is the use of the so-called

Morison's equation. The second is the use of diffraction theory. The Morison's equation can properly account, with correct choice of drag coefficient, for viscous effects while diffraction theory cannot. Diffraction theory, on the other hand, can more accurately account for the effect of the free surface and potential flow effects. Potential flow contribution to loading will, for most CWP application and particularly for larger diameter CWPs, be significantly larger than the viscous flow contributions. For this reason, diffraction theory was used in this study as a basis for predicting wave loading on the CWP.

Internal waves also occur in the ocean. These waves typically occur at a depth of significant seawater density gradient or stratification. These waves are generally ignored in the treatment of ocean structures since their periods are long, and the resulting orbital velocities and accelerations are very small. These periods may, however, correspond to the lowest modal frequencies of the CWP and hence may be important. The effect of internal waves is treated only briefly in Reference 1.

4.9.1 Periodic Wave Loading - Regular or periodic waves produce a force on the CWP which is proportional to fluid particle motion and hence decays exponentially with depth.

Barr and Murphy (4) have given an empirical expression for wave force based on the calculated diffraction theory results of Bai (16):

$$\frac{dF}{dz}(z,t) = 1.1e^{-kD_p}\rho a_w \omega^2 \frac{\pi}{2} D_p{}^2 e^{-kz} \mathrm{Re}[ie^{i\omega t}] \qquad [43]$$

where

$\frac{dF}{dz}$ is force per unit length of CWP.

k is wave number = ω^2/g

D_p is CWP outside diameter.
a_w is wave surface amplitude.
ω is wave frequency
k is depth below the water surface.
ρ is water mass density.

This expression is used to calculate the wave exciting force for all CWPs.

4.9.2 Irregular Wave Loading - Ocean waves are almost always irregular or random. Such irregular waves can be suitably described by an energy spectrum or spectral density distribution $S(\omega)$, where energy $S(\omega)$ is proportional to the square of wave height. For a linear system, the statistics of response in irregular waves are obtained from the energy spectrum and the regular wave response or RAO by standard methods of linear superposition such as described by Barr, et al. (7). It is thus not necessary to consider the actual random wave forces acting on the CWP for a linear system.

4.9.3 Internal Waves - The significance of CWP loading due to internal ocean waves will depend on three factors:

- The relationship between wave frequency and lower modal frequencies of the CWP.
- The amplitude of the internal waves.
- The location of the density gradient layer producing these waves.

Internal waves should probably be considered only if their frequency corresponds to one of the first few CWP modal frequencies.

The loads due to internal waves can be calculated by a

method analagous to that of Equation [43]:

$$\frac{dF}{dz}(z,t) = \rho a_i(z)\omega^2 \frac{\pi}{2} D_p^{\,2} \mathrm{Re}\,[\,ie^{i\omega t}]$$

where

$a_i(z)$ is internal wave amplitude at depth z.

The distribution of internal wave orbital amplitudes can be determined from the theory for internal waves or waves in stratified fluid [see for example, Lamb (20)]. These orbital amplitudes decay exponentially in both directions from the density gradient or stratification layer.

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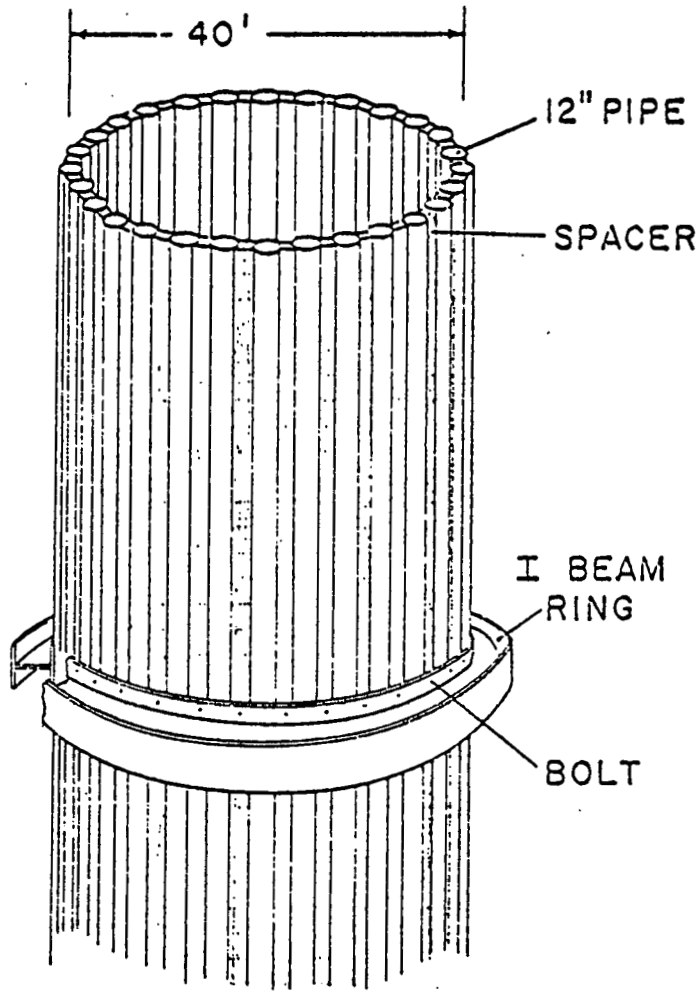
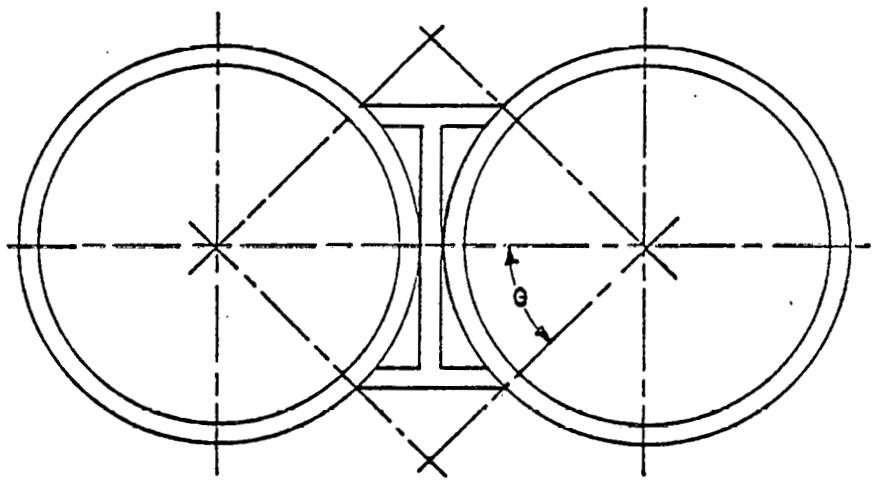


a. OVERALL VIEW OF CWP



TUBES WITH I SPACERS

b. TYPICAL TUBE SEPARATOR DETAIL

FIGURE 4-1 - TYPICAL STOCKADE COLD WATER PIPE CONSTRUCTION

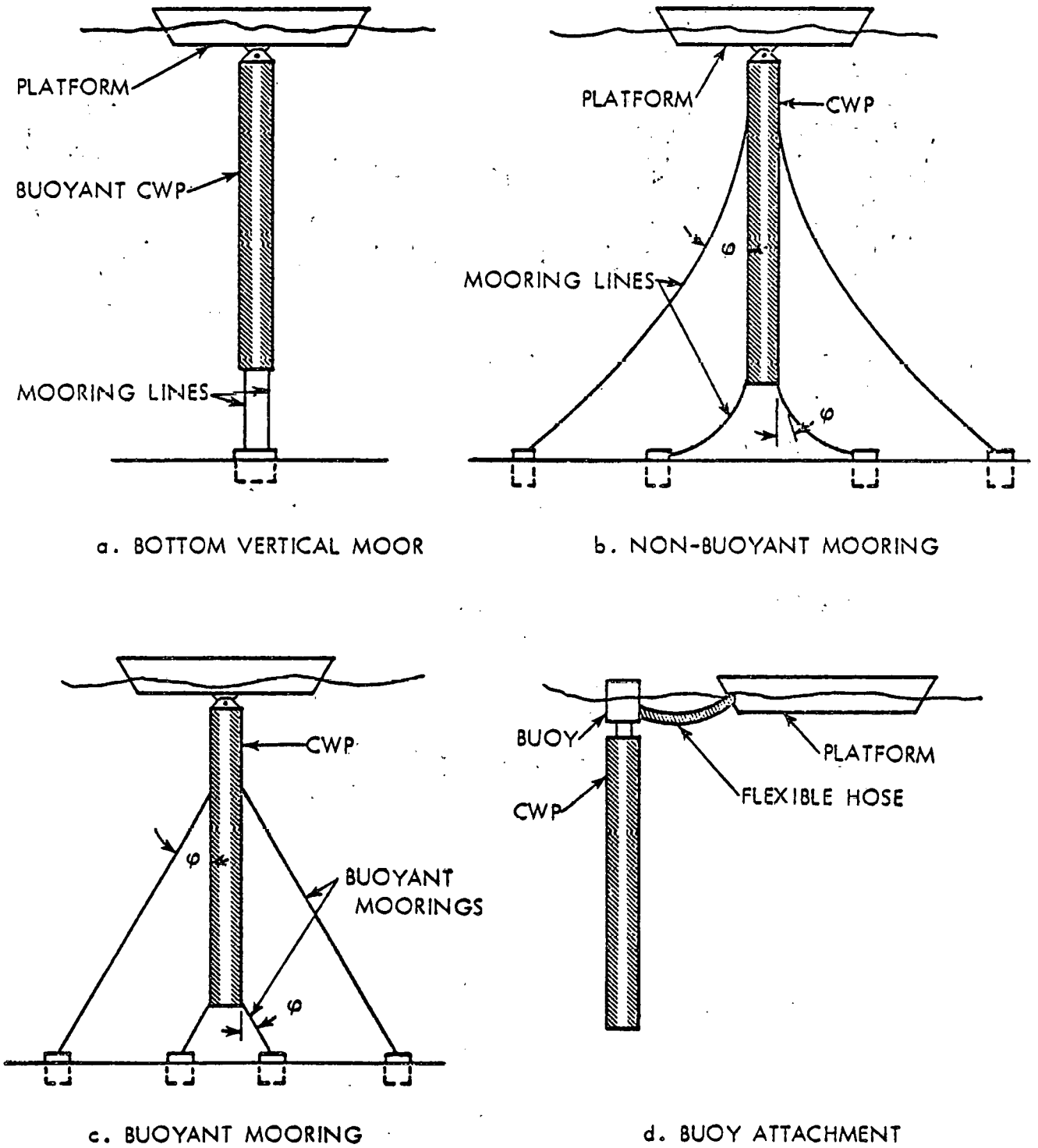
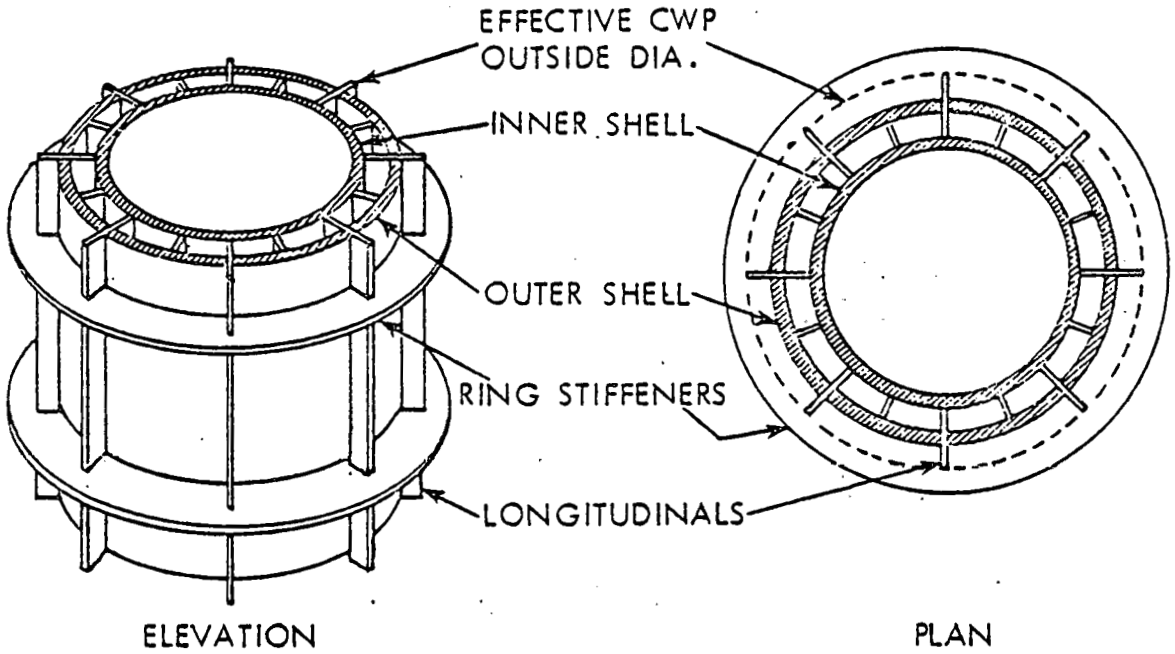
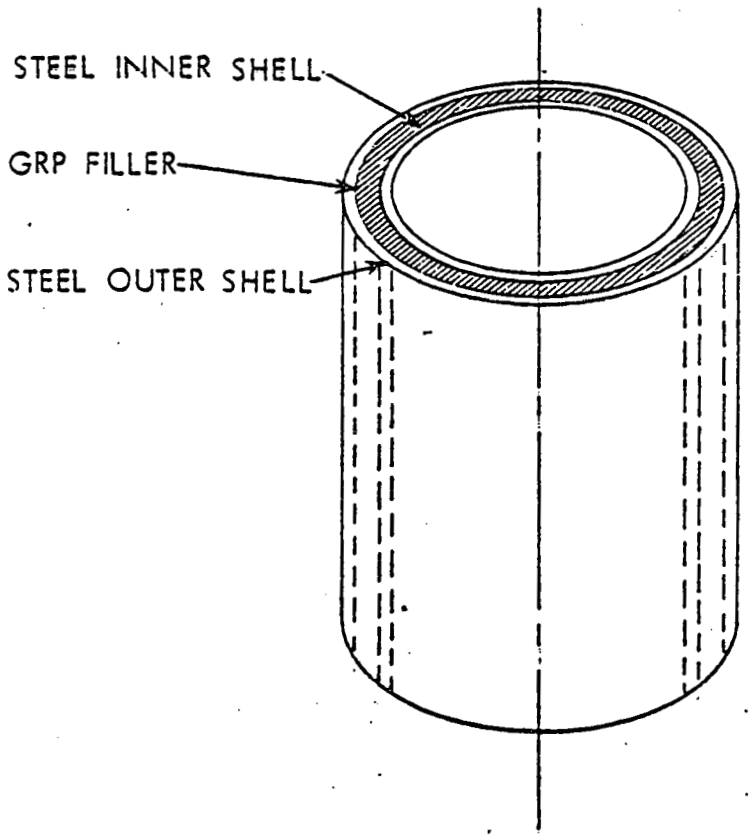


FIGURE 4-2 - CWP MOORING AND ATTACHMENTS



a. TYPICAL COMPLEX CWP STRUCTURE



b. STEEL-GRP SANDWICH CONSTRUCTION

FIGURE 4-3 - EXAMPLES OF COMPLEX CWP STRUCTURES

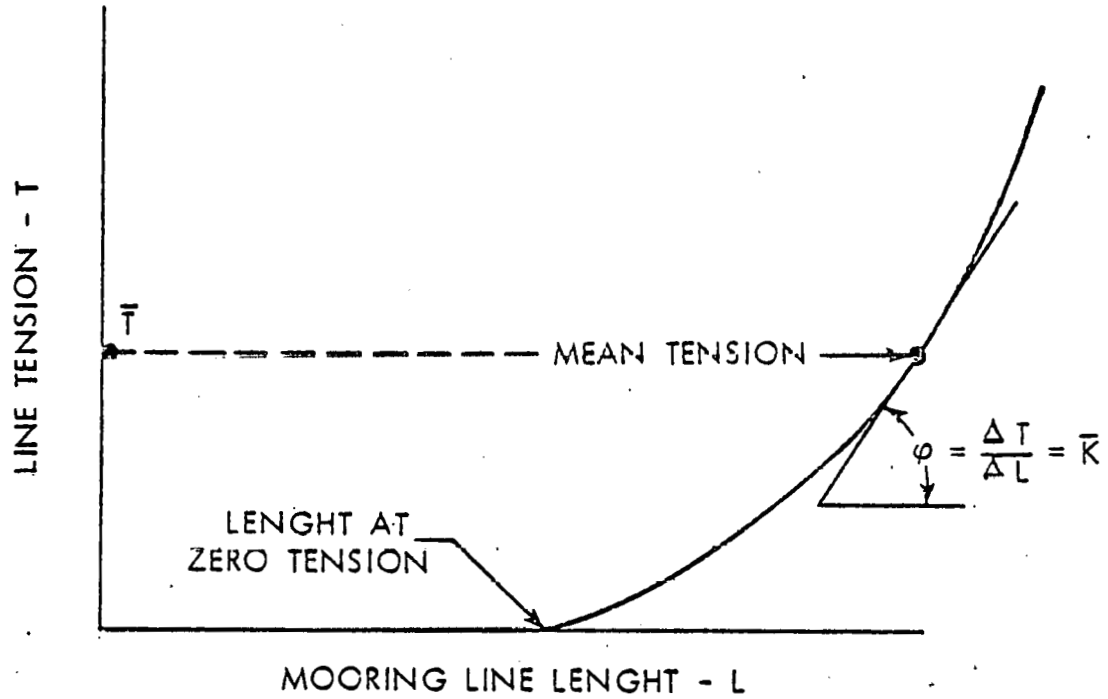


FIGURE 4-4 - MOORING LINE ELASTIC CHARACTERISTICS

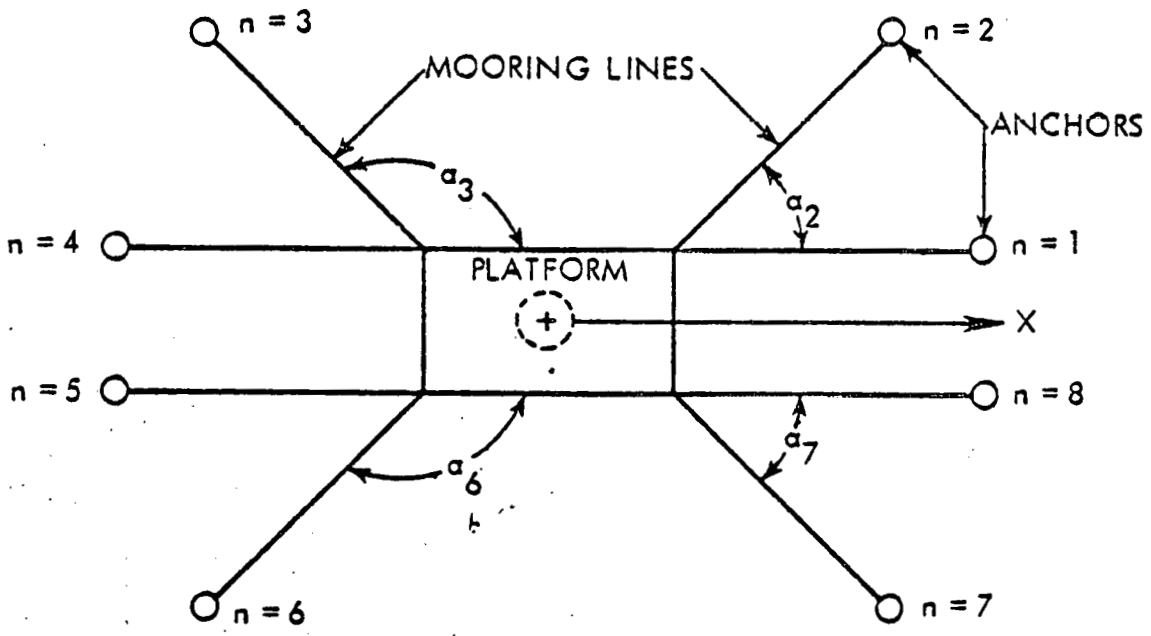


FIGURE 4-5 - TYPICAL MULTI-POINT MOORING

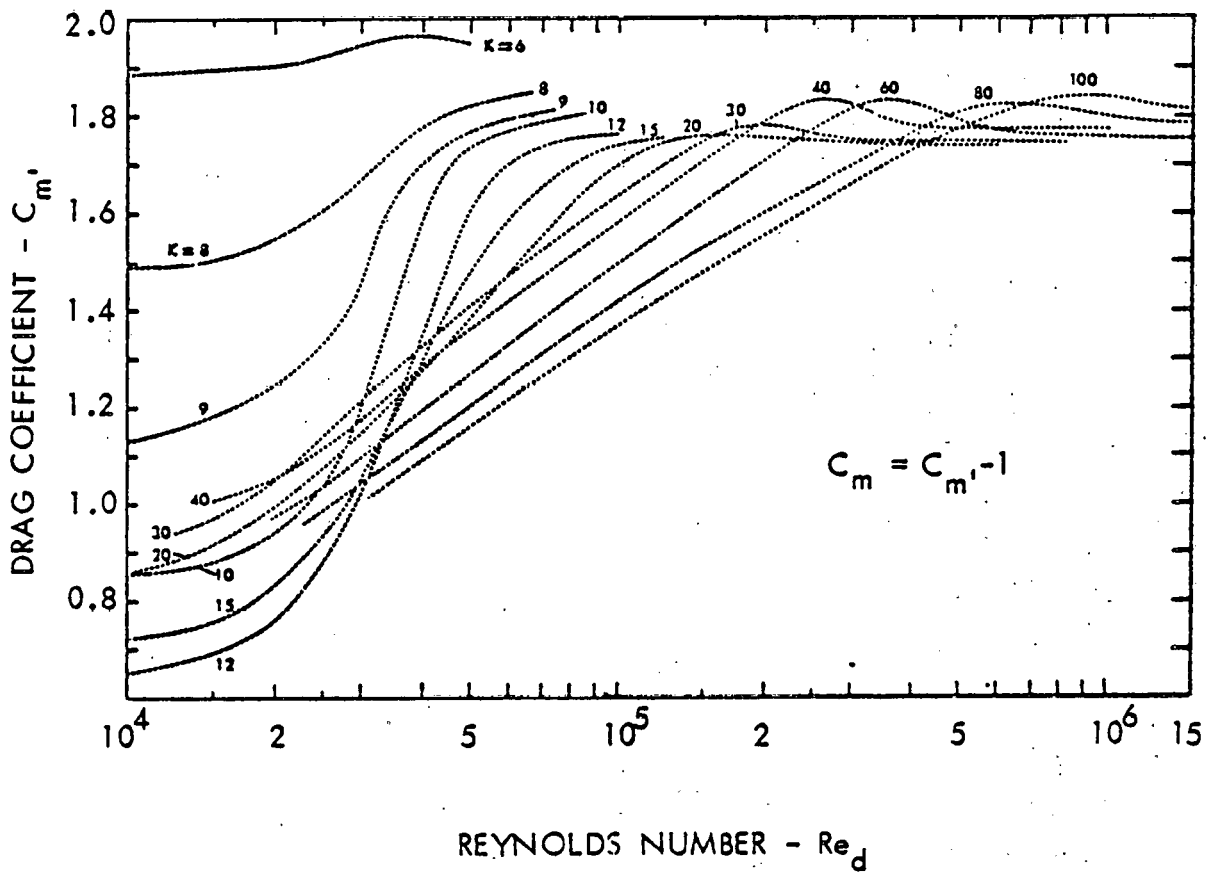


FIGURE 4-6 - INERTIA COEFFICIENTS FOR SMOOTH CIRCULAR CYLINDERS FROM REFERENCE 15

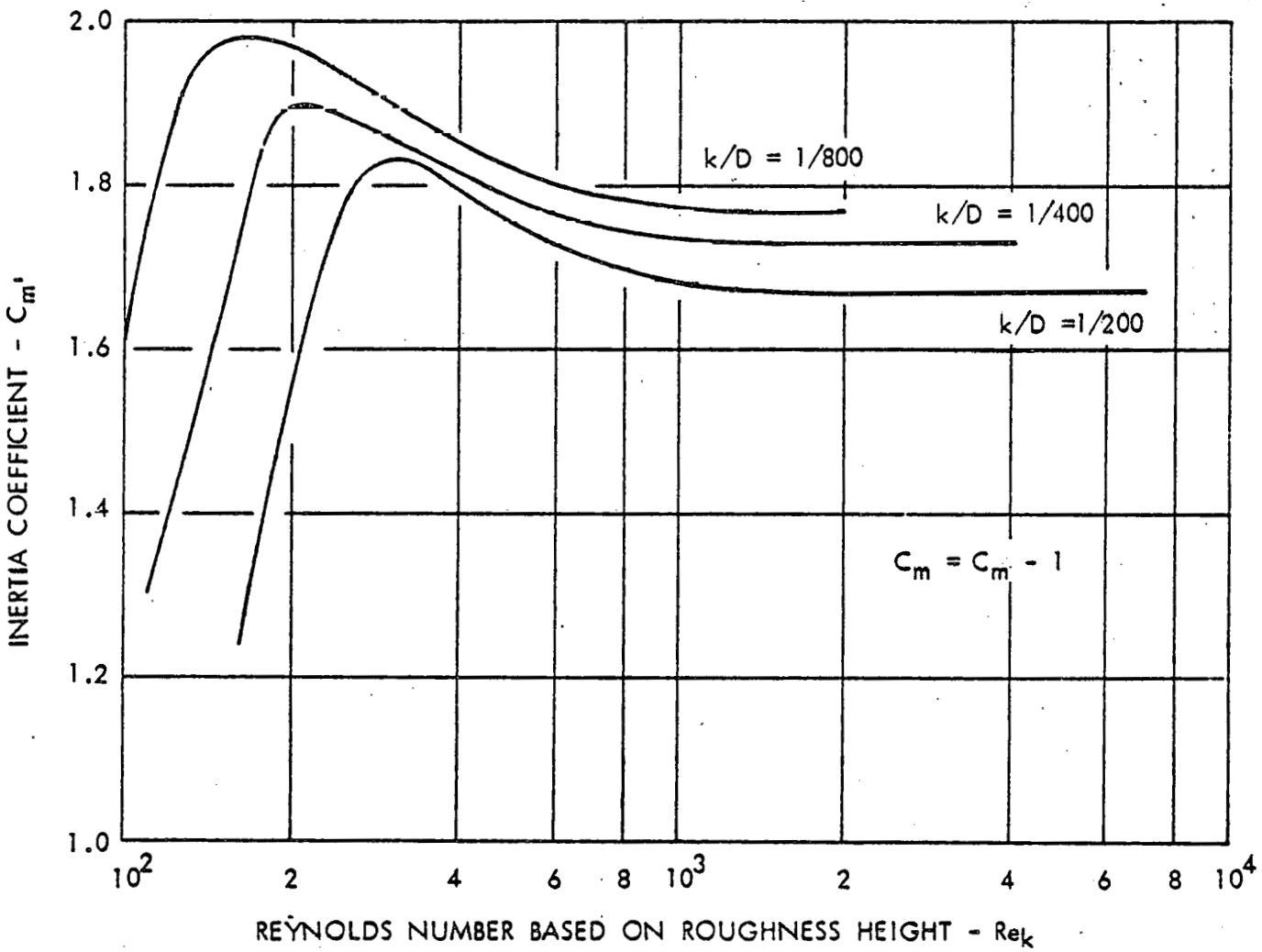


FIGURE 4-7 - INERTIA COEFFICIENTS FOR ROUGH CIRCULAR CYLINDERS FROM REFERENCE 15

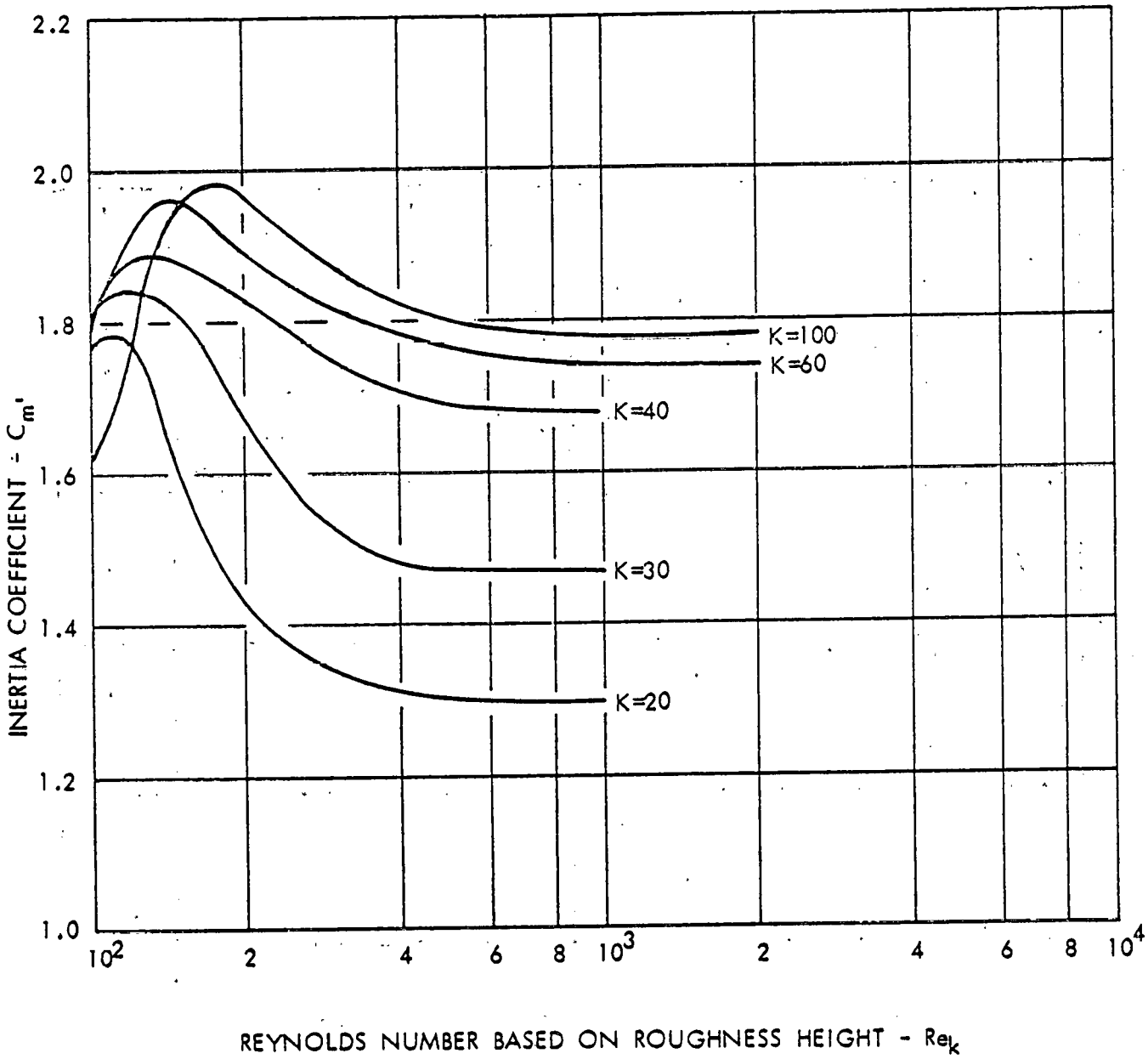


FIGURE 4-8 - INERTIA COEFFICIENTS FOR ROUGH CYLINDERS (k/D = 1/800) IN OSCILLATORY FLOW

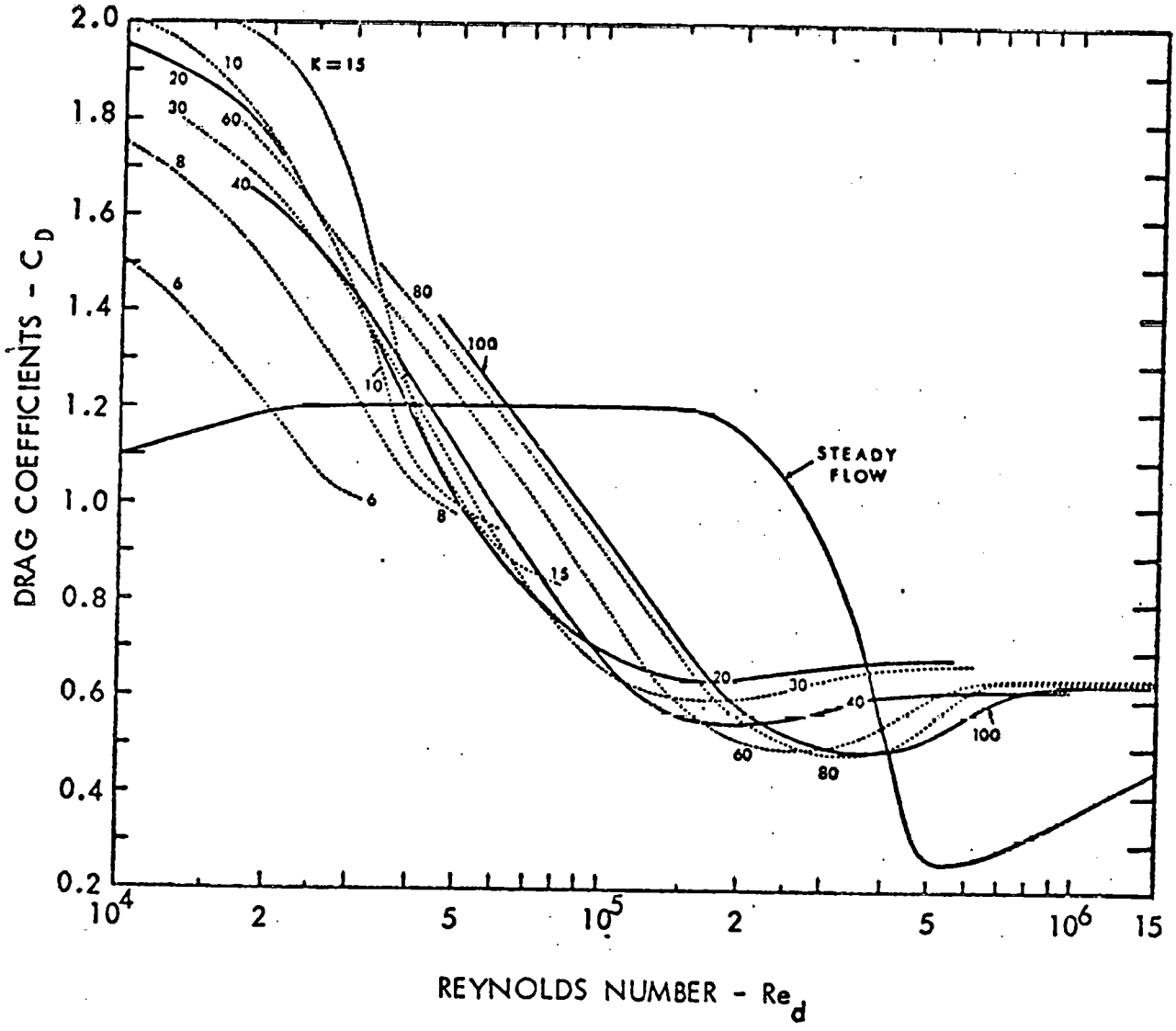


FIGURE 4-9 - DRAG COEFFICIENTS FOR SMOOTH CIRCULAR CYLINDERS FROM REFERENCE 15

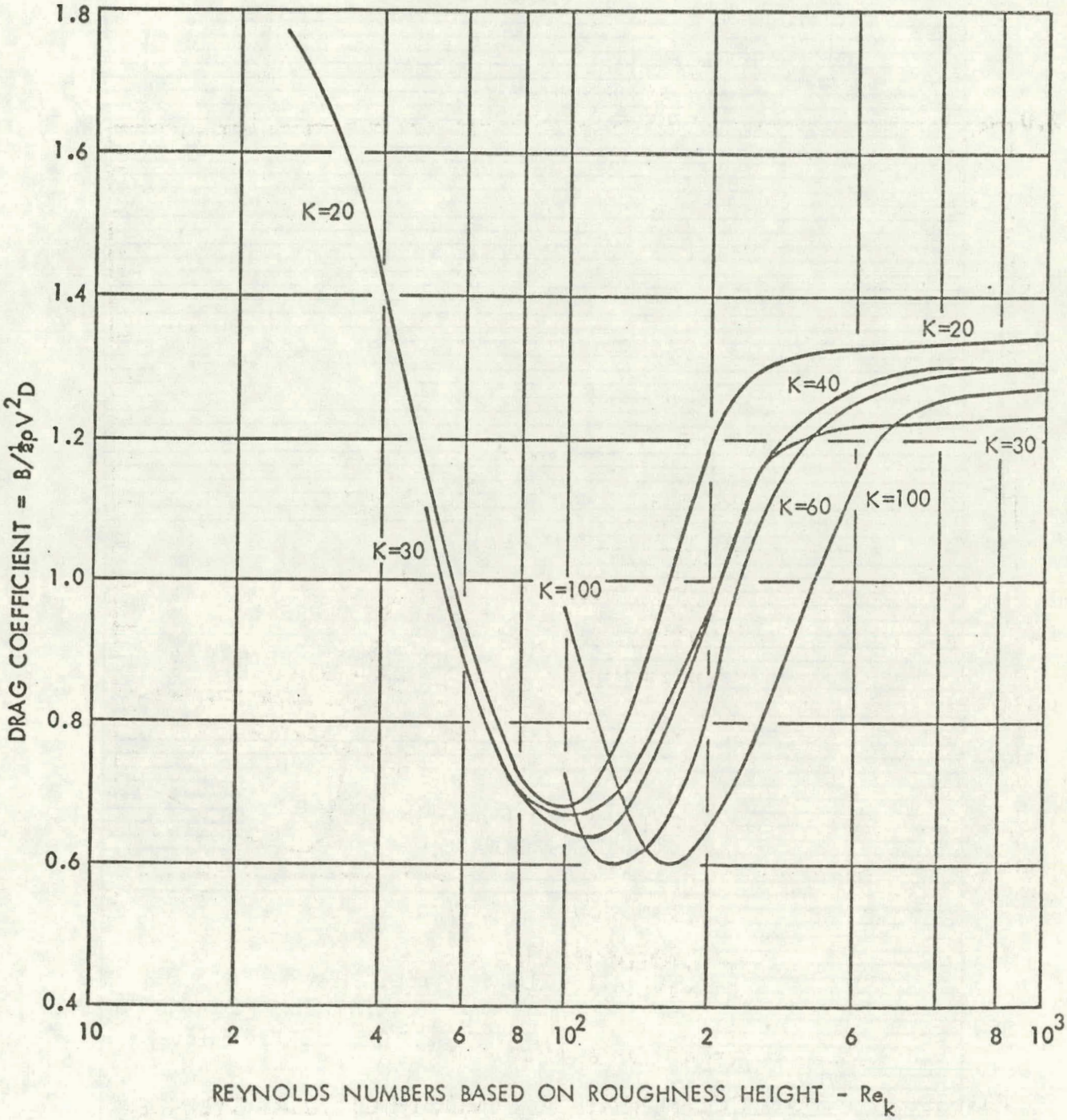


FIGURE 4-10 - DRAG COEFFICIENTS FOR ROUGH CYLINDERS
(k/D = 1/800) IN OSCILLATORY FLOW

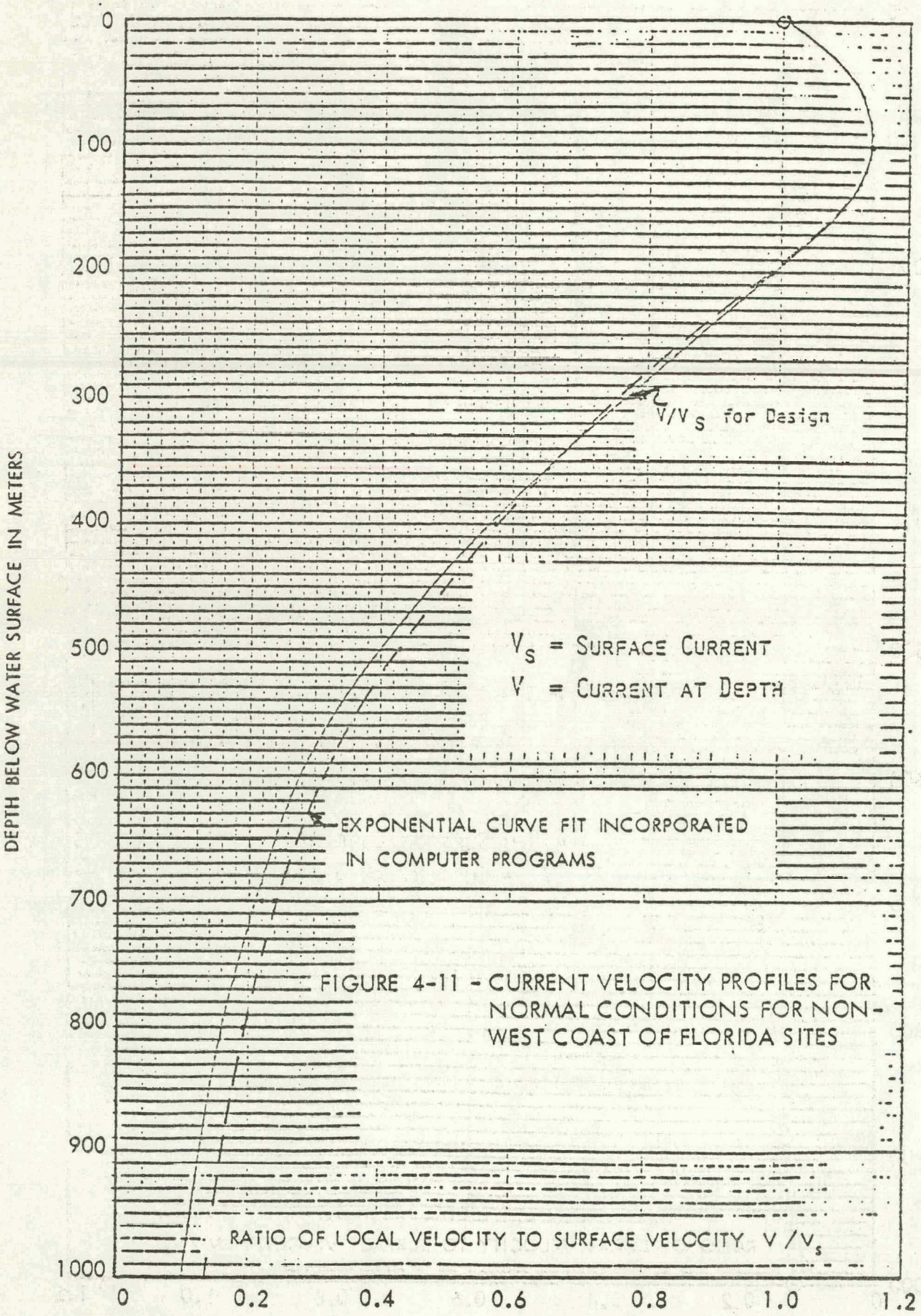


FIGURE 4-11 - CURRENT VELOCITY PROFILES FOR NORMAL CONDITIONS FOR NON-WEST COAST OF FLORIDA SITES

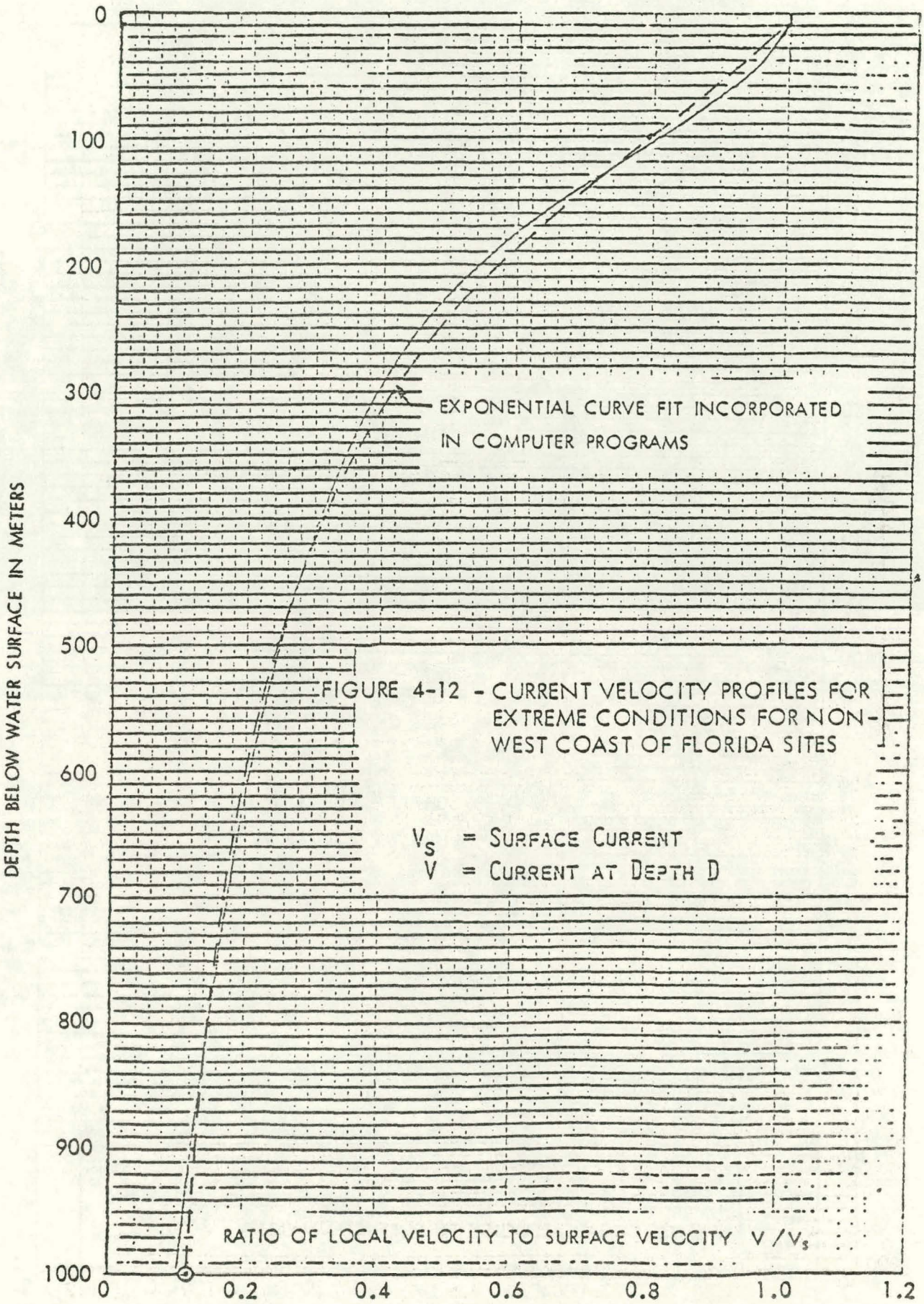


FIGURE 4-12 - CURRENT VELOCITY PROFILES FOR EXTREME CONDITIONS FOR NON-WEST COAST OF FLORIDA SITES

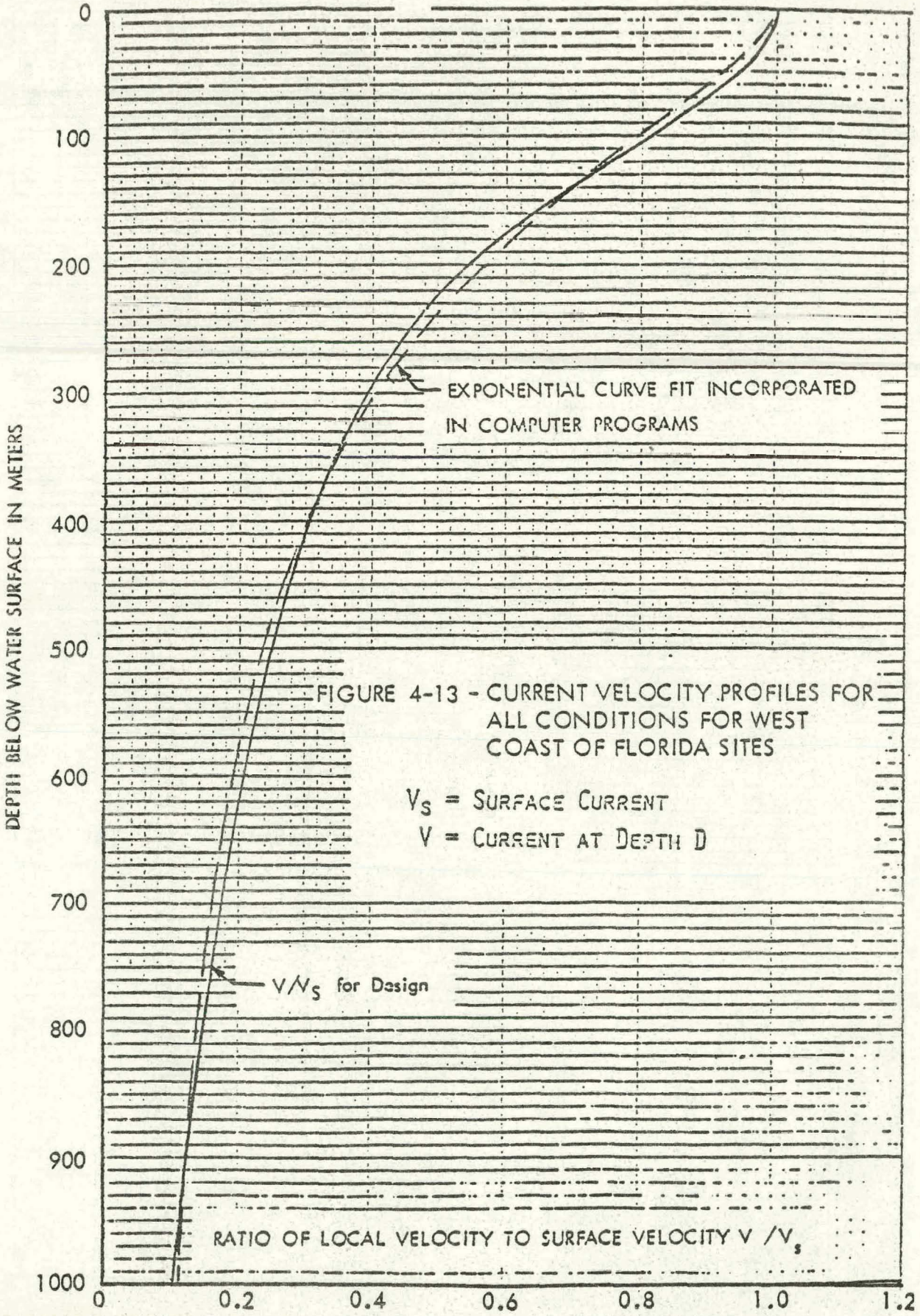


FIGURE 4-13 - CURRENT VELOCITY PROFILES FOR ALL CONDITIONS FOR WEST COAST OF FLORIDA SITES

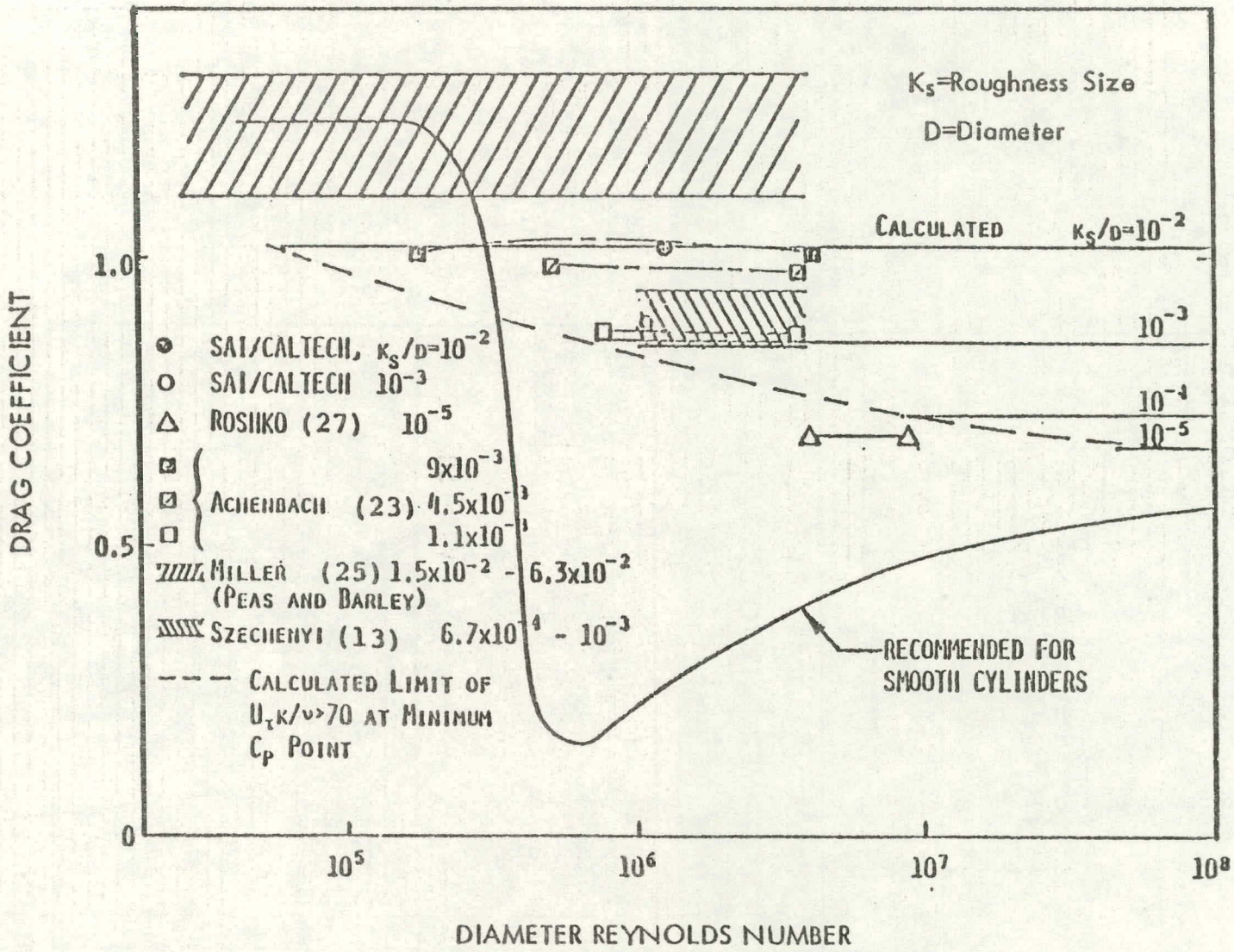
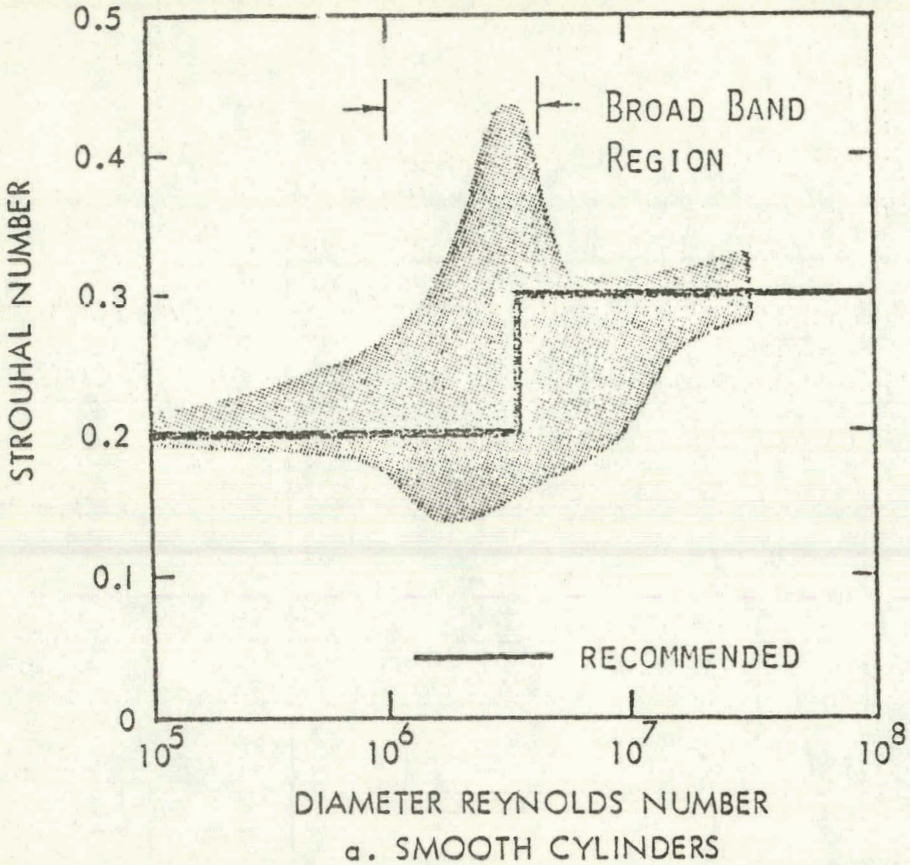
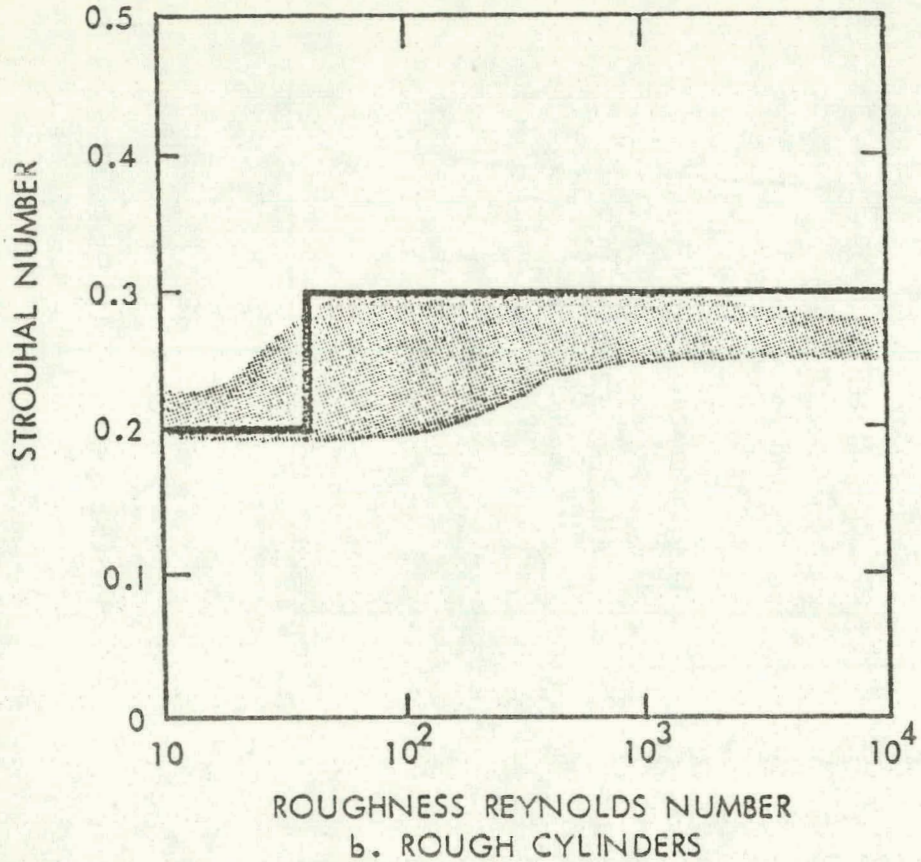


FIGURE 4-14 - MEAN DRAG COEFFICIENTS FOR CIRCULAR CYLINDERS FROM SAI - REFERENCE 1

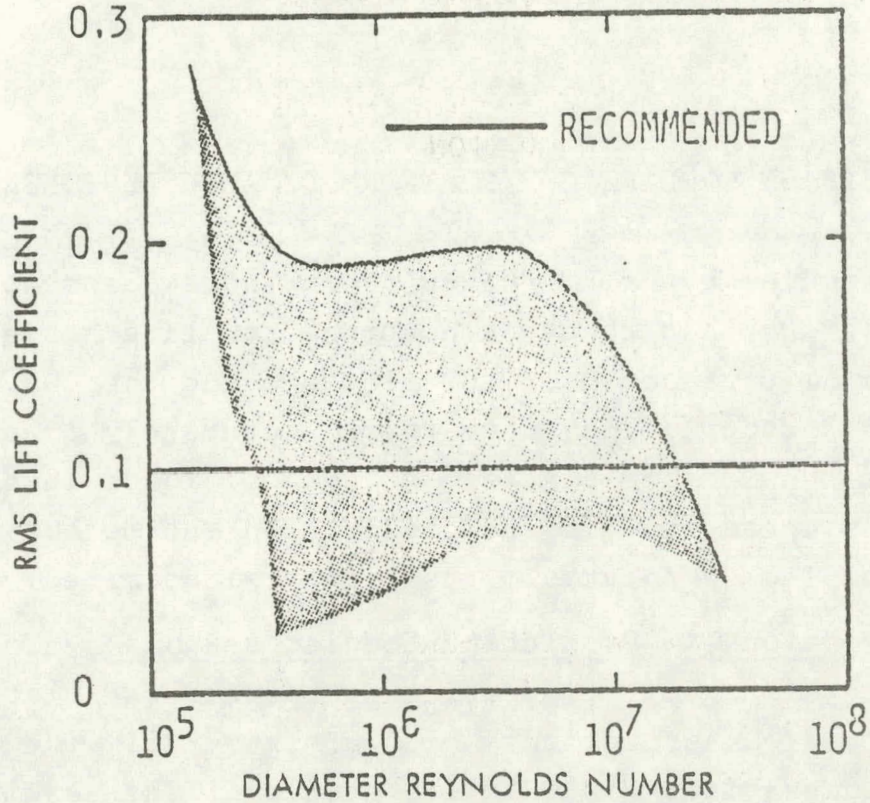


a. SMOOTH CYLINDERS

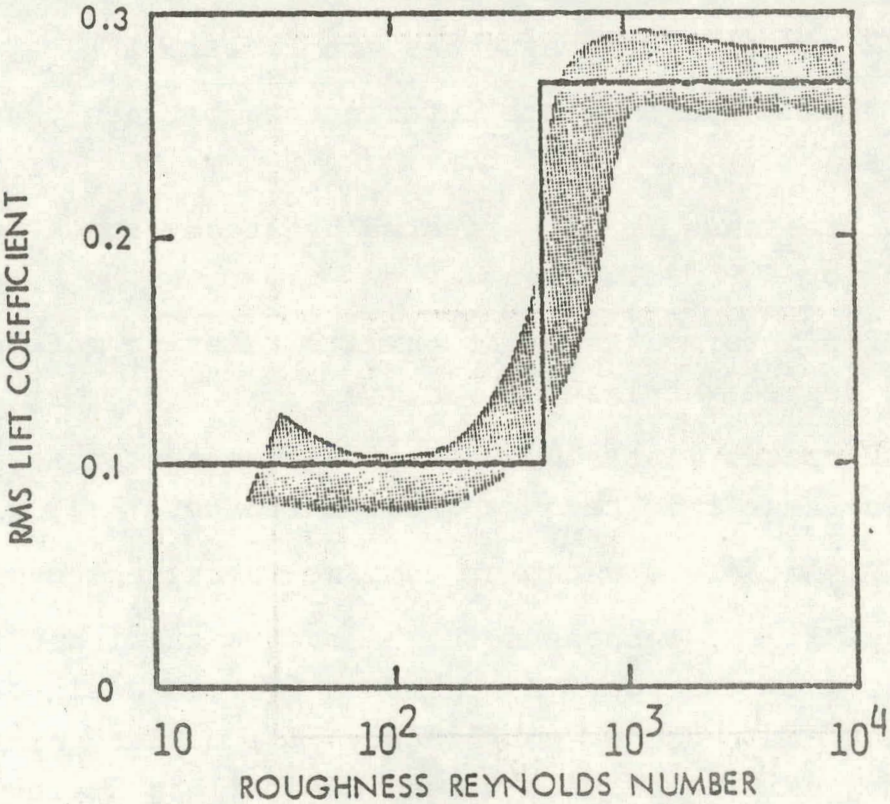


b. ROUGH CYLINDERS

FIGURE 4-15 VARIATION OF CYLINDER SHEDDING FREQUENCY



a. SMOOTH CYLINDERS



b. ROUGH CYLINDERS

FIGURE 4-16 VARIATION OF CYLINDER RMS LIFT COEFFICIENT WITH REYNOLDS NUMBER-FROM SAI-REFERENCE 1

5.0 ANALYSIS OF COUPLED CWP/PLATFORM DYNAMIC RESPONSE

Previous studies by HYDRONAUTICS, References 3 and 4, and by others have shown that there is a strong coupling between the wave induced dynamic response of the platform and the CWP. This coupling must be properly accounted for to accurately predict the response of the CWP and platform to dynamic loads such as those induced by ocean waves. In this section the methods used to calculate coupled CWP/platform response are described.

5.1 Basic Assumptions in Predicting Coupled Response - The methods used in this study for predicting coupled CWP/platform response are based on assumptions which are generally identical to those used in previous HYDRONAUTICS studies. The assumptions are:

- The CWP and platform responses are linear.
- There are no hydrodynamic interactions between the CWP and platform.
- Dynamic response is not effected by steady-state loads, motions or CWP deflections.
- The CWP/platform attachment permits relative motion in all degrees of freedom but yaw.
- The CWP/platform attachment stiffnesses are arbitrary and can range from zero to quasi-infinite.
- The CWP/platform attachment damping is neglected.

The assumption of linear responses is the most significant and most questionable assumption. A number of factors could make the CWP and platform response non-linear. The most significant, CWP hydrodynamic damping, is discussed in detail in Section 4.5, where it is noted that an equivalent linearized drag can be used

to closely approximate quadratic drag. Uncoupled platform motions for most platforms are, except for extreme wave heights, linear. Motions of semi-submersible do show some significant nonlinearities, however.

5.2 General Method of Approach

The method of approach used here is similar to that used in earlier HYDRONAUTICS studies. This approach is outlined by the flow chart shown in Figure 5 - 1. In this approach, all CWP static and dynamic responses and transfer functions are first calculated. Only the wave induced loads are, at this time, used as inputs to the analysis of the coupled CWP/platform responses, although the coupled responses to other dynamic loads could also be calculated.

5.3 Formulation of the Platform Response

The platform response is described in the frequency domain by a set of six ordinary differential equations:

$$\left\{ \sum_{R-1}^{6} \left[-\omega^2 (M_{jk} + A_{jk}) + i\omega B_{jk} + C_{jk} \right]_k = F_j \right\}_{j=1,b} \qquad [44]$$

where

ω is frequency of motion.

M_{jk} is platform mass matrix.

A_{jk} is platform added mass matrix.

B_{jk} is platform hydrodynamic damping matrix.

C_{jk} is platform hydrostatic restoring force matrix.

η_k is response or motion in k^{th} degree-of-freedom.

F_j is wave exciting force in the jth degree-of-freedom.

and where j=1,...6 denote surge, sway, heave, roll, pitch and yaw, respectively. For platforms having transverse symmetry, these six coupled equations decouple into two sets of three coupled equations, one for vertical plane motions (surge, heave and pitch) and one for lateral plane motions (sway, roll and yaw):

$$\left\{\sum_{n=1,3,5} [\quad]\eta_k\right\} = F_j \qquad j=1,3,5$$

$$\left\{\sum_{n=2,4,6} [\quad]\eta_k\right\} = F_j \qquad j=2,4,6 \qquad [45]$$

where the square bracket terms are identical to that in Equation [44].

In all previous HYDRONAUTICS studies and platform computer programs, References 3 and 7, the platform is assumed to have lateral symmetry and the three-degree-freedom (3DOF) equations of motion, Equation [45] , are used. In Garrison's platform motions program the full six-degree-of-freedom (6DOF) equations of motion, Equation [44], are used. In this study the 3 DOF equations only are used since almost all proposed OTEC platforms have lateral symmetry. The only notable exception is the DOT triangular platform when operating in beam and oblique seas.

Equations [45] can be readily solved, when the coefficient and force matrices are defined, by standard matrix inversion techniques. In the present study the Gauss reduction method is used. The method used to calculate the coefficient and force matrices depends on the platform geometry. The methods considered in this study for claculating hull hydrodynamic coeffi-

cients and forces are considered in Section 5.5.

5.4 CWP/Platform Coupling

The coupling of the CWP and platform equations of motion are determined by the treatment of the CWP/platform attachment and the independent degrees of freedom permitted to the CWP. The treatment of coupling is greatly facilitated in this study by the methods used in the CWP analysis methods, as described in Section 3.

5.4.1 CWP Degrees of Freedom - In earlier HYDRONAUTICS studies the CWP was assumed to have three degrees-of-freedom relative to the platform. These were heave, pitch and roll. The treatment of these degrees of freedom are discussed in References 3 and 4. In the present study two additional degrees-of-freedom relative to the platform, surge and sway are permitted. These are treated in a different manner than used for roll/pitch in Reference 3.

The CWP is assumed to be connected to the platform with a connection or attachment which provides stiffness, but no damping, in surge, sway, heave, roll and pitch. This stiffness can have different values from zero to approximately infinity, in each degree of freedom. If all stiffnesses are zero, the CWP is not attached to any platform; if all stiffnesses are infinite, the CWP is rigidly attached to the platform. With zero pitch and roll stiffness and other stiffnesses infinite, the attachment is a fixed pin or ball joint, of the type frequently proposed for OTEC use.

It should be noted that no actual attachment will have infinite stiffnesses due to the flexibility of the platform structure. The use of methods and computer programs providing arbitrary attachment stiffness precludes the use of infinite stiffness. However, it is possible, even on small computers

such as the IBM 1130, having limited precision, to use large enough stiffnesses (10^{14} pound-feet per radian in roll/pitch, for example) to insure negligable relative motion between CWP and platform. In this and previous HYDRONAUTICS studies such large stiffnesses are and have been used to simulate rigid attachments and are called quasi-infinite attachment stiffnesses.

In this study the CWP has no freedom, relative to the platform, in yaw. Yaw motions are generally small and should have little influence on CWP behavior and loads.

5.4.2 Mathematical Treatment of Coupling - In the present method of solving the coupled platform/CWP equations of motion it is not necessary to use independent degrees-of-freedom and displacements for CWP surge, sway, roll and pitch. These CWP motions are Specified by platform motions; since

$$\eta_p = \frac{F_a}{K_s} + \eta_h$$

where

η_p is CWP motion.
η_h is platform or hull motion.
F_a is force or moment at the attachment.
K_s is attachment stiffness.

This relationship allows equations of motion to be written and solved only in terms of platform motions. The resulting equations are solved for platform motions and these platform motions are then used to determine CWP motions.

Heave motions are treated somewhat differently. The CWP has two distinct modes of motion in heave. The first is rigid body motions with a natural frequency, ω_o:

$$\omega_o = \sqrt{\frac{k_1}{m + m_a}}$$

where

k_1 is heave attachment stiffness.

m is CWP mass.

m_{a_3} is CWP heave added mass.

The second is CWP longitudinal vibrations, for which the first modal frequency is given, for rigid CWP walls, by:

$$\omega_1 = \frac{\alpha_k \sqrt{E/\rho}}{L}$$

where

α_R is a constant depending on attachment stiffness ($0.5 < \alpha_R < 1.0$).

E is CWP material modulus of elasticity.

ρ is CWP material mass density.

L is CWP length.

For almost any typical CWP, the value of ω_1 will be much larger than any important wave exciting frequencies, and CWP longitudinal vibrations will have no significant effect on platform motions. With finite k_1, the value of ω_0 can correspond to significant wave exciting frequencies and thus the CWP can have a particularly large effect on heaving motions.

In this study the coupling of rigid body heave motions and platform heave motions is considered. Rigid body heave motions are treated as an independent, coupled degree of freedom. CWP heave motion, denoted η_7, is calculated using a linear equation of motion.

5.4.3 <u>Coupled Equations of Motion</u> - The coupled CWP/platform equations of motion are similar in form to Equation [45] . These seven equations are:

$$\left\{ \sum_{k=1,3,5,7} \left[-\omega^2 (M_{jk} + A_{jk}) + i\omega B_{jk} + C_{jk} + T_{p_{jk}} \right] \eta_k = F_j + F_{pj} \right\}_{j=1,3,5,7}$$

$$\left\{ \sum_{k=2,4,6} \left[-\omega^2 (M_{jk} + A_{jk}) + i\omega B_{jk} + C_{jk} + T_{p_{jk}} \right] \eta_k = F_j + F_{p_j} \right\}_{j=2,4,6}$$

where

$T_{p_{jk}}$ is CWP transfer function matrix.
F_{p_j} is CWP wave exciting force vector.

and where all other terms are as defined in Section 5.3. The motion vector is the same, except for CWP heave, as that used in Reference 21, where:

η_1 is surge (in x direction).
η_2 is sway (in y direction).
η_3 is heave (in z direction).
η_4 is roll (about x axis).
η_5 is pitch (about y axis).
η_6 is yaw (about z axis).

The coordinate system used in this study is shown in Figure 5 - 2. The pipe heave (in the z direction) is represented by η_7. For $j \leq 6$ and $k \leq 6$, the terms of the matrices M_{jk}, A_{jk}, B_{jk}, C_{jk} and the vector F_j are those for the hull or platform alone, as described in Reference 3. For $j = 7$ and for $k = 7$, the only non-zero terms in these matrices are:

$$M_{77}$$
$$A_{77}$$
$$B_{77}$$
$$C_{77} = k_1$$
$$C_{77} = C_{73} = -k_1$$

For this study the CWP was assumed to have no ring stiffness, flanges, etc., which would produce significant CWP heave added mass and the terms A_{77} was assumed to be zero. The damping B_{77} was assumed linear. The term M_{77} is the inertial mass of the CWP. The CWP was assumed to be attached to the platform through an attachment which has a heave stiffness of k_1 pounds per foot of motion. The tern M_{π} can include any estimated added mass.

The CWP transfer functions due to CWP motions, $T_{p_{jk}}$, and due to wave loads on the CWP, F_{pj}, are defined in Tables 5 - 1 and 5 - 2.

Due to assumed transverse symmetry, the seven equations of motion consist of two sets of coupled equations, the four coupled vertical plane equations of motion (surge, heave, pitch, CWP heave) and three coupled lateral plane equations of motion (sway, roll and yaw). These two sets of equations are solved separately by standard matrix inversion methods. The calculated platform motions, η_k, are used to calculate the CWP attachment point motions, η_{p_k}:

$$\eta_{p_1} = \eta_1 + \eta_5 z_p$$
$$\eta_{p_2} = \eta_2 - \eta_4 z_p + \eta_6 x_p$$
$$\eta_{p_3} = \eta_3 - \eta_5 x_p$$
$$\eta_{p_4} = \eta_4$$
$$\eta_{p_5} = \eta_5$$
$$\eta_{p_6} = 0$$
$$\eta_{p_7} = \eta_7$$

where x_p and z_p are the x and z coordinates of the CWP attachment point ($y_p \equiv 0$). The motions η_{p1}, η_{p2}, η_{p4}, and η_{p5} are, in turn, used to calculate the actual responses of the CWP. The response amplitude operators or transfer functions for motions and cold water pipe loads are given by the values of η, η_p, etc. for a range of regular wave frequencies.

5.5 Evaluation of Hull Hydrodynamic Coefficients and Forces

A number of methods exist for the determination of added mass, damping and wave exciting forces for surface and submerged, floating platforms or hulls. Most methods are designed to treat one of the following specific platform types:

- Slender hulls, such as ships and submarines.
- Axisymmetric hulls such as floating or spar buoys.
- Semi-submersibles consisting primarily of submerged, slender hulls and tubular members.
- Catamarans having two slender, shiplike hulls.

In general all of these methods assume transverse hull symmetry. Recently methods have become available for treating platforms having arbitrary three-dimensional geometry. The method of Garrison (8) is a notable example of such methods.

The methods used in this study all have certain common characteristics:

- The methods are applicable to zero forward speed.
- Wave amplitude is small compared with platform length, beam and draft and linear theory is applicable.
- It is not necessary to assume that wave length is large compared with length, beam and draft, although accuracy increases as wave length increases.

In this section, methods applicable to this study are briefly described.

5.5.1 Slender Ship and Submersible Hulls - Slender floating and submerged mono-hulls are treated in this study using methods described by Barr, et al (7). These methods are essentially identical to the strip theory method of Salvesen, et al (21) for zero forward speed. The methods have been shown in Reference 7 to give excellent agreement with other well validated strip theory seakeeping computer programs.

The hull added mass, damping and wave exciting forces are calculated by integration of computed values for a number of transverse ship section. These sectional values are computer using the Frank close-fit method (22). In the present computer programs section shapes can be specified either by specification of a series of section offsets or by specification of section beam, draft and area and use of a Lewis form section shape.

5.5.2 Axisymmetric Hulls - A number of methods, such as those of Bai (16) and Garrett (23), are available for efficient computation of the zero forward speed added mass, damping and wave exciting forces of axisymmetric hulls. The present methods accept matrices of these values, as computed by a separate computer program.

The method of Garrison (8) can be used for calculation of platform added mass, damping and wave exciting forces. The preparation of input data is simplified and the computation cost is reduced by the existance of two planes of symmetry. Hull geometry need only be specified for one quarter of the hull.

5.5.3 Semi-Submersible Hulls - The term semi-submersible covers a wide range of platform geometries and types. In the present study, a semi-submersible has been specified to be a platform with one or two parallel, horizontal, slender, submerged hulls,

each having one or more vertical, surface piercing columns, as shown in Figure 5 - 3. The effects of multiple, cylindrical members are neglected, although the methods can be readily modified to include such members, if important.

The added mass, damping and wave exciting forces are calculated using the methods described in Reference 7. The contributions of the submerged hulls are calculated using the same methods used for single hulls, Section 5.5.1. The contributions of the vertical columns are calculated using methods similar to those used by Paulling (24). Interactions between submerged hulls and columns are neglected.

5.5.4 Arbitrary, Three-Dimensional Hulls - The method of Garrison, which is described in detail in Reference 8, can be used to calculate zero forward speed added mass, damping and wave exciting forces for arbitrary, three-dimensional hulls as well as for hulls having one or two planes of symmetry. This method is based on the Green's function method and uses quadrilateral surface elements of constant strength. The body surface is represented by a series of surface panels and modal points corresponding to the corners of these quadrilateral surface panels.

For complex body shapes, considerable time and skill are required to prepare input to the computer program describing these surface panels. The computation cost is determined primarily by the number of surface panels used or required.

This method has been generally well validated by comparison of computed results for various hull shapes with model tests results, as described in Reference 8. The method does not include any means for introducing viscous damping, although some comparisons in Reference 8 indicate the need for such added damping. In the present methods, means are provided for

introducing additional viscous roll damping.

5.6 Hull Hydrostatic Forces

Platform hydrostatic forces have an important influence on heave, roll and pitch motions. In the present study these forces are calculated from platform geometric and mass properties. Heave hydrostatic restoring force is given by

$$\rho g A_{wp}$$

where A_{wp} is waterplane area. Roll and pitch hydrostatic restoring forces are given by:

$$\Delta \, GM$$

where Δ is platform displacement and where the metacentric height, GM, is given by

$$GM = \frac{I_{wp}}{\nabla} - BG$$

where

BG is vertical distance from the hull center of buoyancy to the hull center of gravity, measured positive upward.

I_{wp} is hull waterplane area moment of inertia.

∇ is hull displaced volume, $\nabla = \Delta/\rho g$.

Waterplane moments of inertia and metacentric heights are calculated for roll and pitch, unless the platform is asixymmetric or square, in which case the values are equal.

The computer program incorporates factors for reducing heave, roll and pitch hydrostatic restoring forces. These reductions are used to represent single or multiple penetrations of the hull waterplane, such as a moonpool for the CWP. The reduction of resorting force for any penetration (S) must be calculated by hand.

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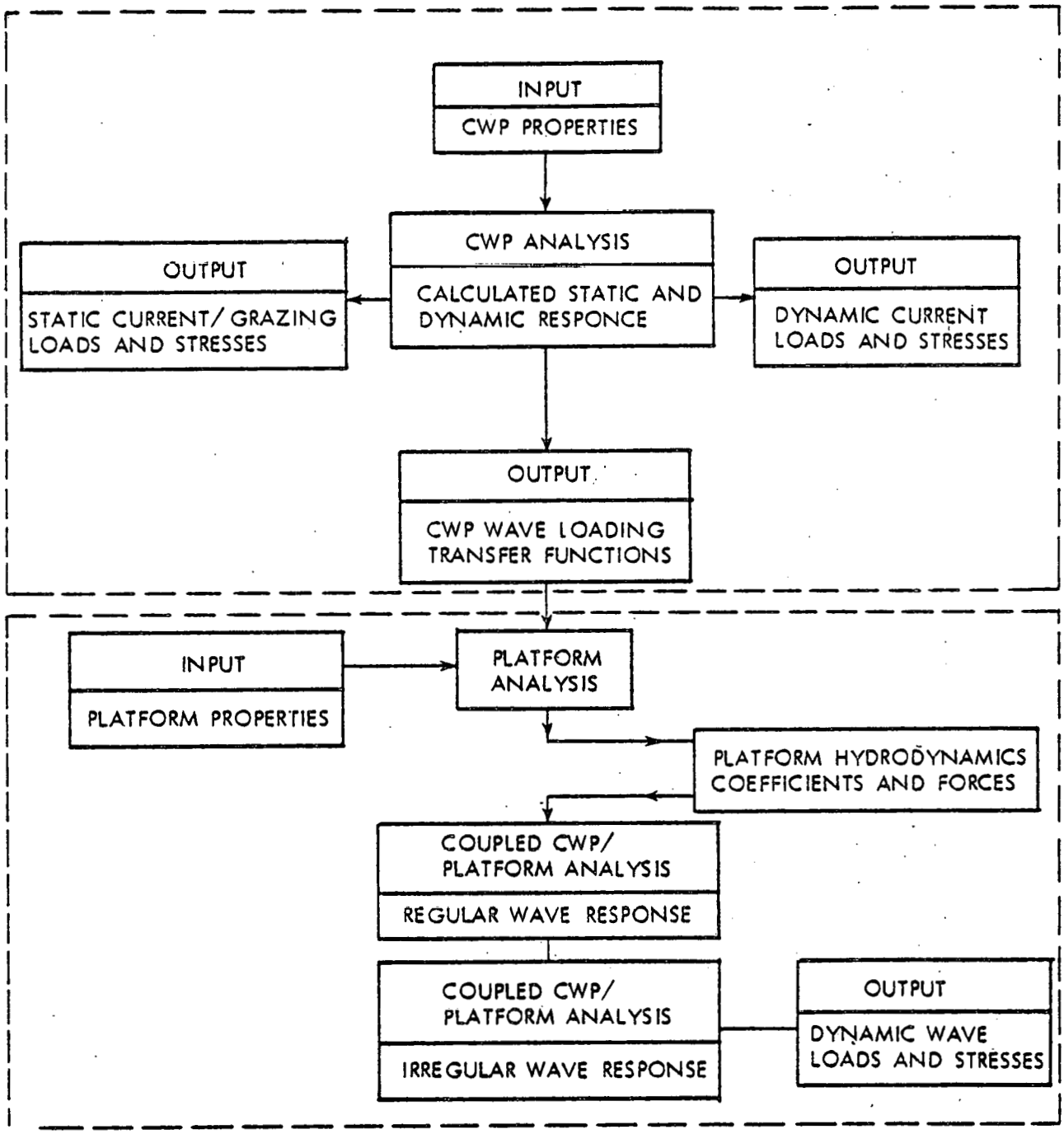

FIGURE 5-1 - FLOW CHART FOR CALCULATION OF COUPLED CWP/PLATFORM STATIC AND DYNAMIC RESPONSE

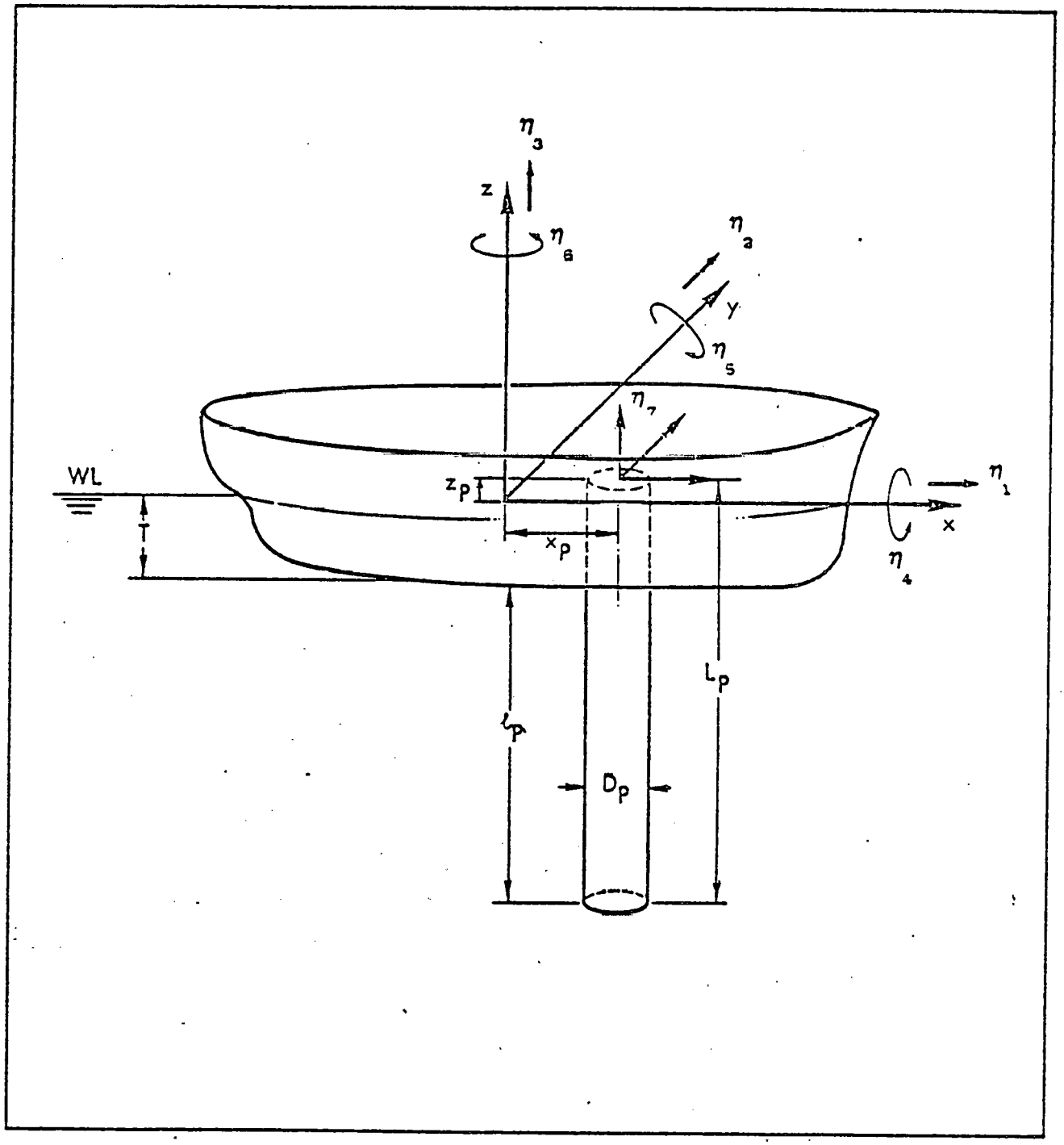

FIGURE 5-2 - DEFINITION OF COORDINATES, MOTION, AND COLD WATER PIPE DIMENSIONS

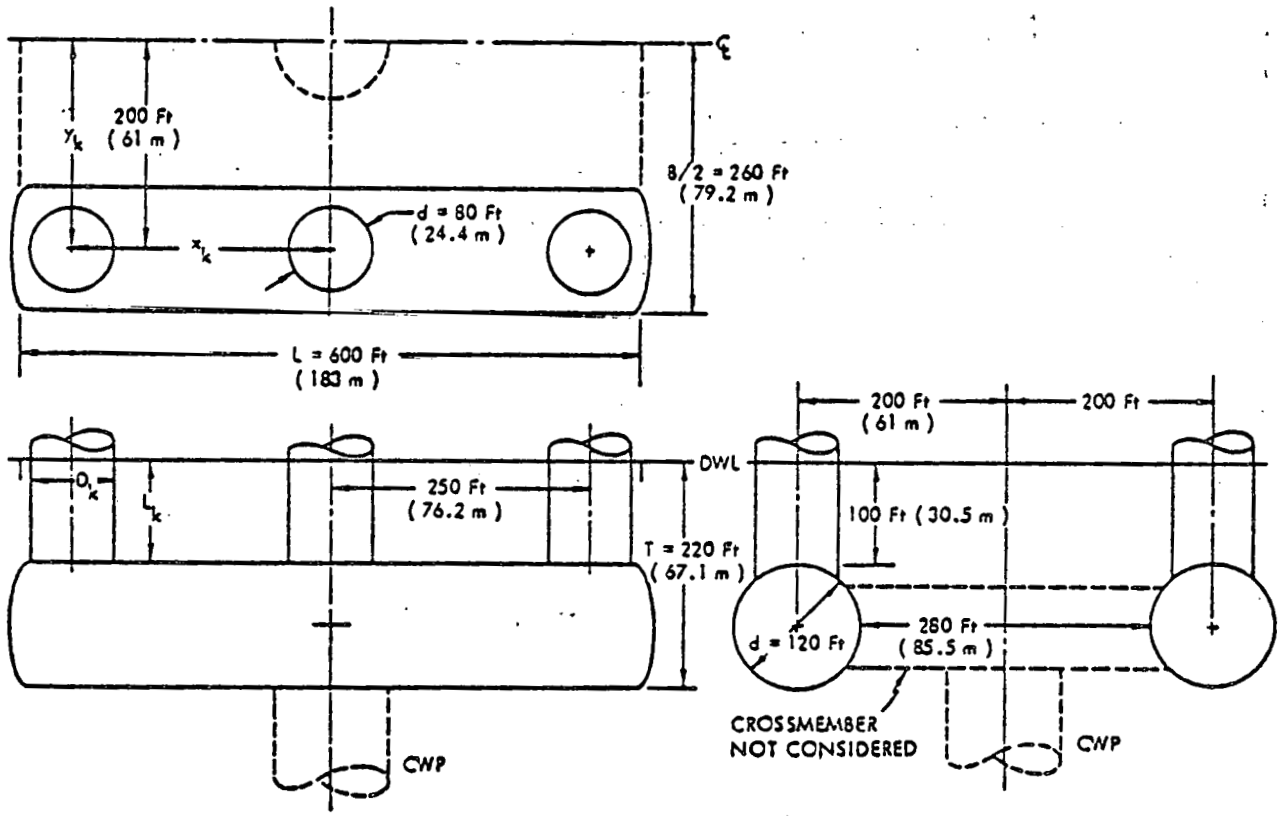

FIGURE 5-3 - SKETCH OF TYPICAL SEMI-SUBMERSIBLE PLATFORM

6.0 DESCRIPTION OF COMPUTER PROGRAMS

The methods described in Section 3 to 5 have been incorporated in several computer programs which can be used to calculate CWP static and dynamic responses and coupled CWP/platform dynamic responses. There are four basic programs which are:

- CWPFLX - Calculate CWP bending responses.
- CWPEXT - Calculate CWP extension (longitudinal) and torsional responses.
- COTEC - Calculate slender hull sectional hydrodynamic properties.
- XOTEC - Calculate coupled CWP/platform behavior in regular and irregular ocean waves.

It was originally intended to provide an additional program, a version of Garrison's program which would calculate the input data required program OTEC. The general features of these programs are described in this section. User's manuals for each program are provided in Appendices B - E of this report. These appendices describe, in detail, program inputs, outputs, etc., and present sample calculations.

6.1 Description of Program "CWPFLX"

The computer program "CWPIPE" calculates the bending responses of the cold water pipe due to the motions of the OTEC platform and loads due to current, waves or other sources. The capabilities of this program include:

6.1.1 Types of Loading Considered

- Translational and rotational motions of OTEC platform. The CWP response due to unit motion of the platform at the CWP/platform attachment is calculated by the program.

- Wave loads. The CWP responses due to harmonic ocean surface waves of specified wave height and wave frequency are calculated.
- Steady current loads. The steady current loads are calculated for a set of parameters (V_s, V_o', a_1, a_2, k_1, k_2) defining a steady current profile as follows =

$$V(z) = V_s(V_o' + a_1 e^{-k_1 z} + a_2 z e^{-k_2 z})$$

- Arbitrary loads. The users can also specify an arbitrary load profile of his own choice. The program accepts uniform force and moment, force and moment gradients, and concentrated forces and moments. With these parameters any arbitrary load distribution can be modeled with good accuracy.

6.1.2 <u>CWP Geometric Properties</u>- The input data for the geometry of each CWP section include:

- Outside diameter
- Wall thickness
- Density of the CWP material
- Density of water
- Modulus of elasticity
- Elastic foundation (if used)
- Rigid section

From these input data the following sectional properties are calculated by the program

- Moment of inertia
- Mass (including added mass and mass of the internal flow)
- Axial force (due to CWP net weight in water)

It has been found for typical CWP applications that the CWP weight is much greater than the inertia force due to CWP heaving motion. All the above properties can be different for different sections.

6.1.3 Special CWP Supports and Connections - For some CWP designs, it may be required to have supports, such as mooring lines, along the CWP or to have special connection members such as very flexible joints. These special connections and supports can be readily handled by this computer program by specifying the location and stiffness of the supports or connections. The specific features which can be handled include:

- Rigid support (No deflection at this point).
- Flexible support or joint
  - Location and linear stiffness
  - Location and rotational stiffness
- Hinge (zero bending moment)

6.1.4 Concentrated Mass and Rotational Inertia - This program can also handle concentrated masses located at various points on the CWP.

6.1.5 Types of Analysis - The program can be used to determine the following responses:

- Responses due to unit CWP/platform attachment translation.
- Responses due to unit CWP/platform attachment rotation.
- Responses due to wave of unit amplitude.
- Responses due to static current.
- Responses due to dynamic loads induced by a current or by other sources.
- Responses due to arbitrary static load distribution.
- Free vibration for natural frequencies and modeshapes.

This program can be used to calculate CWP responses for a number of these loadings at one time. This is much more economical than making separate runs for each load.

The damping distribution is treated in a manner similar to that for the loads so that different damping can be specified for different loads. For each loading condition, up to 20 frequencies of excitation can be analyzed in one run.

6.1.6 Computation Procedure - This program can handle both static and dynamic analyses. For static analysis, many steps necessary only for dynamic analysis are by passed.

For dynamic analysis, the program can compute natural frequencies and modeshapes for up to 20 modes. This is considered quite adequate for the cold water pipe analyses. The users can use more modes if necessary, however.

After the frequencies and modeshapes have been computed, the responses for different modes are then calculated for different loading conditions with the same or different frequencies.

6.1.7 Input Methods and Requirements - This program cost less than $5.00 for static calculation and less than $40.00 for most dynamic calculation using 20 frequencies and all responses. The computer cost is therefore relatively inexpensive in comparison to the manpower costs required to prepare input data. For this reason a time sharing computer system is recommended for calculations. This program is now in the UCS system, but other similar system can be readily used. In most time sharing systems, input data can be loaded through the so called "prompt" method. The users can type in the input line-by-line using a remote terminal. The computer then treats each line as required by the program. If the user makes an error, such as the number of the data records, the type of data, etc., a message from the computer can alert him

to his error. The user can make a correction or re-input the whole line again. The input data can also be loaded through a file. This file can be edited to change input errors or modified for use in treating a different problem. Both of the above methods have certain advantages, but for experienced users it is generally more convenient to create a file. This is discussed in more detail in the User's Manual, Appendix B.

The details of input formats are discussed in Appendix B.

6.2 Description of Program "CWPEXT" - The computer program "CWPEXT" calculates the extension or longitudinal and torsion responses of the CWP due to arbitrary loads acting on the CWP and due to the motions of the OTEC platform. The capabilities of this program include:

6.2.1 Types of Loading Considered

6.2.1.1 For extension analysis

- Weight of the CWP.
- Arbitrary loads.
- Heave motion of the OTEC platform.

6.2.1.2 For torsion analyses

- Arbitrary loads.
- Yawing motion of OTEC platform.

6.2.2 CWP Geometry Properties - The input data required to describe CWP geometry include:

6.2.2.1 For extension analysis

- Cross-sectional area, A. (For CWP with diameter D and thickness t, $A = \pi(D - t)t$).
- Modulus of elasticity, E.
- Rigid section.
- Mass per unit length including added mass.

6.2.2.2 For torsion analysis

- Polar moment of inertia, I_p.

  Where $I_p = \frac{\pi}{8} D^2 t(D - 3t)$

- Shear modulus of elasticity, G,

$$G = \frac{E}{2(1+\nu)}$$

  where ν is the Poisson's ratio.

- Mass polar moment of inertia including added mass moment inertia.

- Rigid section.

6.2.3 Special Supports and Connections

6.2.3.1 For extension analysis

- Connection springs between CWP sections.

These springs connect the sections of the CWP. If k_i is the stiffness of a connection, N_i is the axial force and μ_i is the extension of this spring;

$$N_i = \mu_i k_i$$

- Support springs.

These springs provide longitudinal support to the CWP. If ΔN_j is the change of axial force, k_j and μ_j are the spring stiffness and extension of the CWP:

$$\Delta N_j = \mu_j k_j$$

6.2.3.2 For torsion analysis

- Connection springs.
- Support springs.

These springs have the same functions as those for extension except that they are associated with or resist rotation of the CWP.

6.2.4 Concentrated CWP Parameters

6.2.4.1 For extension analysis

- Concentrated masses at specified locations.
- Concentrated forces at specified locations along the CWP.

6.2.4.2 For torsion analysis

Concentrated mass moments of inertia.
Concentrated torques.

6.2.5 Types of Analyses

6.2.5.1 For extension analysis

Responses due to arbitrary static or dynamic loads.
Responses due to unit heave of the OTEC platform.

6.2.5.2 For torsion analysis

- Responses due to arbitrary, static or dynamic loads.
- Response due to unit yawing of the OTEC platform.

6.2.6 Computation Procedure

This program can treat both static and dynamic analyses. For dynamic analysis, only undamped forced vibration and free vibration are considered. The computational procedures are the same as these for bending, but the transfer matrices are different.

6.2.7 Input Methods

The input data for CWPEXT are quite simple in comparison with those for the bending program CWPFLX. All necessary steps are given in Appendix C. The cost for a typical run is less than two dollars.

6.3 Description of Program "COTEC"

The computer program "COTEC" calculates the zero forward speed sectional hydrodynamic properties for a slender platform or hull, for use as input to program "OTEC" described in Section 6.4. The sectional wave exciting force, added mass and damping are calculated for sway, heave and roll for up to 20 frequencies and up to 7 wave heading angles. These values, for sections normal to the platform axis, are integrated in program "OTEC" to provide wave exciting forces, added mass and damping for the complete platform or hull for all degrees-of-freedom except surge. Surge values are calculated in program "OTEC".

6.3.1 Types of Sections Considered - The program can consider a number of section types, applicable to various hull types. These include:

- Floating monohulls (ships or barges).
- Submerged monohulls (submarines).
- Floating turn hulls (catamarans).
- Submerged turn hulls (semisubmersibles).

The program requires that the hull have transverse symmetry. For floating hulls, bulb sections which have a maximum beam greater than the beam at the waterline can also be treated.

6.3.2 Section Geometric Properties - Hull sectional properties can be specified in one of two ways:

The detailed x-y coordinates or offsets for one-half of the section can be specified.

The half beam, draft and sectional area coefficient (section area divided by beam times draft) and section type (Lewis form or bulb form) can be specified.

The first approach must be used for all section types except the floating monohull, which can be specified by either approach. For floating monohulls it will usually be quite acceptable and will always be much faster and simpler to use the second approach since much less input data are required.

6.3.3 Computational Procedure - The program user the Frank close-fit method, which is described in detail in Reference 22, to calculate the sectional properties. This method determines the hydrodynamic properties of a two-dimensional cylinder(s) having the specified cross-section shape. The perimeter of the cylinder is represented by a number of straight-line chords or segments over which constant singularity strength is assumed. When section offsets are specified, the straight-line chords are those connecting the specified points. When section area is specified, the program fits a mathematical shape to the section and divides the resulting perimeter into an appropriate number of segments or chords.

The selection of offset points to represent a given section shape is discussed in Reference 22. The number of points required for good accuracy depends on section shape. Closer spacing of points is generally required near the free surface and in regions of small radii of curvature.

Added mass and damping are independent of wave heading angle, while wave exciting forces are dependent on wave heading angle. All values are dependent on frequency, and all calculated values are for unit section motions and for unit wave amplitude.

6.3.4 Input Methods and Requirements - Data can be input by cards or using a remote terminal as described in Section 6.1.7. The details of required data inputs and formats are described in Appendix D. It should be noted that the number and values of frequencies specified must correspond exactly to those specified

in program "XOTEC" (Section 6.4) and to those specified for translation, rotation and waves in program "CWPFLX". The number and values of wave heading angle specified must correspond exactly to those specified in program "XOTEC".

6.3.5 Data Output - The basic output of this program are data files. These files are read and used by program "XOTEC" to predict hydrodynamic characteristics of the complete hull. The program also prints out various final and intermediate results. The printout includes specified or calculated section offsets which are useful for checking the input data.

6.4 Description of Program "XOTEC"

Computer program "XOTEC" calculates the coupled response of the OTEC CWP and platform for regular and irregular, long-crested waves. This program uses, as input, a file created by program "CWPFLX" and, except for axisymmetric hulls, files created by program "COTEC".

This program has a number of functions. The basic function is to compute ocean wave induced platform motions, velocities and accelerations, and CWP motions, shear forces and stresses and bending moments and stresses. Platform responses are calculated at the origin and at up to three other specified locations. CWP responses are claculated at a number of specified points along the CWP length.

6.4.1 Organization and Functions - A computer program flow chart for "XOTEC" is shown in Figure 6 - 1. This flow chart indicates all subroutines called by the main line program. The detailed functions of the program, and the subroutines in which these functions are carried out are given in Figure 6 - 1.

6.4.2 Data Inputs and Requirements - Two types of data are required by program "OTEC". The first are data input using data

cards or a remote terminal; the methods used to input such data from a terminal are those described in Section 6.1.7. The second type of data input is from files created by computer programs "COTEC" and "CWPFLX".

The data from the files created by program "COTEC" are used for all non-axisymmetric platform and hence program "COTEC" must be run before program "XOTEC" for all designs with non-axisymmetric platforms. The input data to program "XOTEC" specifies whether the platform is axisymmetric and hence whether this file is read.

The data from the file created by program "CWPFLX" are always read by program "XOTEC" and hence program "CWPFLX" must always be run before program "XOTEC".

The set of frequencies used by programs "XOTEC" "COTEC" and "CWPFLX" must be identical. The set of wave heading angles used by programs "XOTEC" and "COTEC" must also be identical. Program "CWPFLX" must be run with unit wave amplitude when used with program "XOTEC".

6.4.3 Processing of Input Data - Program "XOTEC" reads a number of inputs (see Appendix E), many of which are used to compute the platform mass and stiffness (hydrostatic restoring force) matrices as defined in Equation [44].

For axisymmetric hulls the program reads additional input data giving platform added mass, damping and wave exciting matrices. For non-axisymmetric hull, the program reads sectional added mass, damping and wave exciting force data from a file created previously by program "COTEC". Strip theory methods, Reference 21, are used to determine complete hull added mass, damping and wave exciting force matrices from these sectional data and from hull geometric data (length, section spacing, etc.) read as input by "XOTEC". For semi-submersible hulls, the various matrices reflect the contributions of the submerged hulls and the surface piercing

columns, whose geometry is described by inputs to program "XOTEC".

Program "XOTEC" initially reads only that part of the file created by program "CWPFLX" which gives CWP transfer functions at the top of the CWP. The values are used in assembling the equations of motion. After the platform motions are determined, the program reads the complete file created by "CWPFLX" and uses this file and the platform motion to calculate CWP response.

6.4.4 Computational Procedures - The computational procedures used are outlined in Sections 5 and 6.4.3. All algebraic operations are carried out using complex arithmetic, although most final results are given in polar form, where amplitude and phase are determined by

$$A_n = \left[\eta_r^2 + \eta_i^2\right]^{\frac{1}{2}}$$

$$\phi_n = \tan^{-1}\left[\eta_i/\eta_r\right]$$

where

$$\eta = \eta_r + i\eta_i$$

and where:

A_n is amplitude of response η.
ϕ_n is phase angle of response η.

All phase angles are defined with respect to positive wave amplitude or wave crest. A phase angle of zero degrees thus denotes a motion or load in phase with wave crest.

The coupled equations of motion for vertical or longitudinal motions (surge, heave, pitch and CWP heave) and the lateral motions (sway, roll and yaw) are solved separately using the Gauss reduction method.

6.4.5 Data Output - The data output and the options associated with this output are described in detail in Appendix E. The output is divided into four basic parts, which are:

- Printout of all data input from cards or a terminal and CWP transfer functions for the top of the CWP from the file created by "CWPFLX".
- Calculated and/or input platform hydrodynamic and hydrostatic forces, complete coefficient matrix for the left hand side of the equation of motion and exciting forces.
- Calculated platform and CWP responses in regular waves of unit amplitude and of specified frequencies.
- Calculated platform and CWP responses in irregular waves for the specified sea states.

In the present version of the program all of these outputs are printed out. All of these outputs are labeled. Keys to labeling are given in Appendix E.

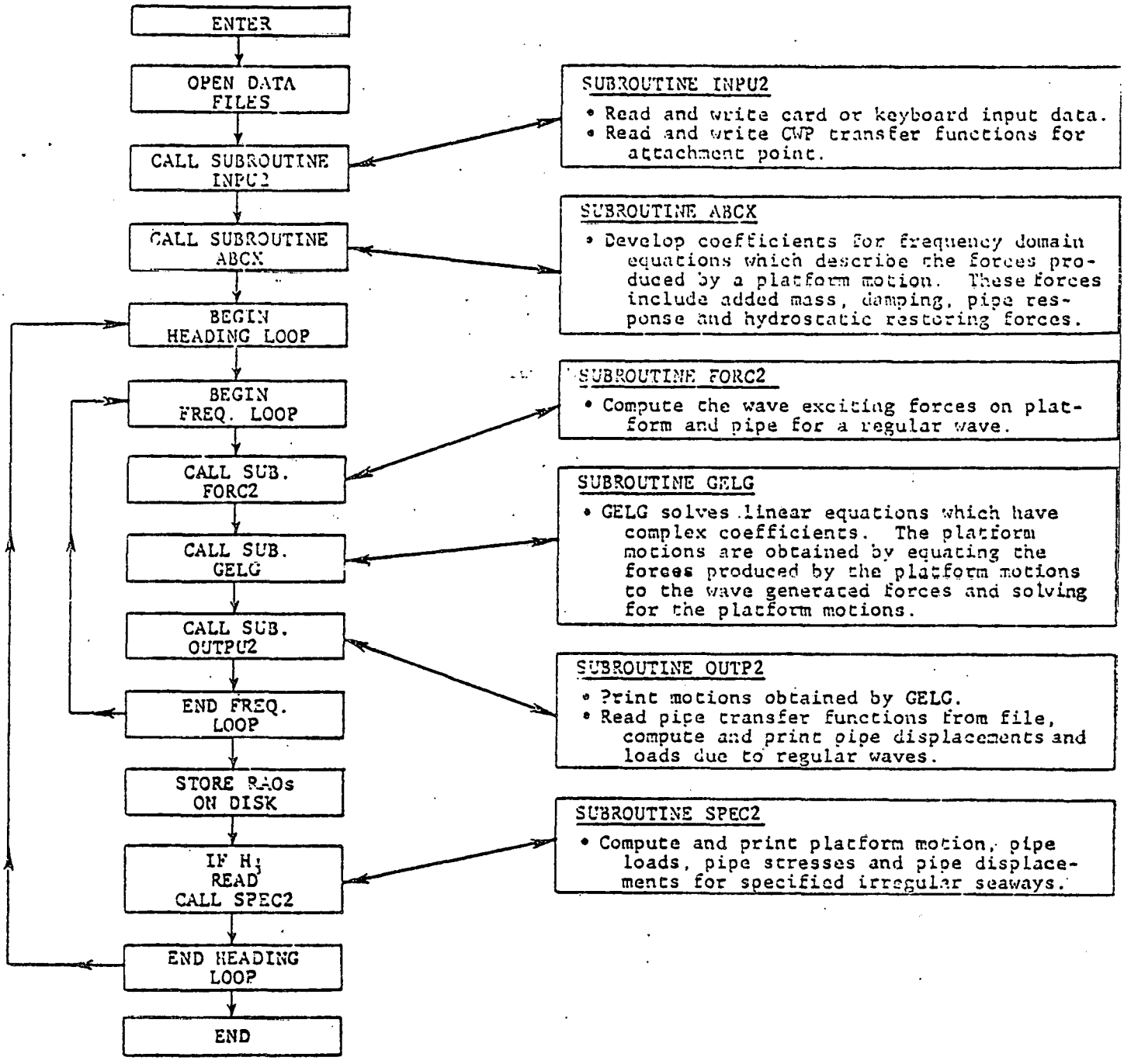

Figure 6-1 FLOW CHART OF PROGRAM "XOTEC"

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7.0 VALIDATION OF METHODS

It is essential to validate or to verify the accuracy of any theoretical method which is to be used in practical engineering problems. This is particularly important when these methods are to be made available to and are intended for use by many organizations and individuals. An important part of the present effort has been validation of the computer programs. Validation has been accomplished using both analytical solutions and model test data, as described in this section. Validation has included results for the CWP alone and results for the coupled CWP and platform in ocean waves. While the validation effort has been concerned primarily with dynamic response, the ability of the programs to calculate static response due to current has also been validated.

7.1 Validation Using OTEC-1 Model Test Data

The ultimate test of any analytical method is its ability to reproduce test results. Test data, usually model test data, is the best basis for validation. When the validation effort for the present methods began, the only available test data were those for an early OTEC-1 configuration using the Hughes Mining Barge (HMB), Reference 5.

The OTEC-1 data were considered a good basis for validation because of their good consistency, lack of scatter and general absence of large non-linearities. In addition, the motions of the HMB without CWP were accurately predicted by programs COTEC and XOTEC (5); this helps to insure that these data are a useful basis for validating program CWPFLX.

Figures 7-1 to 7-4 show comparisons of the predicted and measured platform motions and CWP bending moment response amplitude operations or RAO's for head and beam waves. These results are restricted to the case of the stiff CWP with rigid attachment.

In order to increase clarity, these figures show only mean curves through the data from three sets of irregular wave tests plus regular wave tests. Individual points calculated using the present methods are shown. Calculated results obtained from an earlier HYDRONAUTICS CWP program using finite-difference methods (program PIPE 4), as described in Reference 3, are also shown.

The responses predicted using the present methods and measured responses are in generally good agreement. The predicted and measured platform motions are in particularly good agreement. The only significant discrepancy between predicted and measured bending moments is around five radians per second for the upper location in head seas (Figure 7-2a). This overprediction of bending moment is due to the underprediction of damping for the large motions associated with the CWP modal frequency; the linearized damping was based on rms motions for sea state II, and not on the peak response.

The motions and CWP bending moments predicted using the two theoretical CWP analyses (programs CWPFLX and PIPE 4) are generally very similar. The major difference is the lower peak bending moments predicted using CWPFLX; this is a direct result of the larger, and more realistic, damping used with program CWPFLX.

7.2 Validation Using Analytical Solutions

There are several limitations to using only model test data for validation. The first is the limited amount of available data. The second is the absence of data for a CWP alone; available data are for a coupled CWP and platform. A third limitation could be the lack of knowledge of CWP damping for the small scale models. It was therefore considered essential to use results from analytical solutions as well as model data for validation.

While the general problem of CWP dynamic response cannot be

solved analytically, several important special cases can. These include response of prismatic CWPs with zero tension and with constant tension. Detailed comparisons of results obtained using the present computer programs and using programs based on analytical solutions are described in this section.

Prismatic CWP With No Axial Tension - Analytical solutions are available for dynamic bending of prismatic (constant section) beams without tension. These solutions have been incorporated in an earlier HYDRONAUTICS CWP analysis program (PIPE 3) described in Reference 3. Calculations were carried out for several different CWP designs using program PIPE 3 and program CWPFLX. The results were compared to insure that results from program CWPFLX were in good agreement with the analytical solution. Some results for a GRP CWP were presented in the Interim Report (6). These showed good agreement between the two methods.

A detailed comparison of results for a 58 foot diameter reinforced concrete CWP alone and with a disc-type platform, as described in Table 7-1, is highlighted in Tables 7-2 to 7-4 and Figures 7-5 to 7-10. Table 7-2 compares responses of the CWP to unit translational motion of the upper end of the CWP, at a representative frequency of 0.6 radians per second while Figures 7-5 to 7-7 compare shear forces due to translation at various frequencies. Shear force has been selected for comparison because the computational procedures used make it subject to greater error than displacements on bending moments. Figures 7-8 to 7-10 compare shear forces due to unit rotation of the upper end of the CWP at various frequencies.

Table 7-3 presents a comparison of calculated CWP responses arising from the coupled response of the CWP and disc platform to two irregular, long-crested (uni-directional) seas defined by

TABLE 7-1

CHARACTERISTICS OF CWP AND PLATFORM USED FOR THE COMPARISONS OF TABLES 7-2 TO 7-4 AND FIGURES 7-1 TO 7-6

CWP Characteristics	
Outside Diameter	58 feet
Wall Thickness	2 feet
Length	3181 feet
Modulus of Elasticity	3×10^6 psi
Density	Neutrally buoyant
Joints	None
Pitch/Roll Attachment Stiffness	10^9 pound-feet/radians
Heave Attachment Stiffness	10^6 pounds/foot
Disc Platform Characteristics	
Displacement	228,000 long tons
Diameter	320 feet
Draft	100 feet
Metacentric Height	61 feet
Pitch/Roll Gyradius	110 feet
VCG-below waterline	68 feet

TABLE 7-2

CALCULATED CWP RESPONSES FOR UNIT TRANSLATION
OF CWP ATTACHMENT AT 0.6 RADIANS PER SECOND FREQUENCY

Depth Feet	Displacement Anal.*	Displacement New*	Shear/10^6 Anal.*	Shear/10^6 New*	Bending Mom./10^8 Anal.*	Bending Mom./10^8 New*
0	1.00	1.0	1.03	1.04	0.01	0.01
300	0.72	0.72	0.13	0.13	1.51	1.53
650	0.20	0.20	0.65	0.65	0.64	0.64
900	0.26	0.26	0.61	0.61	1.63	1.63
1350	0.52	0.52	0.24	0.24	2.60	2.60
1700	0.18	0.18	0.73	0.73	0.85	0.86
2050	0.33	0.33	0.60	0.60	1.75	1.75
2400	0.49	0.49	0.06	0.06	2.79	2.80
2750	0.13	0.12	0.52	0.52	1.67	1.67
3181	0.76	0.76	0	0	0	0

* Anal. - Analytical Solution
New. - New NOAA/DOE Methods - CWPFLX

TABLE 7-3

COMPARISON OF CALCULATED CWP RESPONSES
FOR DISC PLATFORM WITH NEUTRALLY BUOYANT CONCRETE CWP
a $H_{1/3}$ = 20 Feet

Depth Feet	Displacement-Feet Anal.3*	CWPFLX*	Shear - 10^6 Pounds Anal.3	CWPFLX	Bending Mom. 10^8 Lb Ft Anal.3	CWPFLX
0	2.60	2.69	1.28	1.22	4.39	4.36
300	1.33	1.38	0.92	0.85	3.07	3.25
650	0.84	0.86	1.08	1.19	4.58	4.75
900	1.20	1.24	1.13	1.19	5.18	5.44
1350	1.11	1.15	1.13	1.12	4.83	4.98
1700	0.55	0.57	1.50	1.51	2.65	2.85
2050	1.17	1.18	1.27	1.33	4.54	4.53
2400	1.31	1.32	0.41	0.43	6.18	6.30
2750	0.27	0.28	1.14	1.17	3.67	3.74
3180	2.16	2.18	-	-	-	-
MAX	2.60	2.69	1.5	1.53	6.2	6.30
a $H_{1/3}$ = 46 Feet						
0	13.01	13.30	6.45	6.48	0.15	0.15
300	7.35	7.43	5.96	5.66	1.79	2.21
650	10.66	9.79	3.99	4.33	3.28	3.84
900	10.66	10.69	3.24	3.37	3.50	3.99
1350	4.86	4.92	7.54	7.66	1.76	1.80
1700	5.41	5.40	7.85	7.79	1.65	2.07
2050	10.50	11.47	3.85	3.84	3.41	4.22
2400	8.79	9.40	3.06	3.38	3.44	4.08
2750	1.08	1.12	5.99	6.30	1.75	2.01
3180	16.51	17.85	-	-	-	-
MAX	16.51	17.85	8.0	8.26	3.60	4.45

* Anal. - Analytical Solution for CWP

* CWPFLX - New NOAA/DOE Methods

TABLE 7-4

COMPARISON OF CALCULATED PLATFORM MOTIONS
FOR DISC PLATFORM WITH NEUTRALLY BUOYANT CONCRETE CWP

Significant Wave Height-Feet	Surge-Feet		Pitch-Degrees	
	Anal.3	CWPFLX	Anal.3	CWPFLX
20	3.60	3.64	2.39	2.37
36	8.06	7.98	5.93	5.84
46	10.71	10.65	7.77	7.63
58	14.48	14.57	9.57	9.37

significant wave heights of 20 and 46 feet and frequencies of maximum energy of 0.61, and 0.46 radians per second. Table 7-4 compares platform motions for the coupled CWP and platform for these plus two additional sea states.

The comparisons presented in Table 7-2 and Figures 7-5 to 7-10 indicate that results for the CWP above are generally in excellent agreement. The largest differences occur at the highest frequency of 1.0 radians per second; response at this frequency is generally not very important. The largest differences tend to be at the top of the CWP. Figures 7-5 through 7-8 show results for both single and double percision versions of program CWPFLX (single precision is based on 32 bit words). The double precision results are in better agreement, as discussed in a later section.

Tables 7-3 and 7-4 indicate that the agreement in CWP responses and platform motions is generally good, particularly for the smaller wave heights. Agreement in calculated platform motions is particularly good. The differences in coupled responses at the large wave heights is probably due to the strong sensitivity of coupled response to changes in CWP transfer functions at some frequencies.

Prismatic CWP With Constant Axial Tension - In general, analytical solutions are not available for bending of beams with tension. Analytical solutions are available, however, for certain cases of undamped, prismatic (constant section) beams with constant tension; these correspond to buoyant CWPs with end loads. Tables 7-5 and 7-6 compares calculated responses from an analytical solution and from program CWPFLX for the stiff OTEC-1 model CWP of Reference 5. For these calculations the CWP was assumed to have no damping, a cantilever (stiff) upper end attachment, a uniform tension of five pounds (comparable to CWP weight in water) and a harmonic, transverse exciting force of one pound amplitude at the free end.

TABLE 7-5

COMPARISON OF CALCULATED CWP RESPONSES FOR OTEC-1 MODEL CWP WITH CONSTANT AXIAL TENSION AND UNIT FREE END EXCITING FORCE AT 0.628 RADIANS PER SECOND FREQUENCY

CALCULATED USING ANALYTICAL SOLUTION				CALCULATED USING PROGRAM CWPFLX			
LOCATION	DEFLECTION	MOMENT	SHEAR	DISTANCE	DISPLACEMENT	BENDING MOMENT	SHEAR FORCE
0.	0.	.2398E+02	-.1813E+01	0.00	0.	.2404D+02	.2813D+01
.1379E+01	-.1136E-01	.2154E+02	-.1812E+01	.13	.1093D-03	.2379D+02	.2813D+01
.2759E+01	-.4386E-01	.1920E+02	-.1810E+01	.36	.7958D-03	.2337D+02	.2813D+01
.4138E+01	-.9521E-01	.1696E+02	-.1806E+01	1.82	.1961D-01	.2075D+02	.2812D+01
.5517E+01	-.1632E+00	.1482E+02	-.1797E+01	3.28	.6130D-01	.1831D+02	.2809D+01
.6897E+01	-.2458E+00	.1276E+02	-.1782E+01	4.74	.1232D+00	.1603D+02	.2802D+01
.8276E+01	-.3408E+00	.1079E+02	-.1762E+01	6.21	.2027D+00	.1382D+02	.2790D+01
.9655E+01	-.4465E+00	.8911E+01	-.1734E+01	7.67	.2975D+00	.1164D+02	.2772D+01
.1103E+02	-.5609E+00	.7115E+01	-.1699E+01	9.13	.4051D+00	.9577D+01	.2745D+01
.1241E+02	-.6824E+00	.5408E+01	-.1655E+01	10.59	.5233D+00	.7675D+01	.2711D+01
.1379E+02	-.8091E+00	.3794E+01	-.1602E+01	12.05	.6499D+00	.5888D+01	.2667D+01
.1517E+02	-.9395E+00	.2273E+01	-.1541E+01	13.51	.7830D+00	.4133D+01	.2614D+01
.1655E+02	-.1072E+01	.8644E+00	-.1470E+01	14.98	.9207D+00	.2454D+01	.2550D+01
.1793E+02	-.1206E+01	-.4409E+00	-.1390E+01	16.44	.1061D+01	.9386D+00	.2476D+01
.1931E+02	-.1339E+01	-.1631E+01	-.1300E+01	17.90	.1203D+01	.3883D+00	.2392D+01
.2069E+02	-.1470E+01	-.2699E+01	-.1201E+01	19.36	.1344D+01	.1619D+01	.2297D+01
.2207E+02	-.1599E+01	-.3637E+01	-.1093E+01	20.82	.1483D+01	.2799D+01	.2191D+01
.2345E+02	-.1725E+01	-.4438E+01	-.9755E+00	22.28	.1619D+01	.3831D+01	.2075D+01
.2483E+02	-.1846E+01	-.5093E+01	-.8497E+00	23.74	.1751D+01	.4610D+01	.1949D+01
.2621E+02	-.1962E+01	-.5593E+01	-.7155E+00	25.21	.1878D+01	.5182D+01	.1814D+01
.2759E+02	-.2072E+01	-.5930E+01	-.5734E+00	26.67	.2000D+01	.5678D+01	.1669D+01
.2897E+02	-.2177E+01	-.6095E+01	-.4236E+00	28.15	.2116D+01	.6079D+01	.1513D+01
.3034E+02	-.2276E+01	-.6078E+01	-.2667E+00	29.63	.2226D+01	.6388D+01	.1349D+01
.3172E+02	-.2369E+01	-.5869E+01	-.1030E+00	31.11	.2328D+01	.5935D+01	.1176D+01
.3310E+02	-.2456E+01	-.5459E+01	.6700E-01	32.60	.2424D+01	.5512D+01	.9964D+00
.3448E+02	-.2538E+01	-.4837E+01	.2430E+00	34.08	.2514D+01	.5077D+01	.8095D+00
.3586E+02	-.2615E+01	-.3993E+01	.4245E+00	35.56	.2598D+01	.4395D+01	.6161D+00
.3724E+02	-.2688E+01	-.2913E+01	.6113E+00	37.04	.2677D+01	.3061D+01	.4165D+00
.3862E+02	-.2758E+01	-.1587E+01	.8032E+00	38.52	.2753D+01	.1225D+01	.2111D+00
.4000E+02	-.2827E+01	-.9095E-12	.1000E+01	40.00	.2827D+01	.2224D-15	0.

TABLE 7-6

COMPARISON OF CALCULATED CWP RESPONSES FOR OTEC-1 MODEL CWP WITH CONSTANT AXIAL TENSION AND UNIT FREE END EXCITING FORCE AT 2.121 RADIANS PER SECOND FREQUENCY

CALCULATED USING ANALYTICAL SOLUTION				CALCULATED USING PROGRAM CWPFLX			
LOCATION	DEFLECTION	MOMENT	SHEAR	DISTANCE	DISPLACEMENT	BENDING MOMENT	SHEAR FOR
0.	0.	-.2685E+02	.3703E+01	0.00	0.	.2644D+02	.2657D
.1379E+01	.1235E-01	-.2181E+02	.3700E+01	.13	.1199D-03	.2596D+02	.2657D
.2757E+01	.4611E-01	-.1688E+02	.3678E+01	.36	.0692D-03	.2515D+02	.2656D
.4138E+01	.9646E-01	-.1210E+02	.3622E+01	1.82	.2076D-01	.1997D+02	.2649D
.5517E+01	.1587E+00	-.7477E+01	.3520E+01	3.28	.6266D-01	.1487D+02	.2615D
.6897E+01	.2283E+00	-.3070E+01	.3365E+01	4.74	.1210D+00	.9878D+01	.2538D
.8276E+01	.3009E+00	.1070E+01	.3154E+01	6.21	.1901D+00	.5126D+01	.2406D
.9655E+01	.3725E+00	.4882E+01	.2884E+01	7.67	.2650D+00	.7022D+00	.2212D
.1103E+02	.4394E+00	.8307E+01	.2558E+01	9.13	.3407D+00	.3399D+01	.1955D
.1241E+02	.4981E+00	.1129E+02	.2182E+01	10.59	.4127D+00	.7164D+01	.1634D
.1379E+02	.5458E+00	.1378E+02	.1764E+01	12.05	.4766D+00	.1047D+02	.1254D
.1517E+02	.5800E+00	.1573E+02	.1312E+01	13.51	.5294D+00	.1318D+02	.8254D
.1655E+02	.5988E+00	.1712E+02	.8391E+00	14.98	.5676D+00	.1526D+02	.3575D
.1793E+02	.6008E+00	.1794E+02	.3577E+00	16.44	.5890D+00	.1677D+02	.1359D
.1931E+02	.5853E+00	.1818E+02	-.1184E+00	17.90	.5920D+00	.1771D+02	.6398D
.2069E+02	.5520E+00	.1786E+02	-.5749E+00	19.36	.5755D+00	.1799D+02	.1138D
.2207E+02	.5012E+00	.1703E+02	-.9977E+00	20.82	.5393D+00	.1756D+02	.1614D
.2345E+02	.4337E+00	.1572E+02	-.1373E+01	22.28	.4838D+00	.1656D+02	.2051D
.2483E+02	.3509E+00	.1402E+02	-.1688E+01	23.74	.4101D+00	.1515D+02	.2432D
.2621E+02	.2542E+00	.1200E+02	-.1931E+01	25.21	.3198D+00	.1335D+02	.2744D
.2759E+02	.1459E+00	.9754E+01	-.2092E+01	26.67	.2145D+00	.1113D+02	.2973D
.2897E+02	.2793E-01	.7399E+01	-.2162E+01	28.15	.9552D-01	.8579D+01	.3107D
.3034E+02	-.9727E-01	.5050E+01	-.2135E+01	29.63	.3310D-01	.6049D+01	.3135D
.3172E+02	-.2274E+00	.2834E+01	-.2005E+01	31.11	.1686D+00	.3744D+01	.3048D
.3310E+02	-.3604E+00	.8828E+00	-.1770E+01	32.60	.3083D+00	.1618D+01	.2843D
.3448E+02	-.4943E+00	-.6655E+00	-.1428E+01	34.08	.4499D+00	.3323D+00	.2516D
.3586E+02	-.6276E+00	-.1671E+01	-.9786E+00	35.56	.5912D+00	.1716D+01	.2067D
.3724E+02	-.7592E+00	-.1992E+01	-.4233E+00	37.04	.7306D+00	.1969D+01	.1497D
.3862E+02	-.8890E+00	-.1483E+01	.2367E+00	38.52	.8679D+00	.1080D+01	.8072D
.4000E+02	-.1017E+01	0.	.1000E+01	40.00	.1004D+01	.2225D-15	0.

Tables 7-5 and 7-6 present results for exciting frequencies of 0.628 and 2.12 radians per second, respectively. These frequencies were selected to be well removed from CWP modal frequencies to insure that accurate comparisons could be obtained. All responses are in excellent agreement for both frequencies. It should be noted that the locations for the two sets of calculations are not identical and that the shear forces have a different reference (the analytical results include the applied force and sign, the results from CWPFLX do not).

7.3 Validation of Static Response

The ability of program "CWPFLX" to accurately predict static response to a typical steady-state current loading has been validated by comparing results obtained with "CWPFLX" with results obtained with an existing HYDRONAUTICS program which uses an iterative, numerical solution of the non-linear static beam equations. This earlier program had been previously validated by comparison with other theoretical methods.

In order to provide a realistic test case, a rather flexible GRP CWP having fairly large deflections was selected for the validation case. This CWP has the following characteristics:

Length	3000 feet
Outside Diameter	30.0 feet
Wall Thickness	0.20 feet
Modulus of Elasticity	2×10^6 psi
Mass Density of GRP	2.85 slugs/foot^3

A surface current velocity of four feet per second and a CWP drag coefficient of 0.80 were used. The velocity profile was taken to be that of Figure 4-12. The CWP was assumed to be cantilevered at

its upper end.

Table 2-7 presents a comparison of calculated deflections and bending moments along the length of the CWP. In all cases the calculated values are within 0.7 percent, with values from "CWPFLX" being always larger. From the comparison it is concluded that there are no significant differences in results and that "CWPFLX" can accurately calculate static responses to steady-state loadings such as current.

7.4 Need for Double Precision

As noted earlier both a single and a double precision version of program CWPFLX" have been developed and checked against analytical results. Based on a comparison of results of both versions of "CWPFLX" and a comparison of these results with the analytical results the following were determined:

- The maximum differences between results from single and double precision versions are, with few exceptions, less than 10 percent for all cases and frequencies of interest.
- Differences between single and double precision results are smallest at the lower frequencies (say less than 0.6 radians per second) where most wave energy will generally exist.
- Calculated forces and stresses are almost always larger with the single precision version.
- Results with the double precision version are generally, but not always, in better agreement with analytical results.
- The cost of a complete CWP analysis using "CWPFLX" is about three times as large with double precision.

Based on these considerations the following conclusions about the use of single and double precision versions were reached:

TABLE 7-7

COMPARISON OF CALCULATED STATIC RESPONSE
OF A 3000 FOOT LONG GRP CWP TO A 4.0 FOOT
PER SECOND SURFACE CURRENT WITH TYPICAL PROFILE

Distance from Top of CWP Feet	Deflection - Feet		Bending Moment-Pound-Feet	
	Numerical*	CWPFLX**	Numerical	CWPFLX
0	0	0	-6.035×10^7	-6.078×10^7
300	3.32	3.35	-2.069	-2.084
600	10.04	10.11	-0.445	-0.448
900	17.54	17.67	+0.158	0.159
1200	24.86	25.04	0.326	0.327
1500	31.72	31.93	0.316	0.317
1800	38.11	38.35	0.242	0.243
2100	44.13	44.41	0.154	0.154
2400	49.92	50.22	0.075	0.075
2700	55.60	55.92	0.020	0.020
3000	61.25	61.58	0	0

* NUMERICAL - numerical solution of non-linear beam equation

** CWPFLX - computer program "CWPFLX" static solution

- Single precision should be used for most parametric, concept and preliminary design studies. Resulting CWP stresses can generally be assumed to be about five to 10 percent too large.
- Double precision should be used for final evaluation of preliminary CWP designs and for any final CWP design studies.

The expected errors introduced by the use of a single precision version of "CWPFLX" are probably significantly smaller than combined errors due to all other sources.

7.5 Conclusions About Validation

Based on the comparison carried out and summarized in this section, it is concluded that the present methods are in generally good agreement with static and dynamic analytical solutions and available model test data and are suitable for use in CWP designer studies and designs at least up to the preliminary design level. It does not appear that other existing methods have received comparable validation.

Further validation using the recently obtained model data for a 400 MW span platform with CWP, Reference 25, or data from the DOT at-sea tests is desirable. It is anticipated that comparisons of the present methods with model data for the 400 MW span with CWP will be presented in Reference 25.

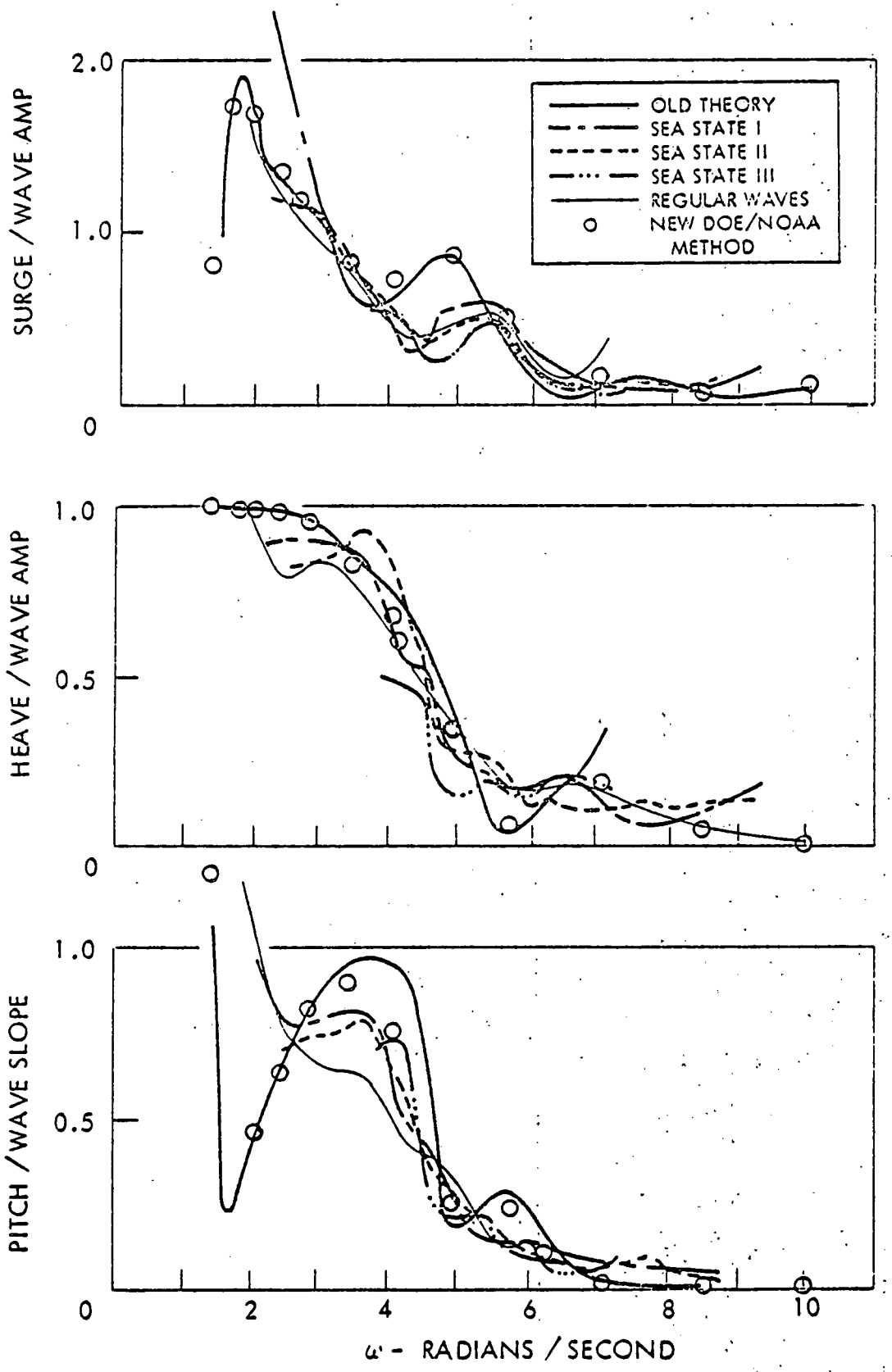
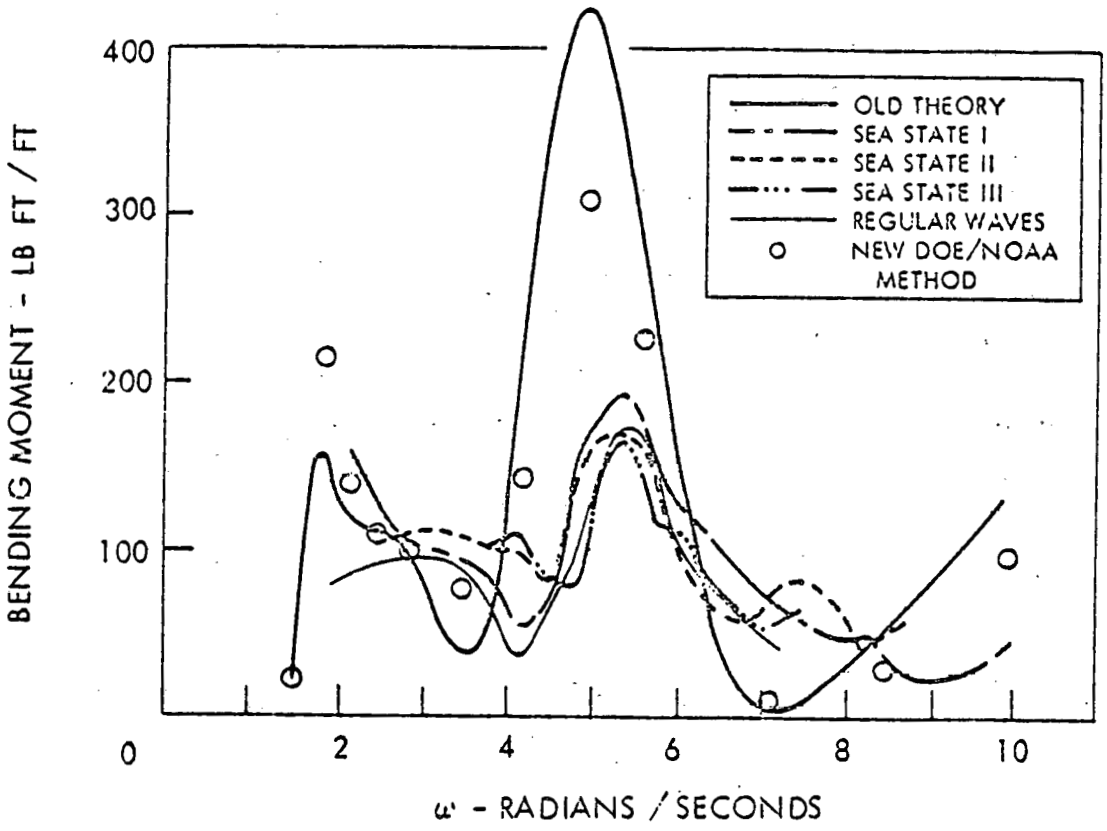
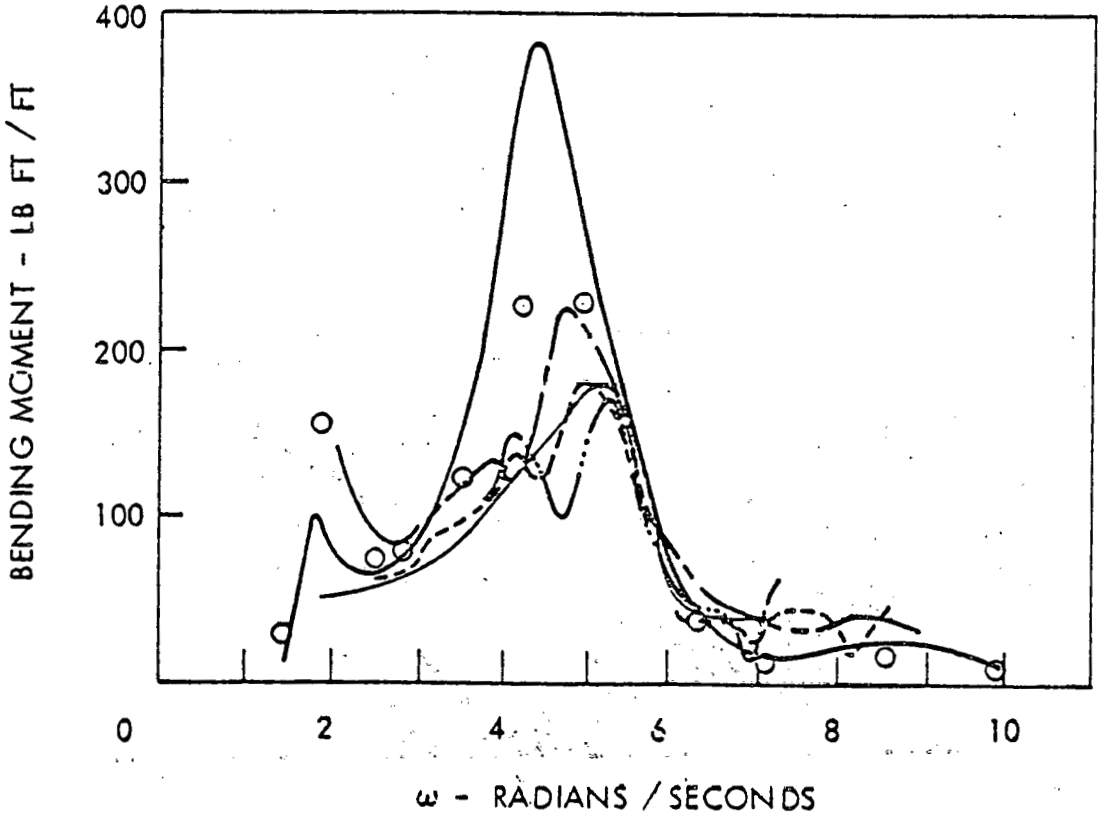


FIGURE 7 - 1 - COMPARISON OF MEASURED AND PREDICTED HMB CG MOTIONS IN HEAD SEAS - STIFF CWP - RIGID ATTACHMENT



a. UPPER LOCATION



b. LOWER LOCATION

FIGURE 7 - 2 - COMPARISON OF MEASURED AND PREDICTED CWP BENDING MOMENTS IN HEAD SEAS - STIFF CWP - RIGID ATTACHMENT

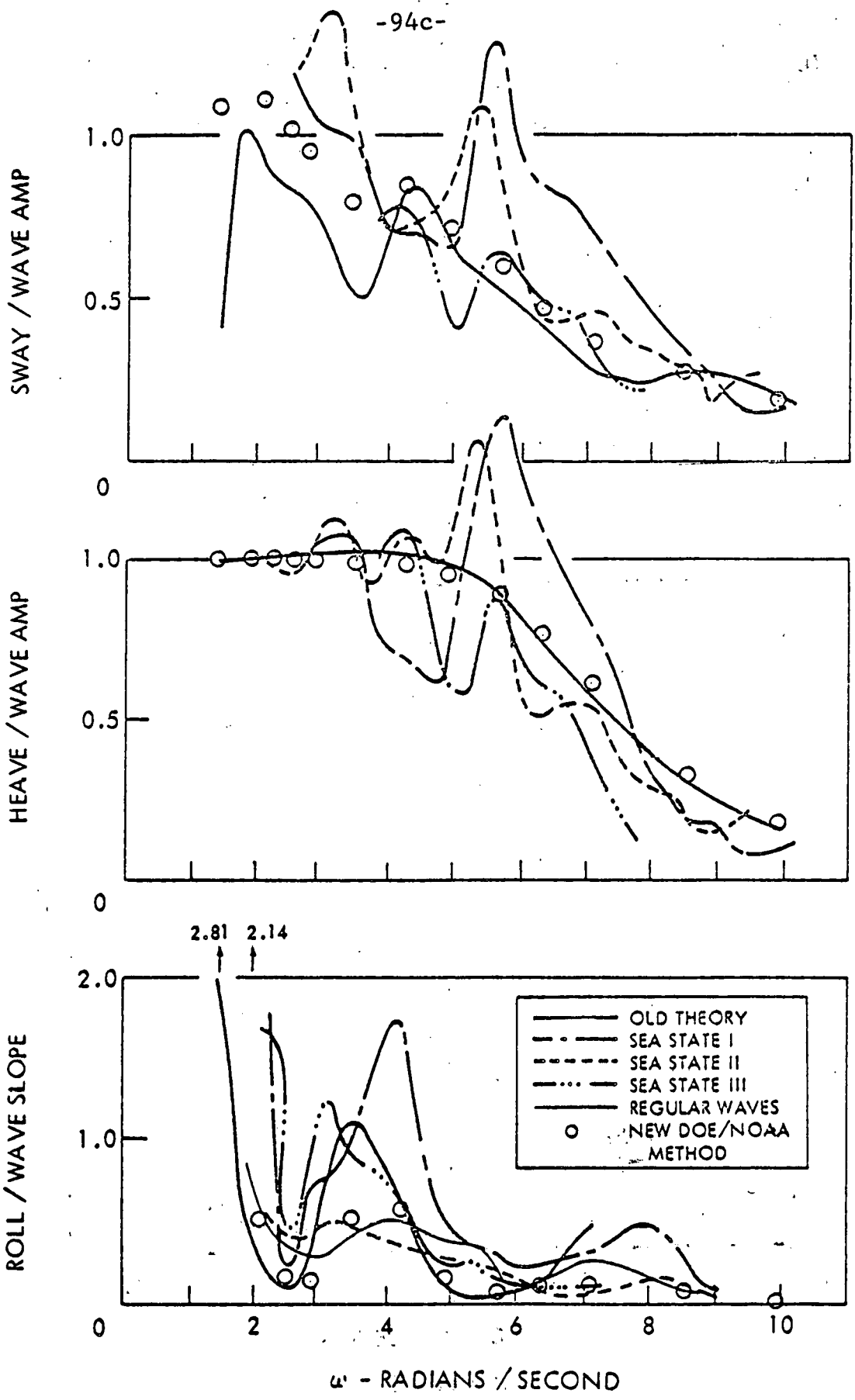


FIGURE 7-3 - COMPARISON OF MEASURED AND PREDICTED HMB CG

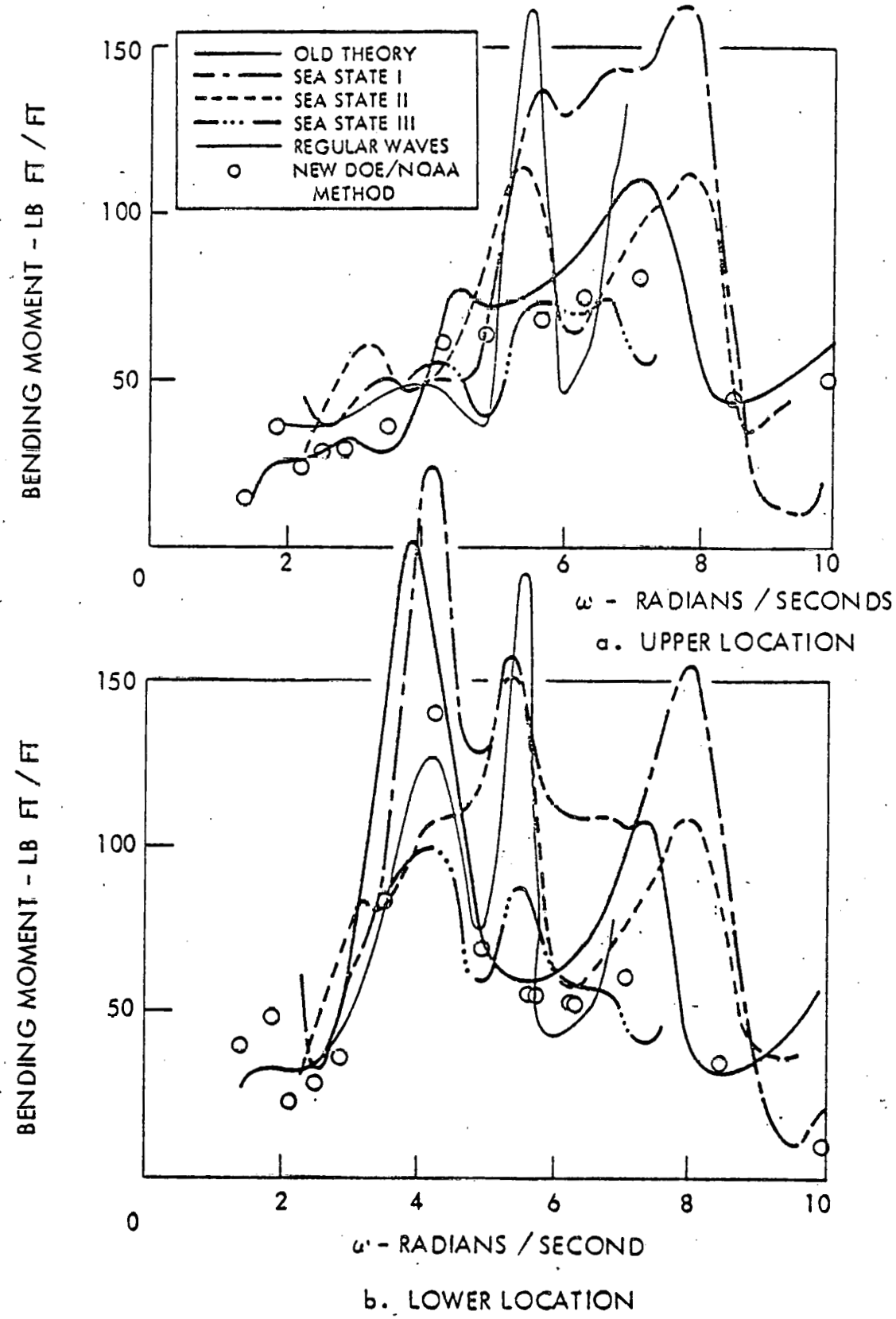


FIGURE 7 - 4 - COMPARISON OF MEASURED AND PREDICTED CWP BENDING MOMENTS IN BEAM SEAS - STIFF CWP - RIGID ATTACHMENT

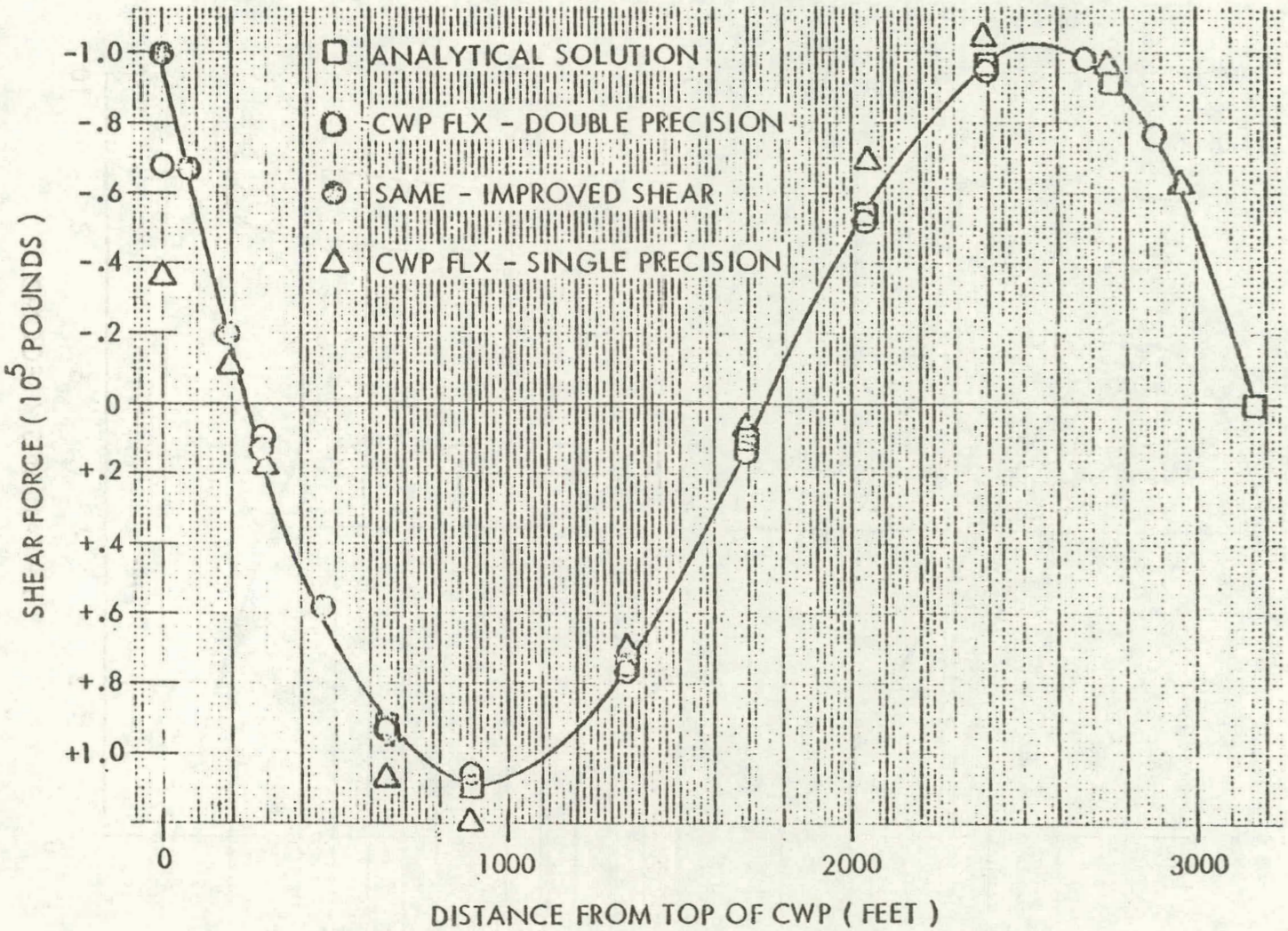


FIGURE 7 - 5 COMPARISON OF CALCULATED SHEAR FORCES ALONG CWP FOR UNIT CWP TRANSLATION AT 0.2 RAD/SEC FREQUENCY

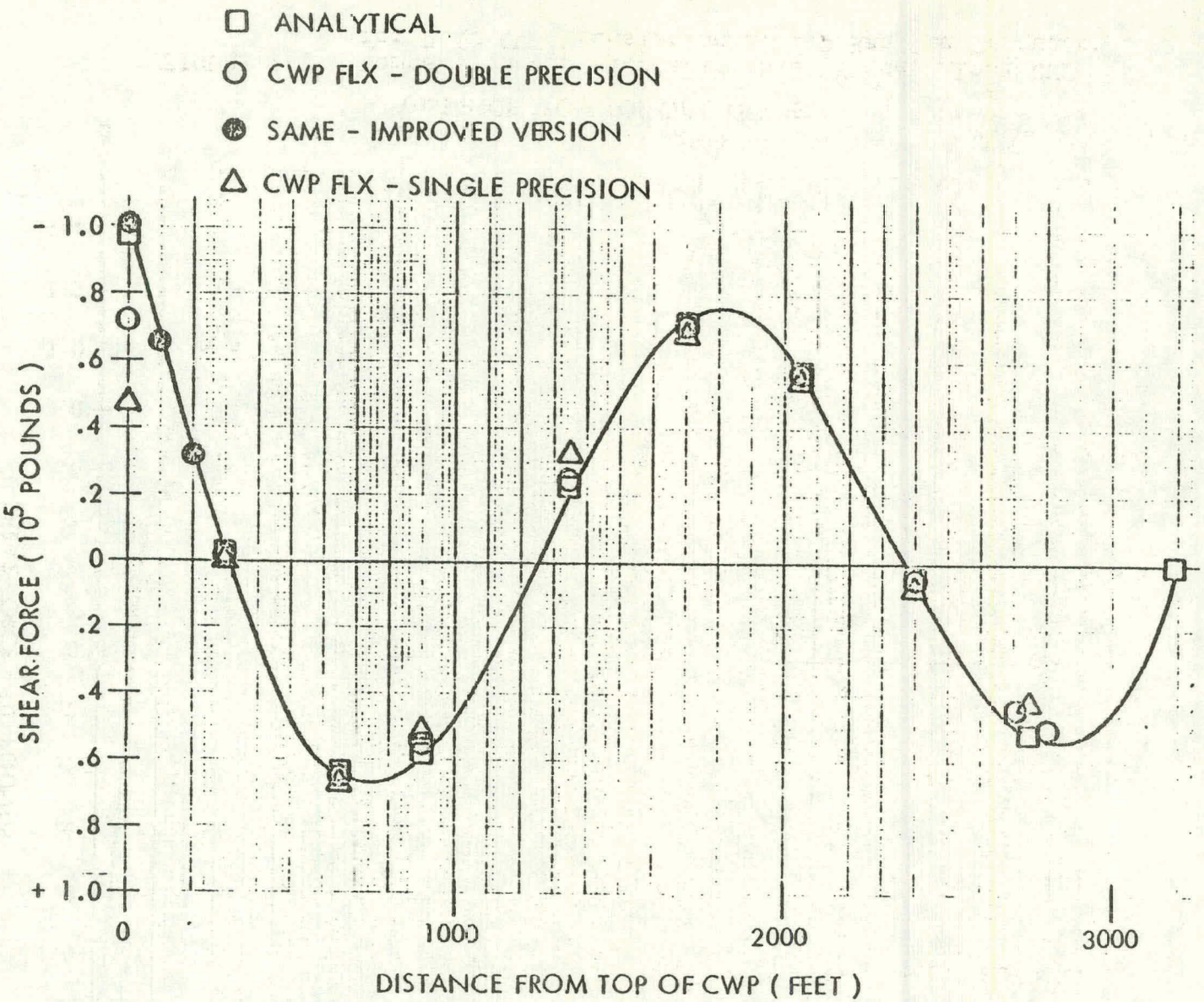


FIGURE 7 - 6 COMPARISON OF CALCULATED SHEAR FORCES ALONG CWP FOR UNIT CWP TRANSLATION AT 0.6 RAD/SEC FREQUENCY

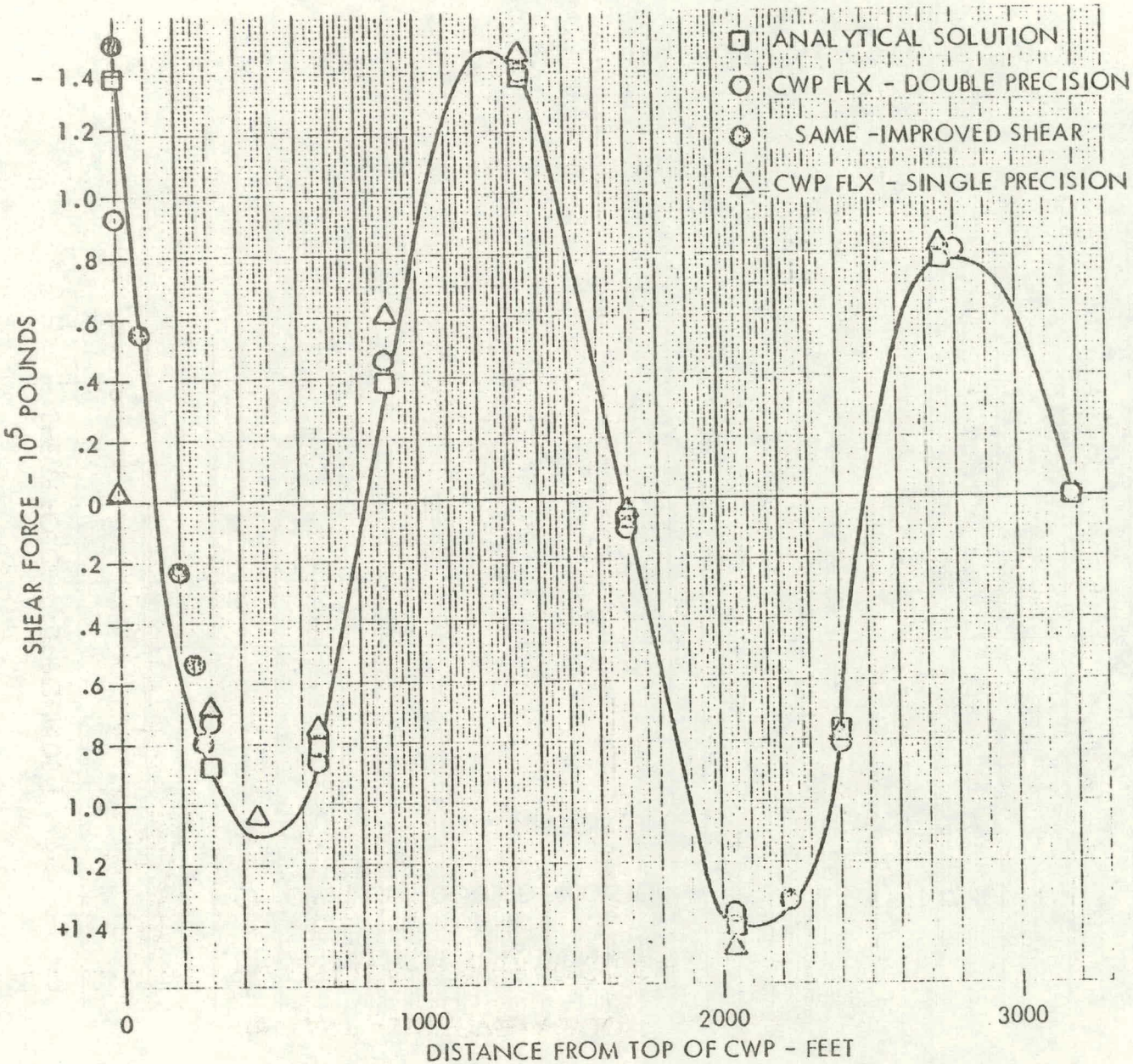


FIGURE 7-7 Comparison of Calculated Shear Forces Along CWP for Unit CWP Translation at 1.0 Rad/Sec Frequency

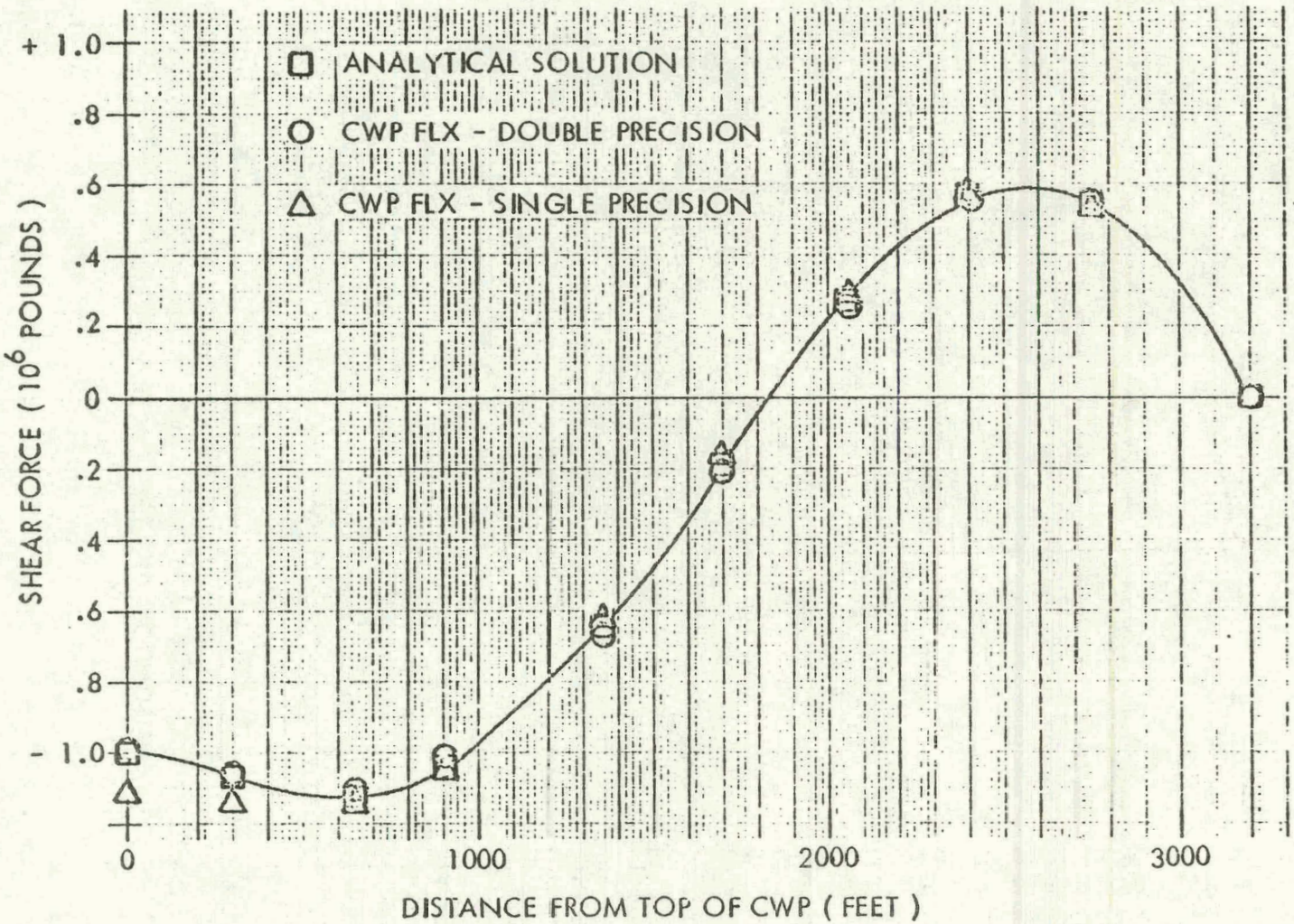


FIGURE 7 - 8 COMPARISON OF CALCULATED SHEAR FORCES ALONG CWP FOR UNIT CWP ROTATION AT 0.2 RAD/SEC FREQUENCY

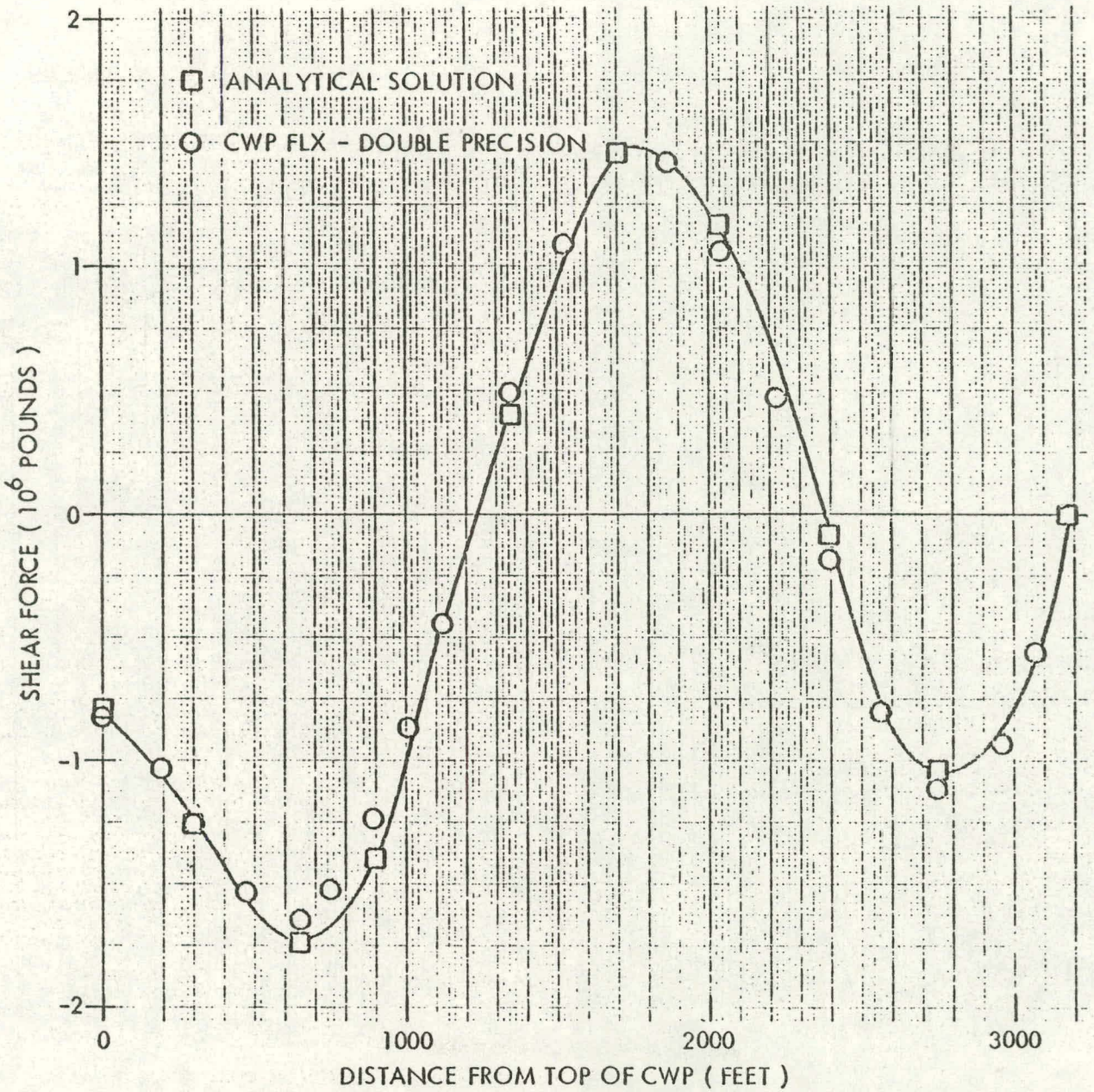


FIGURE 7 - 9 COMPARISON OF CALCULATED SHEAR FORCE ALONG CWP FOR UNIT CWP ROTATION AT 0.6 RAD/SEC FREQUENCY

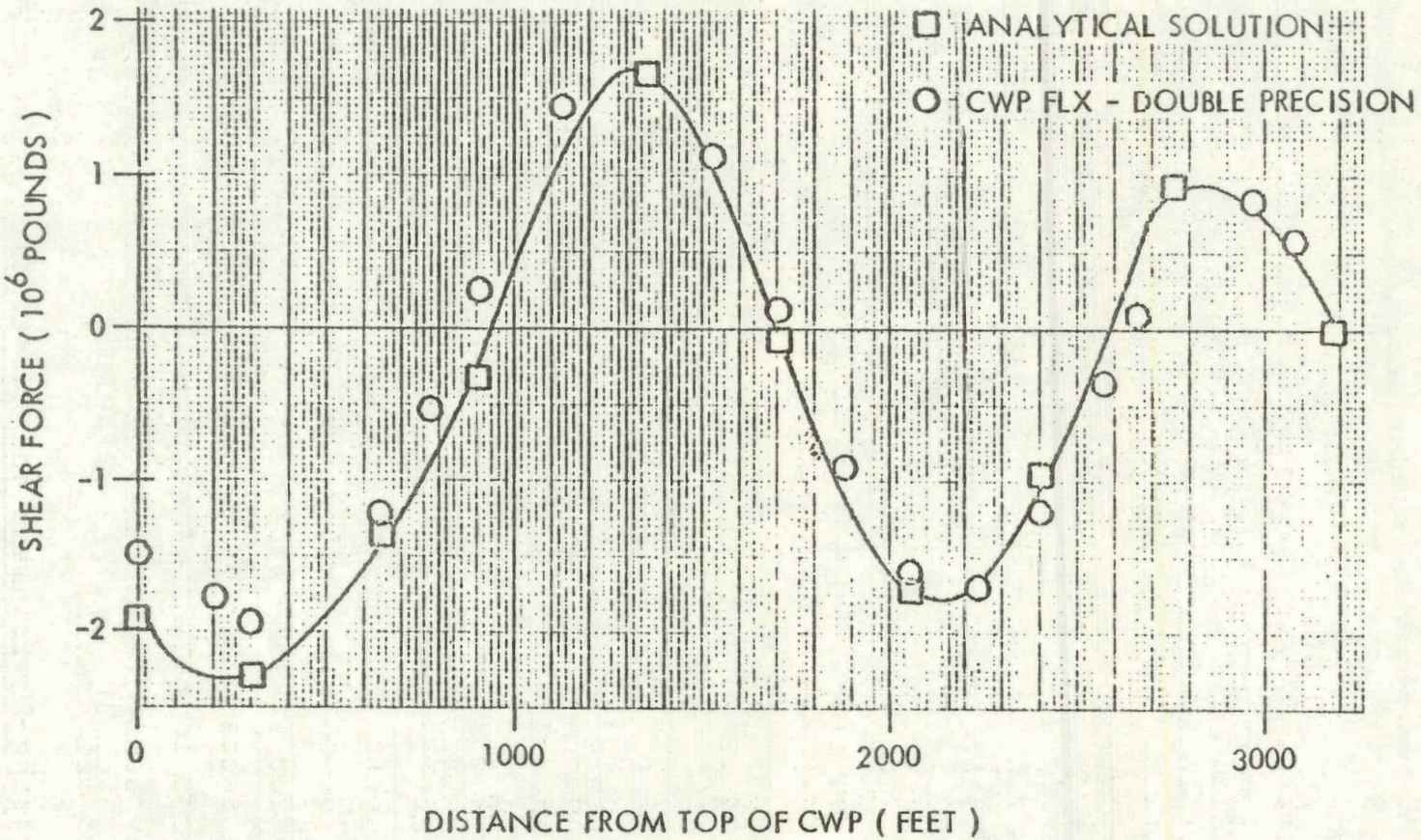


FIGURE 7 - 10 COMPARISON OF CALCULATED SHEAR FORCES ALONG CWP FOR UNIT CWP ROTATION AT 1.0 RAD/SEC FREQUENCY

8.0 ILLUSTRATIVE EXAMPLES

Three illustrative examples were considered to illustrate the application of the methods and computer programs. Results for the first example, the OTEC-1 with stiff CWP as model tested, are described in Section 7 since that example was used to validate the methods. Two examples of current interest were analyzed, as described in this section.

The two illustrative examples were specified by NOAA. These examples are:

- The APL 10/20 MW plant design consisting of a barge-like platform with a continuous, light-weight concrete CWP without flexible joints.
- The MINI-OTEC plant with barge platform and moored polyethelene CWP attached to the barge through a nylon mooring-buoy-hose attachment scheme.

The characteristics of these plant designs and the calculated performance in representative sea states and current are described in this section.

8.1 APL 10/20 MW Modular Experiment Plant

The Johns Hopkins University Applied Physics Laboratory (APL) is carrying out for DOE the preliminary design of a 10/20 MW OTEC plant to be used for at-sea tests of five MW power plant modules. This plant has a rectangular barge platform and a 30 foot nominal diameter, 3000 foot long CWP. This plant is designed to operate in the relatively benign environmental conditions existing in the equatorial waters off Brazil.

8.1.1 Operating Environment and CWP Loading - The operating current and wave data are based on those for the Brazil site from

the DOE environmental data package (2). The current data are as described in Section 4.7. The sea states considered for extreme conditions and for upper limit of plant operation are defined by significant wave heights of 29 and 18 feet and periods of maximum wave energy of 18 and 10 seconds, respectively.

For these calculations the loading conditions considered were regular and irregular waves corresponding to two sea states and head and beam waves.

8.1.2 CWP Characteristics - For these calculations a continuous, unjointed concrete CWP, corresponding to an early CWP concept evaluated by APL, was considered. The final APL CWP design, with 60 flexible joints, was not considered due to the need for special modelling of the joint properties. Since a primary purpose of this example was a comparison with calculations made using Paulling's method, the use of the unjointed CWP seemed more suitable.

The characteristics of the continuous CWP, as supplied by APL are:

Length	3000 feet
Outside Diameter	32 feet
Inside Diameter	30 feet
Material Weight in Air	85 pounds/foot^3
Material Modulus of Elasticity	1.0×10^6 psi

The CWP is essentially rigidly attached to the platform, having attachment stiffnesses of 10^{11} pounds per foot in translation and 10^{14} pound feet per radian in rotation. These values were used in the present calculations. The CWP is assumed to be attached at the platform center of gravity.

In these calculations an equivalent linearized drag corresponding to a quadratic drag coefficient of 0.7 and an estimated

average RMS velocity of 3.0 feet per second was used. The data of Section 4 indicate that a drag coefficient of about 1.4 would be more appropriate for the small amplitude ($K \leq 5$) motions; 0.7 was used in the APL calculations and its use here made a comparison of calculated results meaningful.

8.1.3 Platform Characteristics - The important characteristics of the platform, as supplied by APL, are:

Length	378 feet
Beam	121 feet
Draft	60 feet
Height of CG above Baseline	42.8 feet
Height of CB above Baseline	30 feet
Displacement	78,300 long tons
Transverse GM	7.54 feet
Longitudinal GM	185.6 feet
Roll Gyradius	48.4 feet
Pitch/Yaw Gyradii	125 feet
Longitudinal CG	185.5 feet

Neither the warm water pump housings along the sides of the platform nor the flooded heat exchanger sections were considered in calculating hydrostatic and hydrodynamic forces.

The platform sections are all identical and are all essentially rectangular. The sections were assumed to have a section area coefficient of 0.99 to account for the slight rounding of the bilges.

8.1.4 Calculated Results - The calculated irregular wave results for head seas are summarized in Tables 8-1 and 8-2. Results for the higher sea state (29 foot significant wave height) and beam seas are given in Table 8-3. RMS motions of the platform at its

TABLE 8-1

CALCULATED RMS RESPONSE AMPLITUDES FOR APL PLATFORM WITH CONTINUOUS CONCRETE CWP-HEAD SEAS WITH 29 FOOT WAVE HEIGHT

Platform Motion		Present Methods	Paulling-ROTEC
Surge - Feet		5.9	6.1
Heave - Feet		7.1	6.8
Pitch - Degrees		1.86	1.61
CWP Motions and Loads			
Shear Stress in PSI at Top of CWP		139	100
Displacement at 0 Feet		5.9	6.5
in Feet	500	10.4	9.2
	1650/1750	9.4	9.0
	2400/2500	10.0	9.4
	3000	15.2	14.7
Bending Stress at 0 feet		4060	3170
in psi	500	2910	2300
	1200	2460	2300
	1700	2850	2540
	2500	3620	3050

TABLE 8-2

CALCULATED RMS RESPONSE AMPLITUDES FOR APL PLATFORM WITH CONTINUOUS CONCRETE CWP-HEAD SEAS WITH 18 FOOT WAVE HEIGHT

Platform Motion		
Surge - Feet		1.72
Heave - Feet		1.95
Pitch - Degrees		1.41
CWP Motions and Loads		
Shear Stress in PSI at Top of CWP		107
Displacement at 0 feet		1.42
in Feet	400	6.68
	1100	6.13
	1800	5.70
	2500	5.32
	3000	7.12
Bending Stress at 0 feet		1460
in PSI	400	2060
	1100	2060
	1800	1900
	2500	2050

TABLE 8-3

CALCULATED RMS RESPONSES FOR APL PLATFORM WITH CONTINUOUS CONCRETE CWP-BEAM SEAS WITH 29 FOOT WAVE HEIGHT

Platform Motions		
Sway - Feet		5.82
Heave - Feet		9.36
Roll - Degrees		4.25
CWP Motions and Loads		
Shear Stress at Top of CWP - PSI		290
Displacement at 0 feet		5.28
in Feet	400	17.01
	1100	14.36
	1800	12.74
	2500	12.08
	3000	17.14
Bending Stress at 0 Feet		
in PSI	400	3410
	1100	5020
	1800	4740
	2500	4000
	3000	4280

CG, RMS shear stress at the top of the CWP and RMS CWP displacements and bending stresses at locations (below the top of the CWP) of maximum bending are given for each case.

It can be seen from Tables 8-1 and 8-2 that motions and CWP responses are generally much smaller for the lower sea state. Surge and heave motion and bending stress at the top of the CWP are 65 to 75 percent less with the 18 foot significant wave height. A comparison of Tables 8-1 and 8-3 indicates that platform motions and CWP motions and stresses are generally larger in beam seas. The maximum CWP bending stress is about 25 percent larger in beam seas, while heave is 32 percent larger and roll is more than twice pitch. Calculated CWP natural modes occur at frequencies of 0.32 (fourth mode), 0.51, 0.72 and 1.07 radians per second; the fourth mode natural frequency is close to the frequency for peak energy for the larger sea state (0.349 radians per second), so that CWP damping will be particularly important for this sea state.

8.1.5 Comparison of Calculated Results with Paulling's Results - Table 8-1 compares calculated results from the present methods and a recent version of J.R. Paulling's program, "ROTEC." The comparison was limited, by the available results from "ROTEC," to this one sea state and heading.

It can be seen from Table 8-1 that the calculated RMS motion amplitudes are in generally good agreement, with four percent differences in surge and heave and a 13 percent difference in pitch. These differences are felt to arise primarily from two sources, the difference in assumed platform mass and the differences in calculated added mass and damping. The calculations made using "ROTEC" were made for a displacement of 63,500 long tons, which neglected all on-board water, except ballast; the present calculations were for 78,300 long tons, which includes all on-board water,

as it is expected that most of this water will move with the platform. The differences in added mass and damping are somewhat surprising as the same basic methods are used. The probable source of differences is the treatment of the ends of the barge, which is especially important for the low length-beam ratio of the barge.

The CWP motions and loads are generally quite similar, with the motions and stresses calculated using the present methods being about three to 10 percent and 10 to 30 percent higher, respectively, than the motions and stresses calculated using "ROTEC." These differences are probable due in part to the larger pitch motions with the present methods, and to differences in equivalent linearized damping.

8.2 MINI-OTEC 50 KW Demonstration Plant

A 50 KW OTEC demonstration plant called the MINI-OTEC is currently being developed for operation off the coast of Hawaii. This plant is being developed as a joint effort of the State of Hawaii, Lockheed and Dillingham. Ocean engineering work for this plant is also being done by Makai Ocean Engineering, Inc., which provided the data used for this example. The plant uses an existing 104 foot long barge and a 28 inch diameter polypropelene CWP. The CWP is connected to the barge through a flexible cold water hose and a system of nylon lines and a floating buoy.

8.2.1 Operating Environment and CWP Loading - The operating current velocity profile is:

$$V = 3.91\ e^{-0.0000937z}$$

where

V is current velocity in feet per second

z is depth in feet (always positive)

Two wave energy spectra corresponding to extreme and normal operating conditions were specified. The spectra have significant wave heights of 20 and four feet and frequencies of maximum energy of 0.61 and 1.36 radians per second, respectively, and correspond to the top of sea state six and sea state three, respectively.

For these calculations the following loading cases were considered:

1. Steady current load based on subcritical drag coefficient of 1.1.
2. Regular and irregular wave loads corresponding to the specified sea states, for head seas only.

In all calculations the effect of CWP weights, bottom mooring and top attachment were considered.

8.2.2 CWP Characteristics - The CWP is made up of three sections of 28 inch diameter polyethelene tubing. The characteristics and properties of these sections are given in Table 8-4. The nominal CWP unstretched length is 2150 feet. The CWP has weighted sections at its top and bottom, having net weights in water of 3000 and 8000 pounds, respectively.

The top of the CWP, which has a submergence of about 100 feet, is connected to the barge by a cold water hose, which was assumed to have a negligable effect on dynamic response, and by a set of nylon lines and a floating buoy which provide the following effective spring stiffnesses between the CWP and platform:

Heave	240 pounds per foot
Surge	300 pounds per foot

The top of the actual CWP was specified to be 117 feet forward of midships and 100 feet below the waterline. The connection to the platform was assumed to have zero stiffness in rotation and the

TABLE 8-4
CHARACTERISTICS OF MINI-OTEC CWP

Parameter	Upper Section	Middle Section	Lower Section
Length-feet	500	900	750
Outside Diam-inches	28.03	28.03	28.03
Inside Diam-inches	24.88	25.64	26.21
Wall Thickness inches	1.58	1.20	0.91
Buoyancy-Pounds/foot	4.21	3.25	2.49
Mass Density	1.85	1.85	1.85
Modulus of Elasticity-PSI (at wave frequency)	120,000	120,000	120,000

above stiffnesses in heave and surge.

The bottom of the CWP is moored with a polyethelene mooring line which provides the following approximate effective spring stiffnesses

Longitudinal	385 pounds per foot
Transverse	30 pounds per foot

These values were used in calculating coupled CWP/platform responses. The specified tension at the bottom and top of the CWP were 23,900 and 18,500 pounds, respectively. The resulting mean tension is very large compared with the CWP stiffness.

8.2.3 Platform Characteristics - The important characteristics of the MINI-OTEC barge platform supplied by Makai Ocean Engineering are:

Length on waterline	104.5 feet
Beam	33.9 feet
Draft	3.6 feet
Height of CG above baseline	9.5 feet
Height of CB above baseline	1.8 feet
Displacement	630,000 pounds
Transverse GM	26 feet
Longitudinal GM	318 feet

The pitch/yaw and roll gyradii were specified to be 30.0 and 13.55 feet, respectively. The longitudinal center of gravity (LCG) was assumed at midships.

The barge sections are all rectangular, with a section area coefficient of about 0.98 and 0.99.

The nylon line connecting the barge to the CWP and buoy is attached at the bow, 60 feet forward of the LCG and 8.4 feet above the waterline. The cold water hose is attached just forward of

midships and the warm water intake is attached just aft of midships; these were assumed to have no effect on CWP/platform responses.

8.2.4 Discussion of Calculated Results - Calculations were carried out for the CWP described in Table 8-4 using program "CWPFLX." The results indicated numerical errors in the calculated modal frequencies. The numerical errors arise from computing differences between large numbers associated with the large ratio of tension to stiffness, as described in Section 9. Though such errors could be eliminated by extensive modifications to "CWPFLX", the MINI-OTEC CWP work probably could best be treated as a cable with finite stiffness rather than a beam.

In order to determine the ability of program "CWPFLX" to treat very flexible CWPs with smaller tension, a second set of calculations were carried out with a bottom tension of 5400 pounds, which is equal to the total CWP buoyancy. The calculated results for this tension indicated no numerical errors, but indicated another problem arising from the extremely low stiffness. The highest calculated modal frequency, for the 15th mode, was only 0.41 radians per second. It would be necessary to consider modes higher than the 30th mode to properly analyze response for the specified sea states. The double precision version of "CWPFLX" is only able to accurately analyze about the first 20 modes.

8.2.5 Conclusions from MINI-OTEC Results - Computer program "CWPFLX" is not capable of analyzing very flexible CWP's such as the MINI-OTEC CWP. It is, however, capable of analyzing larger diameter CWP's of highly elastic materials such as polyethelene and reinforced rubber. Several successful calculations have been carried out for 30 foot diameter CWP's having wall thicknesses and modulii of elasticity comparable to that of the MINI-OTEC CWP. Limits on allowable CWP flexibility are discussed in Section 9.

9.0 LIMITATIONS ON USE OF THE METHODS

There are two factors which may limit the use of the programs, accuracy and cost. Accuracy is clearly the more important potential limitation, as discussed below.

9.1 Computational Accuracy

The computational accuracy will not be acceptable if the ratios of mass-to-stiffness or tension-to-stiffness become too large; both of these cases correspond to excessive CWP flexibility. It is estimated that errors may occur when the parameters

$$\alpha = \left(\frac{m\omega^2}{EI}\right)^{\frac{1}{4}} L$$

$$\beta = \left(\frac{N}{EI}\right)^{\frac{1}{2}} L$$

where

- m is total mass per unit length, $m = m_i + m_a + m_p$
- ω is frequency
- EI is stiffness
- N is tension
- L is CWP length

exceed 16 with the single precision "CWPFLX" or 32 with the double precision "CWPFLX". For such problems the CWP is best treated as either a non-uniform string on a stiff cable. As an example, the values of these parameters for the MINI-OTEC CWP, based on the middle section characteristics of Table 8-4, are:

$$\alpha = 80 \text{ at } \omega = 1.0 \text{ radian per second}$$

$$\beta = 110$$

The existance of computational errors for this CWP, as described

in Section 8.2.4, is thus not suprising.

As an example of the influence of CWP diameter on stiffness and accuracy, a 30 foot inside diameter CWP having all other design parameters as in the above example was considered. The resulting values of α and β are

$$\alpha = 29.6 \quad \text{for } \omega = 0.5 \text{ radians per second}$$

$$\beta = 2.27$$

Increasing the tension by a factor of 10 to 210,000 pounds, which would be more typical for a 30 foot diameter CWP, would increase β to 7.2. These values of α and β indicate that good accuracy should be obtained with a double precision versions of "CWPFLX", as described in Section 7.4. This conclusion is borne out by recent experience with program "CWPFLX."

9.2 Computational Costs

Computational costs may limit the number of variables considered or the numer of iterations made to match assumed and calculated CWP damping. Typical costs for the various programs are:

1.	Complete run of single precision version of CWPFLX (40 CWP segments 20 frequencies)	$ 40.00
2.	Complete run of double precision version of CWPFLX (as in 1.)	$130.00
3.	Complete run of COTEC (8 sections, 20 frequencies)	$10.00
4.	Complete run of XOTEC (20 frequencies, 2 headings)	$15.00
5.	Complete run of CWPEXT (40 CWP segments, 20 frequencies)	$5.00

These are commercial costs for a United Computing Services CDC 6600; costs will vary with the computer system used.

10.0 CONCLUSIONS

A number of conclusions arising from this study seem worthy of note. These include:

1. The programs can handle a wide range of CWP and platform designs and loadings.

2. The accuracy of the programs has been validated using available model test data, analytical solutions and existing HYDRONAUTICS computer programs for typical CWP designs.

3. There exist lower limits on allowable CWP stiffness to mass and stiffness to tension ratios for accurate analysis of CWP dynamics. Allowable lower limits have been approximately defined.

4. For very flexible CWP's, where more than the first 10 modal frequencies fall within the range of frequency of important wave energy, it is necessary to use a double precision CDC 6600 version of the program (64 bit words or 36 significant figures) to achieve acceptable accuracy. For other cases a single precision version (32 bit words) should be sufficiently accurate for most applications.

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A number of current and former colleagues at HYDRONAUTICS have contributed to this work. Dr. Douglas Loeser has made a significant contribution to the present study while Mr. Patrick Murphy and Dr. John O'Dea contributed to earlier work which was used in this study.

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APPENDIX A

TRANSFER MATRIX FOR GENERAL BEAM SOLUTION FROM REFERENCE 13

Definitions:

$\lambda = (k - \rho\omega^2)/EI$

$\eta = (k - \rho\omega^2)/GA_s$

$\zeta = (P - d\rho r^2\omega^2 - k^*)/EI$

$$d = \begin{cases} -1 & \text{vibrating beam} \\ 1 & \text{rotating shaft with whirl in same angular direction as rotation} \\ -1 & \text{rotating shaft with whirl in opposite angular direction as rotation} \end{cases}$$

Note: The column 5 definitions on the following page along with case 6 or 7 of the final page of this table apply for any magnitude of λ, ζ, η. However, usually the transfer matrix elements will then be complex quantities, and computations will require computers with complex arithmetic capabilities.

$$U_i = \begin{bmatrix} \sigma_1 + \zeta\sigma_3 & -\sigma_2 & -\sigma_3/EI & -\sigma_4/EI + (\sigma_2 + \zeta\sigma_4)/GA_s & F_V \\ \lambda\sigma_4 & \sigma_1 - \eta\sigma_3 & (\sigma_2 - \eta\sigma_4)/EI & \sigma_3/EI & F_\theta \\ \lambda EI\sigma_3 & EI(\sigma_0 - \eta\sigma_2) & \sigma_1 - \eta\sigma_3 & \sigma_2 & F_M \\ \lambda EI(\sigma_2 + \zeta\sigma_4) & -\lambda EI\sigma_3 & -\lambda\sigma_4 & \sigma_1 + \zeta\sigma_3 & F_V \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

$$F_V = (w_1\sigma_5 + \frac{\Delta w}{\Delta\ell}\sigma_6 + c_1\sigma_4 + \frac{\Delta c}{\Delta\ell}\sigma_5)/EI - w_1(\sigma_3 + \zeta\sigma_5)/GA_s - \frac{\Delta w}{\Delta\ell}(\sigma_4 + \zeta\sigma_6)/GA_s - (M_{T1}\sigma_3 + \frac{\Delta M_T}{\Delta\ell}\sigma_4)/EI$$

$$F_\theta = -\left[w_1\sigma_4 + \frac{\Delta w}{\Delta\ell}\sigma_5 + c_1(\sigma_3 - \eta\sigma_5) + \frac{\Delta c}{\Delta\ell}(\sigma_4 - \eta\sigma_6)\right]/EI + \{M_{T1}(\sigma_2 - \eta\sigma_4) + \frac{\Delta M_T}{\Delta\ell}(\sigma_3 - \eta\sigma_5)\}/EI$$

$$F_M = -w_1\sigma_3 - \frac{\Delta w}{\Delta\ell}\sigma_4 - c_1(\sigma_2 - \eta\sigma_4) - \frac{\Delta c}{\Delta\ell}(\sigma_3 - \eta\sigma_5) + M_{T1}(\sigma_1 - 1 - \eta\sigma_3) + \frac{\Delta M_T}{\Delta\ell}(\sigma_2 - \ell - \eta\sigma_4)$$

$$F_V = -w_1(\sigma_2 + \zeta\sigma_4) - \frac{\Delta w}{\Delta\ell}(\sigma_3 + \zeta\sigma_5) + \lambda(c_1\sigma_5 + \frac{\Delta c}{\Delta\ell}\sigma_6) - M_{T1}\lambda\sigma_4 - \frac{\Delta M_T}{\Delta\ell}\lambda\sigma_5$$

To use this general transfer matrix, follow the steps:

1. Calculate the three parameters λ, ζ, η. If shear deformation is not to be considered, set $1/GA_s = 0$.
2. Compare the magnitude of these parameters and look up the appropriate σ_i functions on the following page.
3. Substitute these σ_i expressions in the general transfer matrix above.

$\lambda < 0$	$\lambda = 0$, $\lambda - \zeta\eta = 0$	$\lambda > 0$, $\lambda - \zeta\eta > 0$		
		$\lambda - \zeta\eta = \frac{1}{4}(\zeta - \eta)^2$	$\lambda - \zeta\eta < \frac{1}{4}(\zeta - \eta)^2$, $\zeta - \eta \neq 0$	$\lambda - \zeta\eta > \frac{1}{4}(\zeta - \eta)^2$
1. $A = \cosh at$, $B = \cos bt$ $C = \sinh at$, $D = \sin bt$ $g = a^2 + b^2$ $a^2 = \sqrt{\beta^4 + \frac{1}{4}(\zeta + \eta)^2} - \frac{1}{2}(\zeta - \eta)$ $b^2 = \sqrt{\beta^4 + \frac{1}{4}(\zeta + \eta)^2} + \frac{1}{2}(\zeta + \eta)$ $\beta^4 = -\lambda$	2. $\zeta > 0$: $a^2 = \zeta$ $A = \cos at$ $B = (\sin at)/a$ 3. $\zeta < 0$: $a^2 = -\zeta$ $A = \cosh at$ $B = (\sinh at)/a$	4. $\zeta - \eta > 0$: $\beta^2 = \frac{1}{2}(\zeta - \eta)$, $A = \cos \beta t$, $B = \beta \sin \beta t$ $C = (\sin \beta t)/\beta$ 5. $\zeta - \eta < 0$: $\beta^2 = -\frac{1}{2}(\zeta - \eta)$ $A = \cosh \beta t$, $D = -\beta \sinh \beta t$ $C = (\sinh \beta t)/\beta$	6. $\zeta - \eta > 0$: $g = b^2 - a^2$, $p = 1$ $A = \cos at$, $B = \cos bt$ $C = \sin at$, $D = \sin bt$ $a^2 = \frac{1}{2}(\zeta - \eta) - \sqrt{\frac{1}{4}(\zeta + \eta)^2 - \lambda}$ $b^2 = \frac{1}{2}(\zeta - \eta) + \sqrt{\frac{1}{4}(\zeta + \eta)^2 - \lambda}$ 7. $\zeta - \eta < 0$: $g = a^2 - b^2$, $p = -1$ $A = \cosh at$, $B = \cosh bt$ $C = \sinh at$, $D = \sinh bt$ $a^2 = -\frac{1}{2}(\zeta - \eta) + \sqrt{\frac{1}{4}(\zeta + \eta)^2 - \lambda}$ $b^2 = -\frac{1}{2}(\zeta - \eta) - \sqrt{\frac{1}{4}(\zeta + \eta)^2 - \lambda}$	8. $A = \cosh at$, $B = \cos bt$ $C = \sinh at$, $D = \sin bt$ $a^2 = \frac{1}{2}\sqrt{\lambda - \zeta\eta} - \frac{1}{4}(\zeta - \eta)$ $b^2 = \frac{1}{2}\sqrt{\lambda - \zeta\eta} + \frac{1}{4}(\zeta - \eta)$

	1. $\lambda < 0$	$\lambda = 0,\ \lambda - \zeta\eta = 0$		$\lambda > 0,\ \lambda - \zeta\eta > 0$		
		2. $\zeta = \eta = 0$	3. $\eta = 0,\ \zeta \neq 0$	4. $\lambda - \zeta\eta = \frac{1}{4}(\zeta - \eta)^2$	5. $\lambda - \zeta\eta < \frac{1}{4}(\zeta - \eta)^2,\ \zeta - \eta \neq 0$	6. $\lambda - \zeta\eta > \frac{1}{4}(\zeta - \eta)^2,$
e_0	$\frac{1}{g}(a^3C - b^3D)$	0	$-\zeta B$	$-\frac{\zeta - \eta}{4}(3C + A\ell)$	$-\frac{1}{g}(b^3D - a^3C)$	$-(\lambda - \zeta\eta)e_4 - (\zeta - \eta)e_2$
e_1	$\frac{1}{g}(a^2A + b^2B)$	1	A	$\frac{1}{2}(2A - B\ell)$	$\frac{\rho}{g}(b^2B - a^2A)$	$AB - \frac{b^2 - a^2}{2ab}CD$
e_2	$\frac{1}{g}(aC + bD)$	ℓ	B	$\frac{1}{2}(C + A\ell)$	$\frac{\rho}{g}(bD - aC)$	$\frac{1}{2ab}(aAD + bBC)$
e_3	$\frac{1}{g}(A - B)$	$\frac{\ell^2}{2}$	$\frac{1}{\zeta}(1 - A)$	$\frac{C\ell}{2}$	$\frac{1}{g}(A - B)$	$\frac{1}{2ab}CD$
e_4	$\frac{1}{g}\left(\frac{C}{a} - \frac{D}{b}\right)$	$\frac{\ell^3}{6}$	$\frac{1}{\zeta}(\ell - B)$	$\frac{2}{(\zeta - \eta)}(C - A\ell)$	$\frac{1}{g}\left(\frac{C}{a} - \frac{D}{b}\right)$	$\frac{1}{2(a^2 + b^2)}\left(\frac{AD}{b} - \frac{BC}{a}\right)$
e_5	$\frac{1}{g}\left(\frac{A}{a^2} + \frac{B}{b^2}\right) - \frac{1}{a^2b^2}$	$\frac{\ell^4}{24}$	$\frac{1}{\zeta}\left(\frac{\ell^2}{2} - e_3\right)$	$\frac{2}{(\zeta - \eta)^2}(-2A - B\ell + 2)$	$\frac{\rho}{g}\left(\frac{B}{b^2} - \frac{A}{a^2}\right) + \frac{1}{a^2b^2}$	$\frac{1 - e_1}{\lambda - \zeta\eta} - \frac{\zeta - \eta}{\lambda - \zeta\eta}e_3$
e_6	$\frac{1}{g}\left(\frac{C}{a^3} + \frac{D}{b^3}\right) - \frac{\ell}{a^2b^2}$	$\frac{\ell^5}{120}$	$\frac{1}{\zeta}\left(\frac{\ell^3}{6} - e_4\right)$	$\frac{2}{(\zeta - \eta)^2}(-3C + A\ell + 2\ell)$	$\frac{\rho}{g}\left(\frac{D}{b^3} - \frac{C}{a^3}\right) + \frac{\ell}{a^2b^2}$	$\frac{\ell - e_2}{\lambda - \zeta\eta} - \frac{\zeta - \eta}{\lambda - \zeta\eta}e_4$

APPENDIX B

USER'S MANUAL FOR THE PROGRAM CWPFLX FOR THE STRUCTURAL ANALYSIS OF OTEC COLD WATER PIPES

BENDING RESPONSE PROGRAM

B.1 General Background

This program carries out a structural analysis of an OTEC power plant cold water pipe (CWP). The cold water pipe is treated as a general beam with up to 49 sections each of which can have different properties, supports, and connections and different loadings.

B.2 Program Capabilities

This program has the capability of treating the following cases:

1. Static analysis of current and other arbitrary static loads.
2. Dynamic analysis of current load and other arbitrary harmonic loads.
3. Responses to harmonic wave loads.
4. Responses due to harmonic translational and rotational motions of the OTEC platform.

B.3 Description of Inputs to "CWPFLX" Program

Card or Line 1 (Title card)

Enter: TITLE (12A8)

TITLE = Any information may be input. (Column 1 - 80)

Card or Line 2

Enter: NTERM, NLOADS (2I5)

NTERM = Number of terms (modal vectors) in series solutions for dynamic analysis [NFTYPE = 0,1,2,3,4 or 5]
Note: A series of 10 terms is generally adequate.

= 0 for static analysis NFTYPE = 6 or 7

NLOADS = Number of load cases, seven options of loading (see card 10) may be analyzed as many times as users' wish.

Card or Line 3

Enter: NTYPE, ST, RIS, SI, SIGMAY, BMZ (I10), 5F10.2)

NTYPE = 1 Pipe *without* ring stiffeners.
= 2 Pipe *with* ring stiffeners.

ST = Spacing of ring stiffeners.
= ϕ. If no ring stiffeners

RIS = Moment of inertia of ring stiffener cross section
= ϕ. If no ring stiffeners.

SI = ϕ.

SIGMAY = Yield stress of CWP-material.

BMZ = (Secondary) loop bending moment.

Card or Line 4

Enter: VELI, DMW, DMP, ZP, DRAFT (5F10.2)

VELI = Velocity of internal water flow (Length/sec).

DMW = Mass density of water (Force-sec^2/ft^4).

DMP = Mass density of CWP-material in air (Force-sec^2/length^4)

ZP = Vertical distance between the water surface and the top of the pipe (attachment). Positive if the pipe attachment is below water surface, negative if above water surface.

DRAFT = Vertical distance between the water surface and the bottom of the ship.

Card or Line 5

Enter: NS, NCP, NM, NBI, NB2, NSUP, NP MPRINT (815)

NS = Number of sections of CW-pipe (max. 49). The number of sections is one less than the number of stations. A station is a connecting point between two sections or a location of an occurrence, e.g., change in cross section, concentrated parameter, or abrupt change in distributed load. Each end of the pipe is considered as a station. A section occurs between two successive stations.

NCP = Number of concentrated parameter stations. (e.g., lumped masses, concentrated forces, concentrated springs, etc.).

NM = 1 for dynamic analysis
= 0 for static analysis

NB1 = n; Top end boundary condition of pipe.

NB2 = n; Bottom end boundary condition of pipe [n = 1, 2, 3, or 4].

1 = fixed. (transverse displacement and slope are zero.)

2 = simply-supported. (transverse displacement and moment are zero).

3 = free. (moment and shear are zero).

4 = guided. (slope and shear are zero).

NSUP	=	Number of inspan supports (rigid, moment released, guided, and shear released supports).
NP	= 1	to print trace of natural frequencies.
	= 0	otherwise
MPRINT	= 1	to print natural mode shapes.
	= 0	otherwise.

Card or Line 6

Enter: SP, DETE, G, (3F10.2)

SP	=	Estimation of the first natural frequency (in cycles/sec). Choose a value less than the actual fundamental frequency.
DETE	=	Frequency increment in cycles/sec for natural frequency search.
G	=	Gravitational acceleration (length/sec^2).
	= 0.	If an axial tension due to the CWP weight is neglected.

Card or Line 7a

Enter: NR(I), XL(I), A(I), EY(I), PI(I), DM(I), XI(I), (I1o, 6F10.2)

NR(I)	= 1	Elastic section.
	= 2	Rigid section.
XL(I)	=	Length of section
A(I)	=	Cross-sectional area (length^2), required only if shear deformation effects are to be taken into account. This area is obtained by multiplying the actual cross-sectional area by the shear shape factor.

Number of sets of card 7 (i.e., 7a, 7b) = NS (in card 5)

= 0. otherwise.

EY(I) = Modulus of elasticity (Force/length^2).

PI(I) = Poisson's ratio of CWP-material, required only if shear deformation effects are to be considered

= 0. otherwise.

DM(I) = Total mass per unit length of the CWP (mass of CWP + mass of internal water + added mass). If DM(0) is set to zero, CWP of a cylindrical shape is assumed by the program and DM(I) is automatically calculated.

XI(I) = Cross-sectional moment of inertia of CWP. If XI(I) is set to zero, CWP of a cylindrical shape is assumed by the program and XI(I) is automatically calculated.

Card or Line 7b

Enter:

XK(I), RK(I), RG(I), DIAM(I), TH(I), FA(I), (6F10.2

XK(I) = Modulus of elastic foundation (Winkler). (Force/length/length)

= 0. if no foundation.

RK(I) = Rotary modulus of elastic foundation (force=length/radian/length).

= 0. if no foundation.

RG(I) = Radius of gyration (length of the cross section, required only if rotary inertia effects are to be considered.

= 0. otherwise.

Card 7b (cont'd)

DIAM(I)	=	Outside diameter of CWP.
TH(I)	=	Wall thickness of CWP.
FA(I)	=	Value of axial force in the CWP section, in addition to that due to CWP's own weight, positive for compression.

No. of Card 8 = NCP (in Card 5)

Card or Line 8 (Concentrated parameter card). Skip this card if no concentrated parameters (NCP = 0 in Card 5), otherwise, one card is needed for each station with concentrated parameter(s).

Enter:

LNCP(I), CK(I), BK(I), CM(I), CN(I), SHP(I), RLHSP(I), (I10,5F10.2)

LNCP(I)	=	Station number of lumped (concentrated) parameters.
CK(I)	=	Linear (extension) spring constant (spring stiffness).
BK(I)	=	Rotary spring constant. (rotary spring stiffness).
CM(I)	=	Value of concentrated mass.
CN(I)	=	Value of radius of gyration of concentrated mass.
HSP(I)	=	Hinged rotary spring constant.

Card or line 9 (In-span support card). Skip this card if no in-span supports (NSUP = 0 in Card 5), otherwise, one card is needed for each in-span support.

No. of Card = NSUP (in Card 5)

Enter: MSUP(I), MTYPE(I) (215)

MSUP(I) = Station number of in-span support.

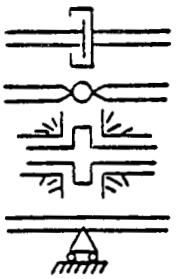
MTYPE(I) = n; Type of supports.

n = 1 shear release.

= 2 moment release.

= 3 guided support.

= 4 rigid support (roller).



Card or Line 10

Enter: NFTYPE, NFREQ (215)

NFTYPE = 0* Calculate responses due to all four types of excitation, i.e., a unit translation, unit rotation at the top of the pipe, current force and wave force.

= 1 Only unit translation excitation is considered.

= 2 Only unit rotation excitation is considered.

= 3 Only responses due to current load are considered.

= 4 Only responses due to wave load are considered.

= 5 Dynamic responses due to arbitrary loads, all dynamic loads are to be supplied by user.

= 6 Static responses due to arbitrary loads, all applied loads are to be supplied by user.

* If NFTYPE = 0 option is selected, the program creates a transfer function file named "CWPTF" (TAPE8) for future use by "XOTEC."

= 7 Static responses due to a static part of the current load. The current load profile parameters are to be supplied by user.

NFREQ = Number of exciting frequencies. (max. 30).

= 0 for static response analysis [NFTYPE = 6 or 7].

Card or Line 11 (Exciting frequency card) Skip this card if static response analysis (NFTYPE = 6 or 7 in Card 10)

Enter: FRQ(1), FRQ(2),..., FRQ(NFREQ) (8F10.2)

FRQ(I) = Values of exciting frequency (in radians/sec), number of exciting frequencies in this card = NFREQ in Card 10. Enter as many cards as required. (max. 30.)

Card or Line 12 (Current load profile coefficient card). This card is needed if NFTYPE = 7 (in Card 10).

Enter: VZ, VS, AX1, AZ2, AK1, AK2 (6F10.2)

VZ = Coefficient, V_o (see velocity profile definition below).

VS = Velocity of current at water surface, V_s (length/sec).

AZ1 = Coefficient, a_1 (see velocity profile definition below).

AZ2 = Coefficient, a_2 (see velocity profile definition below).

AK1 = Coefficient, $k_1 k_2$ (see velocity profile definition below).

AK2 = Coefficient, k_2 (see velocity profile definition below).

Current Velocity Profile Definition

$$V(z) = V_s(V_o + a_1 e^{-k_1 z} + a\ z e^{-k_2 z})$$

No. of Card 13 = NS (in Card 5)

Card or Line 13 (Arbitrary applied static load card, horizontal component). This set of cards is needed if NFTYPE = 6 (in Card 10).

Enter: F(I), F1(I), BM(I), BM1(I) (4F10.2)

F(I) = Applied uniform force (force/length) positive in the direction of positive axis.

F1(I) = Gradient of linearly varying applied distributed force (force/length/length). Positive if the magnitude of positive applied force increases along the positive pipe axis (downward).

BM(I) = Applied uniform bending moment (force-length/length), positive clockwise.

BM1(I) = Gradient of linearly varying applied distributed bending moment (force-length/length/length). Positive if the magnitude of applied clockwise moment increases along the positive pipe axis.

No. of Card 14 = NCP (in Card 5)

Card or Line 14 (Arbitrary applied-static-contrentated-load card, horizontal component). This set of cards is needed if NFTYPE = 6 (in Card 10) and NCP ≠ 0 (in Card 5). Note: If there is no applied concentrated load, enter zero forces at any station with spring.

Enter: LNCP(I), CP(I), CBM(I) (I10,2F10.2)

LNCP(I) = Station number of concentrated parameter(s).

CP(I) = Value of concentrated horizontal force (force), positive in the direction of positive axis.

CBM(I) = Value of concentrated bending moment (force-length), positive clockwise.

No. of Card 15 = NS(in Card 5)

Card or Line 15 Skip this card if NFTYPE = 6 or 7 (in Card 10).

Enter: HDC(I), SDC(I), AD(I) (3F10.2)

HDC(I) = Normal quadratic drag coefficient, C_D (see the definition below).

SDC(I) = Structural damping coefficient, C_s (force-sec/length/length).

AD(I) = Assumed amplitude of motion, a

Hydrodynamic Damping Coefficient Definition:

$$C_H = \frac{4}{3\pi} \rho D a \Omega C_D$$

Card or Line 16 (Current load profile coefficient card). This card is needed if NFTYPE = 0 or 3 (in Card 10).

Enter: VZ, VS, AZ1, AZ2, AK1, AK2 (6F10.2)

VZ = Coefficient, V_o (see velocity profile definition below).

VS = Velocity of current at water surface, V_s (length/sec).

AZ1 = Coefficient, a_1 (see velocity profile definition below).

AZ2 = Coefficient, a_2 (see velocity profile definition below).

AK1 = Coefficient, k_1 (see velocity profile definition below).

AK2 = Coefficient, k_2 (see velocity profile definition below).

Current Velocity Profile Definition:

$$V(z) = V_s(V_o + a_1 e^{-k_1 z} + a_2 z e^{-k_2 z})$$

Card or Line 17 (Wave amplitude card). This card is needed if NFTYPE = 0 or 4 (in Card 10)

Enter AW (F10.2)

AW = assumed amplitude of wave.

Card or Line 18 (Arbitrary dynamic-load card, horizontal component) needed if NFTYPE = 5 (in Card 10). Otherwise, skip this card and Card 19.

Enter: FS(I), FS1(I), BMS(I), BMS1(I), FC(I), FC1(I), BMC(I), BMC1(I), (8F10.2)

The definitions of the four sine components follow. The definitions for the four cosine components are identical.

No. of Card 18 = NS (in Card 5)

FS(I)	=	Sine component of an applied uniform force (force/length), positive in the direction of positive axis.
FS1(I)	=	Sine component of a gradient of linearly varying applied distributed force (force/length/length). Positive if the magnitude of positive applied force increases along the positive pipe axis (downward).
BMS(I)	=	Sine component of an applied uniform bending moment (force-length/length), positive clockwise.
BMS1(I)	=	Sine component of a gradient of linearly varying applied distributed bending moment (force-length/length/length). Positive if the magnitude of applied clockwise moment increases along the positive pipe axis (downward).

<u>Card or Line 19</u> (Arbitrary concentrated dynamic-load card, horizontal component). This card is needed is NFTYPE = 5 (in Card 10) and NCP ≠ 0 (in Card 5).

Note: If there is no applied concentrated load, enter zero forces at any station with spring.

Enter:

```
LNCP(I), CPS(I), CBMS(I), CPC(I), CBMC(I),
(I10,4F10.2)
```

No. of Card 19=NCP (in Card 5)

LNCP(I)	=	Station number of concentrated parameters.
CPS(I)	=	Sine component of a concentrated force (force).
BMS(I)	=	Sine component of a concentrated bending moment (force-length).
CPC(I)	=	Cosine component of a concentrated force (force).
BMC(I)	=	Cosine component of a concentrated bending moment (force-length).

Closing: Repeat Card 10 through Card 19 as many sets as NLOADS (in Card 2).

B.4 Input Preparation

The input for the bending program are divided into three sections, namely, the control section, the geometry section, and the loading section. In order to better illustrate input preparation, the following three examples are presented as sample problems. Note that sample inputs illustrated here are in unformatted forms.

B.4.1 Example 1 - For a 3,000 foot long CWP with 32' diameter and one foot wall thickness, we want to find:

1. Response due to an ocean current with a velocity profile as follows:

$$V(z) = V(o) \left[0.1 + 0.9e^{-0.00012z} + 0.0023ze^{-0.002z}\right]$$

$$V(o) = 4 \text{ ft/sec}$$

2. Response to a harmonic wave with a wave height of 10'.

3. Response due to a unit rotation of OTEC platform.

4. Response due to a unit translation of OTEC platform.

In order to simplify this example, it is assumed that the CWP has uniform diameter and wall thickness. This is not necessary since the geometry of the cold water pipe can be made different from section to section. For illustrative purposes the CWP is divided into 10 sections. The CWP can, if desired, be separated into as many as 49 sections. The following CWP material properties are assumed:

Modulus of elasticity	$= 10^6$ psi
Mass density of CWP material	$= 2.64$ lb-sec^2/ft^4
Mass density of water	$= 1.9905$ lb-sec^2/ft^4
Internal flow velocity	$= 0.$
No ring stiffeners	

A rotational spring connection at the top of the CWP ($z = 0$) with stiffness $= 10^{14}$ ft-lbs per radian is assumed.

B.4.2 Example 2 - a 3,000 foot long CWP with 30 foot diameter and 0.2 foot thickness subjected to static current load with the same current profile as in example 1. The cold water pipe also has a rotational spring connection at $z = 0$ with a stiffness of 10^{14} ft-lbs per radian. For this example, only the static response due to the ocean current is desired.

B.4.3 Example 3 - The same CWP as in Example 2 is assumed. It is desired to find the response of the cold water pipe due to propulsion or grazing of OTEC in calm water with a speed of four feet per second.

B.4.4 Control Inputs - The control inputs specify the type of analysis, the title of the problem, the number of CWP section, the inputs required, the number of supports and concentrated loads,

the number of terms, the number of loading conditions, the number of excitation frequencies, etc.

This program has been formulated so that many loading conditions and excitation frequencies can be included in one run. This is economical both in terms of manpower and computer cost.

Control Input for Example 1

```
RESPONSE OF COLD WATER PIPE DUE TO PLATFORM MOTIONS AND CURRENT AND WAVE
10,1
1,0.,0.,0.,518400.,0.
0.,1.9905,2.64,0,,0.
10,1,1,2,3,0,0,0
0.0001,0.005,0.
```

Control Input for Example 2

```
RESPONSE DUE TO  CURRENT
10,1.
1,0.,0.,0.,518400.,0.
0.,1.9905,2.9347,0.,0.
10,1,1,2,3,0,0,0
0.0001,0.005,0.
```

Control Input for Example 3

Same as those for Example 2.

Explanation

The first line is the title of the problem. Any number of alphanumeric characters up to 80 characters can be entered.

The second line specifies that ten terms (modal vectors) of a series solution (modal superpostion) are needed in the dynamic analysis and only one loading condition is considered in this run. Note that in Example 1, five different type of calculations are to be made but only one loading condition is included for each type of calculation.

The third line is for specifying ring stiffeners and the yield stress of the pipe material (See Section B.3). The fourth line specifies mass density of the water and pipe materials, the depth of the top of the CWP below the water surface and the vertical distance between the bottom of the OTEC platform and the water surface (platform draft). The zeros indicate that the top of the pipe is at the water surface and that there is no submerged platform.

The fifth line specifies that there are 10 pipe sections, one concentrated connection, that computed modeshape of the pipe are required, and that the boundary at the upper and lower ends of the CWP are hinged and free. The last three zeros indicate the following:

1. NSUP = 0. There are no inspan supports such as mooring line etc.

2. NP = 0. No printout of trace of the natural frequency calculation.

The program determines the CWP modal or natural frequencies by iteration. If NP is greater than zero, the program prints out the calculated values of the frequencies after each iteration.

4. NPRINT = 0. Modeshape output is not wanted if desired set NPRINT = 1.

The fifth line specifies an initial estimated value, and an assumed increment for the first mode (fundamental) frequency. For most problems these two values can be used. If for a particular CWP, no frequency is obtained after 80 iterations, the computer program will provide a suitable message. In this case the increment value of 0.005 should be increased to 0.01. For exceedingly flexible CWPs it may be necessary to use a value less than 0.0001 for the first value.

B.4.5 <u>Geometric Input</u> - The geometric input includes the properties of all pipe sections and the concentrated supports and connections.

Geometry of CWP for Example 1

```
1,300.,0.,1.44E+08,0.3
0.,0.,0.,32.,1.,0.
1,300.,0.,1.44E+08,0.3
0.,0.,0.,32.,1.,0.
1,300.,0.,1.44E+08,0.3
0.,0.,0.,32.,1.,0.
1,300.,0.,1.44E+08,0.3
0.,0.,0.,32.,1.,0.
1,300.,0.,1.44E+08,0.3
0.,0.,0.,32.,1.,0.
1,300.,0.,1.44E+08,0.3
0.,0.,0.,32.,1.,0.
1,300.,0.,1.44E+08,0.3
0.,0.,0.,32.,1.,0.
1,300.,0.,1.44E+08,0.3
0.,0.,0.,32.,1.,0.
1,300.,0.,1.44E+08,0.3
0.,0.,0.,32.,1.,0.
1,300.,0.,1.44E+08,0.3
0.,0.,0.,32.,1.,0.0
1,0.,1.0E+14,0.,0.
```

Geometry of CWP for Example 2

```
1,300.,0.,2.88E+08,0.3
0.,0.,0.,30.,0.2,0.
1,300.,0.,2.88E+08,0.3
0.,0.,0.,30.,0.2,0.
1,300.,0.,2.88E+08,0.3
0.,0.,0.,30.,0.2,0.
1,300.,0.,2.88E+08,0.3
0.,0.,0.,30.,0.2,0.
1,300.,0.,2.88E+08,0.3
0.,0.,0.,30.,0.2,0.
1,300.,0.,2.88E+08,0.3
0.,0.,0.,30.,0.2,0.
1,300.,0.,2.88E+08,0.3
0.,0.,0.,30.,0.2,0.
1,300.,0.,2.88E+08,0.3
0.,0.,0.,30.,0.2,0.
1,300.,0.,2.88E+08,0.3
0.,0.,0.,30.,0.2,0.
1,300.,0.,2.88E+08,0.3
0.,0.,0.,30.,0.2,0.
```

Geometry of CWP for Example 3

These are the same as those for Example 2.

Explanation

Explanation of these inputs are given in Section B.3. Only the first parameter needs to be explained here. This parameter, NR(I), allows the user to specifiy that the Ith section is rigid by setting NR(I) = 2. This is a useful option for the modeling of some practical CWP designs.

Note that each section requires two lines of input and the total lines must be consistent with the control number NS = 10. For this example, the section properties have been specified to be the same for all sections, but this is not necessary. All these properties can vary from section to section.

B.4.6 CWP Loadings

Example 1

```
0,1
0.0308
0.12,0.,100.
0.12,0.,100.
0.12,0.,100.
0.12,0.,100.
0.12,0.,100.
0.12,0.,100.
0.12,0.,100.
0.12,0.,100.
0.12,0.,100.
0.12,0.,100.
0.1,4.,0.9,0.0023,0.0012,0.002
10.
```

Example 2

```
7,0
0.1,4.,0.9,0.0023,0.0012,0.002
```

Example 3

Explanation

The first line indicates the type of analysis and number of excitation frequencies. For Example 1, the first number, equal to zero, indicates that the four basic analyses are, or as is, namely, responses due to OTEC platform translation, and rotation to waves, and due to current. The second number, equal to 1, indicates one excitation frequency for each calculation. For Example 2 and 3, the first number, equal to 7, indicates that static response due to current is required. The second number, equal to zero, indicates that no frequency input is required.

The second line indicates the excitation frequency, equal to 0.0308 radian/sec for Example 1. This line is not required for Example 2 and 3.

Lines 3 through line 12 specify the damping coefficient, C_t and the estimated amplitude of deflection. This allows the user to adjust the damping according to the following equivalent linearized expressions (see Section 4.5):

$$C_t = C_s + C_H$$

$$C_H = \frac{4}{3\pi} \rho D \omega C_D a$$

where

ρ is density of water.
ω is excitation frequency.
C_D is cylinder drag coefficient.
a is the amplitude of motion or deflection.
C_H is hydrodynamic damping.
C_s is structural damping.

For static analysis, such as those of Example 2 and 3, these input data are not required.

The next line, line 13 for Example 1 and line 2 for Example 2 and 3, specifies the coefficients defining the current profile and hence the following specific velocity profile.

$$V(z) = V(o)\left(0.1 + 0.9e^{-0.0012z} + 0.0023ze^{-0.002z}\right)$$

The last line for Example 1, line 14, is the wave height.

B.5 Data Input Using a Remote Keyboard Terminal

B.5.1 Prompt Entry Method - The input data can be loaded into the computer as follows:

a. Call the cold water pipe program by typing

   "FOR, OLD, CWPFLX"

b. Run the program after the computer responds with *RDY* by typing

   RUN, CM = 10000.

c. Type the 1st input line after the computer responds with "?"

   For Example 2 type

   "RESPONSE DUE TO CURRENT"

   after the mark "?"

d. Type the next line after the computer accepts the first line of input and again responds with the mark "?" This process is continued until all data have been inputed.

This method has several disadvantages. It is time consuming. If the user makes any errors before all input has been loaded, the whole input may be lost and the whole input process must be repeated.

B.5.2 Remote Job Entry Method - The input can be typed and stored in a file as follows:

a. Give the data file a name by typing

   "FOR, NEW, DATIN"

   The computer then responses with *RDY*

b. Type

   "ATAPE"

   indicate that the data will be typed.

c. Type the input data line by line after the computer responses with *RDY*

```
/RESPONSE DUE TO CURRENT
 10,1
 ................
 ................
 ................
 7.0
 0.1, 4., 0., 9., 0.0023, 0.0012, 0.002/
```

d. Save the file DATIN by typing

   "SAVE"

e. Set up a control file for running the program as follows:

```
00100 JOBBEAM,CM10000,T100.
00110 ACCOUNT, XXXXXXX,YYYY
00120 GET,DYNAMPY,INPUT=DATIN.
00130 RFL,100000.
00140 TSRUN(C, CWPFLX
00150 RFL,10000.
00160 REWIND,OUTPUT.
00170 SAVE,OUTPUT=BEAMOUT.
00175 COST.
00180 DFD,BEAMDAY,R.
00200 EXIT.
00210 RFL,10000.
00220 REWIND,OUTPUT.
00230 SAVE,OUTPUT=BEAMOUT.
00235 COST.
00240 DFD,BEAMDAY,R.
00260 EXIT.
00280 RFL,10000.
00285 COST.
00290 DFD,BEAMDAY,R.
00310 EOF.
```

It is necessary for the user to have some knowledge of the time sharing system in order to understand the functions of all lines in the above program. For the UCS system the user can copy and use this program by putting the account number in the spaces shown as XXXXXXX,YYYY.

In general, this control file or program run the program CWPFLX using the input data stored in DATIN. After the calculation is completed, the output is stored in the file "BEAMOUT" and the day file is stored in "BEAMDAY".

In lines 00175 and 00235 the cost of each run is desired. The user can use other names for the input file, outfile and day file.

f. Run the control program as described in e, by typing

OLD, BEAMDO (The name of the control program)
RDY
RJE (Remote job entry).

g. To obtain the output, type

"OLD, BEAMOUT"

after *RDY*, type "LIST"

In case the calculation is not yet completed, the computer will respond with "NOT-FOUND". The user should then wait a reasonable time before again entering "OLD BEAMOUT" again.

Note that user must purge any previous output by typing "UNSAVE BEAMOUT" before a new run can be made and the results saved. Other BEAMOUT contains only the output for the previous run.

h. The cost of each run can be obtained by typing

"OLD, BEAMDAY"
RDY
"LIST".

For Example 1, the day file is as follows:

```
12.40.443JOBBEAM,CM10000,T100.
12.40.443AC  XXXXXXX.              1A
12.40.44. 11/08/78.LN3BGOV
12.40.44.GET,DYNAMPY,INPUT=DATIN.
12.40.45.READY -   DYNAMPY
12.40.45.READY -   DATIN
12.40.45.RFL,100000.
12.40.45$FL    4096    0.001        0        0,
12.40.45$FI       0        2
12.40.46.TSRUN(0, CWPFLX
12.40.55.BBEAM   --066000
12.40.55$FL   32768    4.023      107       25
12.50.38.RFL,10000.
12.50.38$FL   27648   13.506      489      322,
12.50.38$FI       0        1
12.50.39.REWIND,OUTPUT.
12.50.39.SAVE,OUTPUT=BEAMOUT.
12.50.40.READY -   BEAMOUT
12.50.40.COST.
12.50.40$FL    4096   13.506        0        0,
12.50.40$FI       0        1
12.50.41.          SERV. UNITS-1 =     53
12.50.41.          JOB COST=$      15.90
12.50.42.DFD,BEAMDAY,R.
12.50.42$FL   12288   13.519        6        5
```

The cost of this run, inlcuding four types of calculations, 10 natural frequencies, and one excitation frequency, is $15.90. This is considerably cheaper than other methods, such as the finite element or finite difference methods.

B.6 Program Output

The input and output for Example 1, 2, and 3 are given in the following pages:

B.5.1 Input/Output for Example 1

Input

```
   RESPONSE OF COLD WATER PIPE DUE TO PLATFORM MOTIONS AND CURRENT AND WAVE
10,1
1,0.,0.,0.,518400.,0.
0.,1.9905,2.64,0.,0.
10,1,1,2,3,0,0,0,0
0.0001,0.005,0.
1,300.,0.,1.44E+08,0.3
0.,0.,0.,32.,1.,0.
1,300.,0.,1.44E+08,0.3
0.,0.,0.,32.,1.,0.
1,300.,0.,1.44E+08,0.3
0.,0.,0.,32.,1.,0.
1,300.,0.,1.44E+08,0.3
0.,0.,0.,32.,1.,0.
1,300.,0.,1.44E+08,0.3
0.,0.,0.,32.,1.,0.
1,300.,0.,1.44E+08,0.3
0.,0.,0.,32.,1.,0.
1,300.,0.,1.44E+08,0.3
0.,0.,0.,32.,1.,0.
1,300.,0.,1.44E+08,0.3
0.,0.,0.,32.,1.,0.
1,300.,0.,1.44E+08,0.3
0.,0.,0.,32.,1.,0.
1,300.,0.,1.44E+08,0.3
0.,0.,0.,32.,1.,0.0
1,0.,1.0E+14,0.,0.
0,1
0.0308
0.12,0.,100.
0.12,0.,100.
0.12,0.,100.
0.12,0.,100.
0.12,0.,100.
0.12,0.,100.
0.12,0.,100.
0.12,0.,100.
0.12,0.,100.
0.12,0.,100.
0.1,4.,0.9,0.0023,0.0012,0.002
10.
```

Control Program BEAMDO

```
00100 JOBBEAM,CM10000,T100.
00110 ACCOUNT,XXXXXXXXX.
00120 GET,DYNAMPY,INPUT=DATIN.
00130 RFL,100000.
00140 TSRUN(C,CWPFLX
00150 RFL,10000.
00160 REWIND,OUTPUT.
00170 SAVE,OUTPUT=BEAMOUT.
00175 COST.
00180 DFD,BEAMDAY,R.
00200 EXIT.
00210 RFL,10000.
00220 REWIND,OUTPUT.
00230 SAVE,OUTPUT=BEAMOUT.
00235 COST.
00240 DFD,BEAMDAY,R.
00260 EXIT.
00280 RFL,10000.
00285 COST.
00290 DFD,BEAMDAY,R.
00310 EOF.
```

Execution Statements

```
OLD,BEAMDO
*RDY-FOR*
RJE
 RJE COMPLETE,ID =  LH3DGQV
*RDY*
```

Request for Output

```
OLD,BEAMOUT
*RDY-FOR*
LIST
```

Output Listing

```
*****************************************************
  FLEXURAL VIBRATION OF A COLD-WATER PIPE
*****************************************************

   RESPONSE OF COLD WATER PIPE DUE TO PLATFORM MOTIONS AND CURRENT AND WAVE


 VELOCITY OF INTERNAL WATER FLOW =     0.        LENGTH/SECOND

 NO. OF SECTIONS =        10
 NO. OF LUMPED STATIONS =        1
 NO. OF INSPAN BOUNDARY CONDITIONS =         0
```

CROSS-SECTIONAL PROPERTIES OF THE COLD-WATER PIPE

SECTION	LENGTH	MOD. OF ELAS.	MO. INERTIA	MASS DENSITY
1	3.000000E+02	1.440000E+08	1.171107E+04	3.264965E+03
2	3.000000E+02	1.440000E+08	1.171107E+04	3.264965E+03
3	3.000000E+02	1.440000E+08	1.171107E+04	3.264965E+03
4	3.000000E+02	1.440000E+08	1.171107E+04	3.264965E+03
5	3.000000E+02	1.440000E+08	1.171107E+04	3.264965E+03
6	3.000000E+02	1.440000E+08	1.171107E+04	3.264965E+03
7	3.000000E+02	1.440000E+08	1.171107E+04	3.264965E+03
8	3.000000E+02	1.440000E+08	1.171107E+04	3.264965E+03
9	3.000000E+02	1.440000E+08	1.171107E+04	3.264965E+03
10	3.000000E+02	1.440000E+08	1.171107E+04	3.264965E+03

SECTION	OUTSIDE DIAM	WALL THICKNESS
1	3.200000E+01	1.000000E+00
2	3.200000E+01	1.000000E+00
3	3.200000E+01	1.000000E+00
4	3.200000E+01	1.000000E+00
5	3.200000E+01	1.000000E+00
6	3.200000E+01	1.000000E+00
7	3.200000E+01	1.000000E+00
8	3.200000E+01	1.000000E+00
9	3.200000E+01	1.000000E+00
10	3.200000E+01	1.000000E+00

SECTION	ELAS. FDN	ROT. ELAS. FDN	SHEAR AREA	POISSON RATIO
1	0.	0.	0.	3.000000E-01
2	0.	0.	0.	3.000000E-01
3	0.	0.	0.	3.000000E-01
4	0.	0.	0.	3.000000E-01
5	0.	0.	0.	3.000000E-01
6	0.	0.	0.	3.000000E-01
7	0.	0.	0.	3.000000E-01
8	0.	0.	0.	3.000000E-01
9	0.	0.	0.	3.000000E-01
10	0.	0.	0.	3.000000E-01

SECTION	AXIAL FORCE	RADIUS OF GYRATN	THERMAL MOMENT	TH MOMENT GRAD.
1	-6.307484E+06	0.	0.	0.
2	-5.676735E+06	0.	0.	0.
3	-5.045987E+06	0.	0.	0.
4	-4.415239E+06	0.	0.	0.
5	-3.784490E+06	0.	0.	0.
6	-3.153742E+06	0.	0.	0.
7	-2.522993E+06	0.	0.	0.
8	-1.892245E+06	0.	0.	0.
9	-1.261497E+06	0.	0.	0.
10	-6.307484E+05	0.	0.	0.

CONCENTRATED PARAMETERS

STATION	MASS	LINEAR SPRING	ROT SPRING	RADIUS GYRATN
1	0.	0.	1.000000E+14	0.

LEFT END BOUNDARY CONDITION

.....BOUNDARY SIMPLY SUPPORTED

RIGHT END BOUNDARY CONDITION

.....BOUNDARY FREE

STATIC FORCE

SECTION	FORCE	FOR GRADIENT	MOMENT	MOMENT GRADIENT
1	0.	0.	0.	0.
2	0.	0.	0.	0.
3	0.	0.	0.	0.
4	0.	0.	0.	0.
5	0.	0.	0.	0.
6	0.	0.	0.	0.
7	0.	0.	0.	0.
8	0.	0.	0.	0.
9	0.	0.	0.	0.
10	0.	0.	0.	0.

FREQUENCY 1 = 4.7120E-03 CYCLES PER SECOND

FREQUENCY 2 = 1.2080E-02 CYCLES PER SECOND

FREQUENCY 3 = 2.7957E-02 CYCLES PER SECOND

FREQUENCY 4 = 5.1855E-02 CYCLES PER SECOND

FREQUENCY 5 = 8.2911E-02 CYCLES PER SECOND

FREQUENCY 6 = 1.2340E-01 CYCLES PER SECOND

FREQUENCY 7 = 1.7106E-01 CYCLES PER SECOND

FREQUENCY 8 = 2.2666E-01 CYCLES PER SECOND

FREQUENCY 9 = 2.9019E-01 CYCLES PER SECOND

FREQUENCY 10 = 3.6131E-01 CYCLES PER SECOND

MODE	NUMBER OF ITERATIONS	FREQUENCIES IN CYCLES PER SECOND
1	15	.0047
2	14	.0121
3	15	.0280
4	18	.0519
5	16	.0829
6	12	.1234
7	9	.1711
8	13	.2267
9	15	.2902
10	9	.3613

COLD WATER PIPE RESPONSE

	STRUCTURAL DAMPING	HYDRO DAMPING	ASSUMED AMPLITUDE
1	0.	1.2000E-01	1.0000E+02
2	0.	1.2000E-01	1.0000E+02
3	0.	1.2000E-01	1.0000E+02
4	0.	1.2000E-01	1.0000E+02
5	0.	1.2000E-01	1.0000E+02
6	0.	1.2000E-01	1.0000E+02
7	0.	1.2000E-01	1.0000E+02
8	0.	1.2000E-01	1.0000E+02
9	0.	1.2000E-01	1.0000E+02
10	0.	1.2000E-01	1.0000E+02

CURRENT PROFILE

V0	VS	A1	A2	K1	K2
1.0000E-01	4.0000E+00	9.0000E-01	2.3000E-03	1.2000E-03	2.0000E-03

..... FORCES DUE TO A UNIT TRANSLATION OF THE PLATFORM .....

EXCITING FREQUENCY ..... .03080 RADIANS/SEC

SINE FORCING AMPLITUDES

SECTION	UNIFORM FORCE	FORCE GRAD.	UNIFORM MOMENT	MOMENT GRAD.
1	3.077397E-01	0.	0.	0.
2	3.077397E-01	0.	0.	0.
3	3.077397E-01	0.	0.	0.
4	3.077397E-01	0.	0.	0.
5	3.077397E-01	0.	0.	0.
6	3.077397E-01	0.	0.	0.
7	3.077397E-01	0.	0.	0.
8	3.077397E-01	0.	0.	0.
9	3.077397E-01	0.	0.	0.
10	3.077397E-01	0.	0.	0.

COSINE FORCING AMPLITUDES

SECTION	UNIFORM FORCE	FORCE GRAD.	UNIFORM MOMENT	MOMENT GRAD.
1	3.097276E+00	0.	0.	0.
2	3.097276E+00	0.	0.	0.
3	3.097276E+00	0.	0.	0.
4	3.097276E+00	0.	0.	0.
5	3.097276E+00	0.	0.	0.
6	3.097276E+00	0.	0.	0.
7	3.097276E+00	0.	0.	0.
8	3.097276E+00	0.	0.	0.
9	3.097276E+00	0.	0.	0.
10	3.097276E+00	0.	0.	0.

..... FORCES DUE TO A UNIT ROTATION OF THE PLATFORM .....

EXCITING FREQUENCY ..... .03080 RADIANS/SEC

SINE FORCING AMPLITUDES

SECTION	UNIFORM FORCE	FORCE GRAD.	UNIFORM MOMENT	MOMENT GRAD.
1	0.	3.077397E-01	0.	0.
2	9.232191E+01	3.077397E-01	0.	0.
3	1.846438E+02	3.077397E-01	0.	0.
4	2.769657E+02	3.077397E-01	0.	0.
5	3.692876E+02	3.077397E-01	0.	0.
6	4.616095E+02	3.077397E-01	0.	0.
7	5.539314E+02	3.077397E-01	0.	0.
8	6.462534E+02	3.077397E-01	0.	0.
9	7.385753E+02	3.077397E-01	0.	0.
10	8.308972E+02	3.077397E-01	0.	0.

COSINE FORCING AMPLITUDES

SECTION	UNIFORM FORCE	FORCE GRAD.	UNIFORM MOMENT	MOMENT GRAD.
1	0.	3.097276E+00	0.	0.
2	9.291828E+02	3.097276E+00	0.	0.
3	1.858366E+03	3.097276E+00	0.	0.
4	2.787548E+03	3.097276E+00	0.	0.
5	3.716731E+03	3.097276E+00	0.	0.
6	4.645914E+03	3.097276E+00	0.	0.
7	5.575097E+03	3.097276E+00	0.	0.
8	6.504280E+03	3.097276E+00	0.	0.
9	7.433462E+03	3.097276E+00	0.	0.
10	8.362645E+03	3.097276E+00	0.	0.

CHECK CURRENT A1,A2,K1,K2,VS,VZ
9.0000E-01 2.3000E-03 1.2000E-03 2.0000E-03 4.0000E+00 1.0000E-01

..... FORCES DUE TO OCEAN CURRENT .....

EXCITING FREQUENCY ..... .03080 RADIANS/SEC

SINE FORCING AMPLITUDES

SECTION	UNIFORM FORCE	FORCE GRAD.	UNIFORM MOMENT	MOMENT GRAD.
1	1.273920E+02	9.534807E-02	0.	0.
2	1.559964E+02	-1.337392E-01	0.	0.
3	1.158747E+02	-1.487852E-01	0.	0.
4	7.123911E+01	-1.025710E-01	0.	0.
5	4.046780E+01	-5.979544E-02	0.	0.
6	2.252917E+01	-3.244905E-02	0.	0.
7	1.279445E+01	-1.719197E-02	0.	0.
8	7.636863E+00	-9.151646E-03	0.	0.
9	4.891369E+00	-4.981363E-03	0.	0.
10	3.396960E+00	-2.797533E-03	0.	0.

COSINE FORCING AMPLITUDES

SECTION	UNIFORM FORCE	FORCE GRAD.	UNIFORM MOMENT	MOMENT GRAD.
1	1.273920E+02	9.534807E-02	0.	0.
2	1.559964E+02	-1.337392E-01	0.	0.
3	1.158747E+02	-1.487852E-01	0.	0.
4	7.123911E+01	-1.025710E-01	0.	0.
5	4.046780E+01	-5.979544E-02	0.	0.
6	2.252917E+01	-3.244905E-02	0.	0.
7	1.279445E+01	-1.719197E-02	0.	0.
8	7.636863E+00	-9.151646E-03	0.	0.
9	4.891369E+00	-4.981363E-03	0.	0.
10	3.396960E+00	-2.797533E-03	0.	0.

CURRENT PROFILE

VO	VS	A1	A2	K1	K2
1.0000E-01	4.0000E+00	9.0000E-01	2.3000E-03	1.2000E-03	2.0000E-03

CHECK WAVE HEIGHT = 10.00000

..... FORCES DUE TO OCEAN WAVES .....

WAVE FREQUENCY ..... .03080 RADIANS/SEC

SINE FORCING AMPLITUDES

SECTION	UNIFORM FORCE	FORCE GRAD.	UNIFORM MOMENT	MOMENT GRAD.
1	0.			
2	0.			
3	0.			
4	0.			
5	0.			
6	0.			
7	0.			
8	0.			
9	0.			
10	0.			
11	0.			
12	0.			
13	0.			
14	0.			
15	0.			
16	0.			
17	0.			
18	0.			
19	0.			
20	0.			
21	0.			
22	0.			
23	0.			
24	0.			
25	0.			
26	0.			
27	0.			
28	0.			
29	0.			
30	0.			
31	0.			

COSINE FORCING AMPLITUDES

SECTION	UNIFORM FORCE	FORCE GRAD.	UNIFORM MOMENT	MOMENT GRAD.
1	3.339423E+01			
2	3.329599E+01			
3	3.319804E+01			
4	3.310038E+01			
5	3.300301E+01			
6	3.290592E+01			
7	3.280912E+01			
8	3.271260E+01			
9	3.261637E+01			
10	3.252042E+01			
11	3.242476E+01			
12	3.232937E+01			
13	3.223427E+01			
14	3.213944E+01			
15	3.204489E+01			
16	3.195063E+01			
17	3.185664E+01			
18	3.176292E+01			
19	3.166948E+01			
20	3.157632E+01			
21	3.148343E+01			
22	3.139081E+01			
23	3.129847E+01			
24	3.120640E+01			
25	3.111459E+01			
26	3.102306E+01			
27	3.093180E+01			
28	3.084081E+01			
29	3.075008E+01			
30	3.065962E+01			
31	3.056943E+01			

WAVE HEIGHT = 10.0000

******** DYNAMIC RESPONSE OF A COLD-WATER PIPE ********

COLD WATAR PIE RESPONSE TO UNIT PLATFORM TRANSLATION

EXCITING FREQUENCY = .0308 RADIANS/SECOND

DAMPING COEFFICIENT = 9.99155 FORCE-SEC/LENGTH2

STATION	DISTANCE	DISPLACEMENT	PHASE	SLOPE	PHASE	SHEAR STRESS
1	0.	1.0000E+00	0.	1.0561E-07	229.99	1.0254E+01
2	100.00	9.8107E-01	358.67	5.8009E-04	229.73	1.0261E+01
3	200.00	9.3057E-01	354.67	1.0815E-03	229.43	1.0298E+01
4	300.00	8.6149E-01	347.57	1.5227E-03	229.12	1.0358E+01
5	400.00	7.9349E-01	336.58	1.9166E-03	228.80	1.0410E+01
6	500.00	7.5571E-01	321.27	2.2735E-03	228.50	1.0418E+01
7	600.00	7.8223E-01	303.11	2.6052E-03	228.21	1.1331E+01
8	700.00	8.9429E-01	285.75	2.9137E-03	227.95	1.1215E+01
9	800.00	1.0880E+00	271.97	3.1999E-03	227.71	1.1047E+01
10	900.00	1.3469E+00	261.99	3.4741E-03	227.48	1.2118E+01
11	1000.00	1.6563E+00	254.89	3.7335E-03	227.26	1.1841E+01
12	1100.00	2.0056E+00	249.76	3.9752E-03	227.07	1.1490E+01
13	1200.00	2.3882E+00	245.95	4.2088E-03	226.90	1.2614E+01
14	1300.00	2.8000E+00	243.05	4.4291E-03	226.75	1.2090E+01
15	1400.00	3.2373E+00	240.79	4.6307E-03	226.61	1.1485E+01
16	1500.00	3.6973E+00	238.99	4.8243E-03	226.49	1.2590E+01
17	1600.00	4.1785E+00	237.52	5.0027E-03	226.38	1.1821E+01
18	1700.00	4.6781E+00	236.32	5.1594E-03	226.29	1.0955E+01
19	1800.00	5.1942E+00	235.31	5.3057E-03	226.22	1.1956E+01
20	1900.00	5.7253E+00	234.46	5.4341E-03	226.15	1.0887E+01
21	2000.00	6.2687E+00	233.73	5.5375E-03	226.10	9.7208E+00
22	2100.00	6.8225E+00	233.10	5.6289E-03	226.05	1.0550E+01
23	2200.00	7.3853E+00	232.56	5.7011E-03	226.02	9.1959E+00
24	2300.00	7.9544E+00	232.09	5.7476E-03	225.99	7.7382E+00
25	2400.00	8.5279E+00	231.68	5.7831E-03	225.96	8.3177E+00
26	2500.00	9.1047E+00	231.31	5.8020E-03	225.95	6.6446E+00
27	2600.00	9.6825E+00	230.99	5.7995E-03	225.94	4.8704E+00
28	2700.00	1.0260E+01	230.71	5.7929E-03	225.93	5.1489E+00
29	2800.00	1.0837E+01	230.45	5.7790E-03	225.93	3.1802E+00
30	2900.00	1.1412E+01	230.22	5.7558E-03	225.93	1.1078E+00
31	3000.00	1.1985E+01	230.02	5.7434E-03	225.93	9.3707E-03

STATION	DISTANCE	BENDING MOMENT	PHASE	SHEAR FORCE	PHASE	BENDING STRESS
1	0.	1.0561E+07	229.99	1.6886E+04	233.04	1.0020E+02
2	100.00	9.0621E+06	229.42	1.6898E+04	232.96	8.5978E+01
3	200.00	7.9008E+06	228.72	1.6959E+04	232.52	7.4960E+01
4	300.00	7.0277E+06	227.95	1.7058E+04	231.73	6.6676E+01
5	400.00	6.2987E+06	227.21	1.7143E+04	230.82	5.9761E+01
6	500.00	5.7764E+06	226.55	1.7157E+04	230.02	5.4805E+01
7	600.00	5.4520E+06	226.02	1.8660E+04	229.32	5.1727E+01
8	700.00	4.9904E+06	225.45	1.8470E+04	228.89	4.7347E+01
9	800.00	4.7015E+06	224.97	1.8193E+04	228.47	4.4607E+01
10	900.00	4.5849E+06	224.65	1.9957E+04	227.95	4.3500E+01
11	1000.00	4.2042E+06	224.23	1.9501E+04	227.51	3.9889E+01
12	1100.00	3.9848E+06	224.00	1.8922E+04	227.12	3.7807E+01
13	1200.00	3.9342E+06	223.97	2.0774E+04	226.83	3.7327E+01
14	1300.00	3.5344E+06	223.70	1.9911E+04	226.62	3.3533E+01
15	1400.00	3.3068E+06	223.59	1.8915E+04	226.43	3.1374E+01
16	1500.00	3.2596E+06	223.67	2.0735E+04	226.25	3.0926E+01
17	1600.00	2.7986E+06	223.43	1.9467E+04	226.04	2.6553E+01
18	1700.00	2.5244E+06	223.40	1.8042E+04	225.85	2.3951E+01
19	1800.00	2.4482E+06	223.64	1.9690E+04	225.81	2.3228E+01
20	1900.00	1.9214E+06	223.34	1.7929E+04	225.75	1.8229E+01
21	2000.00	1.6075E+06	223.22	1.6009E+04	225.69	1.5251E+01
22	2100.00	1.5173E+06	223.47	1.7375E+04	225.68	1.4396E+01
23	2200.00	9.6262E+05	222.69	1.5144E+04	225.56	9.1331E+00
24	2300.00	6.5014E+05	222.17	1.2744E+04	225.44	6.1683E+00
25	2400.00	5.9369E+05	222.94	1.3698E+04	225.51	5.6327E+00
26	2500.00	9.2980E+04	212.60	1.0943E+04	225.50	8.8217E-01
27	2600.00	1.2791E+05	52.29	8.0209E+03	225.50	1.2136E+00
28	2700.00	4.6157E+04	56.85	8.4795E+03	225.61	4.3792E-01
29	2800.00	3.6751E+05	46.60	5.2373E+03	225.49	3.4868E+00
30	2900.00	3.5823E+05	46.08	1.8244E+03	225.14	3.3988E+00
31	3000.00	1.0629E+02	354.32	1.5432E+01	12.89	1.0084E-03

******** DYNAMIC RESPONSE OF A COLD-WATER PIPE ********

COLD WATER PIPE RDSPONSE DUE TO UNIT PLATFORM ROTATION

EXCITING FREQUENCY = .0308 RADIANS/SECOND

DAMPING COEFFICIENT = 9.99155 FORCE-SEC/LENGTH2

STATION	DISTANCE	DISPLACEMENT	PHASE	SLOPE	PHASE	SHEAR STRESS
1	0.	0.	0.	9.9984E-01	359.99	2.3587E+04
2	100.00	7.3781E+01	318.40	9.6236E-01	277.56	2.3585E+04
3	200.00	1.8858E+02	278.96	1.8789E+00	250.58	2.3568E+04
4	300.00	4.0541E+02	260.54	2.7965E+00	242.70	2.3518E+04
5	400.00	7.1667E+02	251.73	3.6319E+00	239.07	2.3415E+04
6	500.00	1.1109E+03	246.77	4.3910E+00	236.96	2.3241E+04
7	600.00	1.5799E+03	243.61	5.0961E+00	235.55	2.5103E+04
8	700.00	2.1182E+03	241.42	5.7504E+00	234.54	2.4745E+04
9	800.00	2.7200E+03	239.80	6.3556E+00	233.77	2.4279E+04
10	900.00	3.3813E+03	238.55	6.9340E+00	233.15	2.6507E+04
11	1000.00	4.0995E+03	237.56	7.4802E+00	232.65	2.5793E+04
12	1100.00	4.8705E+03	236.75	7.9878E+00	232.23	2.4937E+04
13	1200.00	5.6915E+03	236.07	8.4786E+00	231.87	2.7316E+04
14	1300.00	6.5608E+03	235.49	8.9412E+00	231.56	2.6145E+04
15	1400.00	7.4743E+03	234.99	9.3643E+00	231.30	2.4804E+04
16	1500.00	8.4292E+03	234.56	9.7703E+00	231.08	2.7153E+04
17	1600.00	9.4237E+03	234.18	1.0145E+01	230.88	2.5447E+04
18	1700.00	1.0453E+04	233.85	1.0473E+01	230.72	2.3546E+04
19	1800.00	1.1514E+04	233.55	1.0780E+01	230.58	2.5689E+04
20	1900.00	1.2605E+04	233.29	1.1049E+01	230.46	2.3382E+04
21	2000.00	1.3720E+04	233.06	1.1266E+01	230.37	2.0870E+04
22	2100.00	1.4855E+04	232.85	1.1457E+01	230.30	2.2645E+04
23	2200.00	1.6008E+04	232.66	1.1608E+01	230.24	1.9712E+04
24	2300.00	1.7172E+04	232.50	1.1704E+01	230.20	1.6564E+04
25	2400.00	1.8346E+04	232.35	1.1778E+01	230.17	1.7816E+04
26	2500.00	1.9525E+04	232.22	1.1817E+01	230.16	1.4234E+04
27	2600.00	2.0706E+04	232.10	1.1810E+01	230.15	1.0436E+04
28	2700.00	2.1886E+04	231.99	1.1795E+01	230.16	1.1044E+04
29	2800.00	2.3063E+04	231.90	1.1765E+01	230.16	6.8132E+03
30	2900.00	2.4237E+04	231.82	1.1715E+01	230.18	2.3654E+03
31	3000.00	2.5406E+04	231.74	1.1689E+01	230.19	8.3147E+00

STATION	DISTANCE	BENDING MOMENT	PHASE	SHEAR FORCE	PHASE	BENDING STRESS
1	0.	2.3609E+10	227.56	3.8845E+07	227.99	2.2400E+05
2	100.00	2.0144E+10	227.48	3.8841E+07	227.98	1.9112E+05
3	200.00	1.7435E+10	227.37	3.8813E+07	227.95	1.6542E+05
4	300.00	1.5387E+10	227.24	3.8731E+07	227.89	1.4598E+05
5	400.00	1.3685E+10	227.10	3.8562E+07	227.82	1.2984E+05
6	500.00	1.2469E+10	226.94	3.8275E+07	227.73	1.1830E+05
7	600.00	1.1709E+10	226.79	4.1342E+07	227.62	1.1109E+05
8	700.00	1.0660E+10	226.62	4.0752E+07	227.53	1.0114E+05
9	800.00	9.9984E+09	226.45	3.9965E+07	227.44	9.4862E+04
10	900.00	9.7231E+09	226.33	4.3653E+07	227.30	9.2250E+04
11	1000.00	8.8832E+09	226.17	4.2478E+07	227.20	8.4281E+04
12	1100.00	8.4056E+09	226.05	4.1069E+07	227.09	7.9750E+04
13	1200.00	8.3021E+09	226.00	4.4986E+07	226.97	7.8763E+04
14	1300.00	7.4427E+09	225.88	4.3057E+07	226.88	7.0614E+04
15	1400.00	6.9575E+09	225.83	4.0849E+07	226.79	6.6011E+04
16	1500.00	6.8645E+09	225.86	4.4718E+07	226.71	6.5129E+04
17	1600.00	5.8800E+09	225.78	4.1908E+07	226.64	5.5788E+04
18	1700.00	5.3029E+09	225.78	3.8777E+07	226.58	5.0313E+04
19	1800.00	5.1552E+09	225.87	4.2306E+07	226.57	4.8911E+04
20	1900.00	4.0336E+09	225.79	3.8508E+07	226.54	3.8270E+04
21	2000.00	3.3698E+09	225.78	3.4369E+07	226.52	3.1971E+04
22	2100.00	3.1879E+09	225.89	3.7293E+07	226.53	3.0245E+04
23	2200.00	2.0060E+09	225.67	3.2463E+07	226.51	1.9032E+04
24	2300.00	1.3477E+09	225.52	2.7279E+07	226.49	1.2787E+04
25	2400.00	1.2412E+09	225.74	2.9341E+07	226.51	1.1776E+04
26	2500.00	1.7220E+08	222.05	2.3442E+07	226.51	1.6337E+03
27	2600.00	2.8852E+08	48.46	1.7186E+07	226.49	2.7374E+03
28	2700.00	1.0691E+08	49.63	1.8183E+07	226.52	1.0144E+03
29	2800.00	7.9502E+08	46.82	1.1221E+07	226.50	7.5429E+03
30	2900.00	7.7139E+08	46.68	3.8955E+06	226.40	7.3187E+03
31	3000.00	1.8130E+04	354.32	1.3693E+04	45.57	1.7201E-01

******** DYNAMIC RESPONSE OF A COLD-WATER PIPE ********

COLD WATER PIPE RESPONSE DUE TO CURRENT

EXCITING FREQUENCY = .0308 RADIANS/SECOND

DAMPING COEFFICIENT = 9.99155 FORCE-SEC/LENGTH2

STATION	DISTANCE	DISPLACEMENT	PHASE	SLOPE	PHASE	SHEAR STRESS
1	0.	0.	0.	5.8768E-07	139.34	7.0417E+01
2	100.00	1.6586E-01	141.74	3.2397E-03	143.03	6.9735E+01
3	200.00	6.3478E-01	144.35	6.0938E-03	147.14	6.6391E+01
4	300.00	1.3748E+00	147.06	8.7038E-03	151.36	6.1579E+01
5	400.00	2.3657E+00	149.76	1.1168E-02	155.38	5.8599E+01
6	500.00	3.5943E+00	152.33	1.3535E-02	158.98	5.8537E+01
7	600.00	5.0528E+00	154.73	1.5852E-02	162.08	6.5640E+01
8	700.00	6.7367E+00	156.93	1.8109E-02	164.72	6.6983E+01
9	800.00	8.6386E+00	158.92	2.0289E-02	166.99	6.8121E+01
10	900.00	1.0754E+01	160.71	2.2441E-02	168.94	7.7645E+01
11	1000.00	1.3079E+01	162.34	2.4526E-02	170.60	7.8657E+01
12	1100.00	1.5604E+01	163.80	2.6502E-02	171.99	7.8697E+01
13	1200.00	1.8323E+01	165.12	2.8419E-02	173.15	8.7741E+01
14	1300.00	2.1229E+01	166.29	3.0231E-02	174.10	8.4852E+01
15	1400.00	2.4309E+01	167.34	3.1901E-02	174.90	8.1197E+01
16	1500.00	2.7552E+01	168.26	3.3499E-02	175.58	8.9644E+01
17	1600.00	3.0950E+01	169.12	3.4976E-02	176.16	8.5222E+01
18	1700.00	3.4488E+01	169.87	3.6278E-02	176.64	7.9854E+01
19	1800.00	3.8152E+01	170.54	3.7483E-02	177.03	8.7082E+01
20	1900.00	4.1932E+01	171.14	3.8538E-02	177.35	7.9269E+01
21	2000.00	4.5808E+01	171.68	3.9398E-02	177.62	7.0812E+01
22	2100.00	4.9766E+01	172.16	4.0156E-02	177.84	7.6939E+01
23	2200.00	5.3795E+01	172.60	4.0763E-02	178.03	6.7726E+01
24	2300.00	5.7875E+01	172.99	4.1166E-02	178.17	5.7599E+01
25	2400.00	6.1991E+01	173.34	4.1471E-02	178.27	6.1575E+01
26	2500.00	6.6134E+01	173.65	4.1639E-02	178.34	4.9019E+01
27	2600.00	7.0285E+01	173.93	4.1641E-02	178.39	3.5744E+01
28	2700.00	7.4436E+01	174.18	4.1605E-02	178.41	3.7506E+01
29	2800.00	7.8582E+01	174.40	4.1513E-02	178.43	2.3346E+01
30	2900.00	8.2715E+01	174.60	4.1348E-02	178.43	8.2848E+00
31	3000.00	8.6835E+01	174.79	4.1259E-02	178.43	5.6766E-01

STATION	DISTANCE	BENDING MOMENT	PHASE	SHEAR FORCE	PHASE	BENDING STRESS
1	0.	5.8768E+07	139.[illegible]	1.1597E+05	101.97	5.5757E+02
2	100.00	5.1079E+07	147.23	1.1484E+05	102.83	4.8462E+02
3	200.00	4.6350E+07	156.55	1.0934E+05	107.63	4.3976E+02
4	300.00	4.3997E+07	165.41	1.0145E+05	117.60	4.1743E+02
5	400.00	4.2473E+07	172.62	9.6506E+04	130.89	4.0297E+02
6	500.00	4.1571E+07	177.71	9.6402E+04	143.26	3.9441E+02
7	600.00	4.1158E+07	181.01	1.0810E+05	153.01	3.9050E+02
8	700.00	3.9495E+07	183.98	1.1031E+05	158.49	3.7472E+02
9	800.00	3.8509E+07	186.03	1.1219E+05	162.98	3.6536E+02
10	900.00	3.8195E+07	187.08	1.2787E+05	167.49	3.6238E+02
11	1000.00	3.5347E+07	188.43	1.2954E+05	171.06	3.4011E+02
12	1100.00	3.4141E+07	188.84	1.2960E+05	173.79	3.2392E+02
13	1200.00	3.3313E+07	188.40	1.4450E+05	175.20	3.1607E+02
14	1300.00	3.0176E+07	188.99	1.3974E+05	176.03	2.8630E+02
15	1400.00	2.8215E+07	189.10	1.3372E+05	176.73	2.6769E+02
16	1500.00	2.7466E+07	188.54	1.4763E+05	177.40	2.6059E+02
17	1600.00	2.3849E+07	189.26	1.4035E+05	178.39	2.2627E+02
18	1700.00	2.1422E+07	189.15	1.3151E+05	179.24	2.0324E+02
19	1800.00	2.0349E+07	188.13	1.4341E+05	179.27	1.9306E+02
20	1900.00	1.6223E+07	189.11	1.3055E+05	179.35	1.5392E+02
21	2000.00	1.3671E+07	189.56	1.1662E+05	179.47	1.2970E+02
22	2100.00	1.2714E+07	188.76	1.2671E+05	179.57	1.2063E+02
23	2200.00	8.4687E+06	191.46	1.1154E+05	180.27	8.0348E+01
24	2300.00	5.8629E+06	192.91	9.4857E+04	181.01	5.5626E+01
25	2400.00	5.0442E+06	190.06	1.0141E+05	180.65	4.7853E+01
26	2500.00	1.2584E+06	210.01	8.0728E+04	180.50	1.1939E+01
27	2600.00	7.7692E+05	326.10	5.8366E+04	180.27	7.3711E+00
28	2700.00	3.0497E+05	302.14	6.1767E+04	179.71	2.8935E+00
29	2800.00	2.5685E+06	355.71	3.8448E+04	180.30	2.4369E+01
30	2900.00	2.5700E+06	358.12	1.3644E+04	181.74	2.4383E+01
31	3000.00	6.8831E+03	45.00	9.3486E+02	43.02	6.5305E-02

******** DYNAMIC RESPONSE OF A COLD-WATER PIPE ********

COLD WATER PIPE RESPONSE DUE TO WAVE

EXCITING FREQUENCY = .0308 RADIANS/SECOND

DAMPING COEFFICIENT = 9.99155 FORCE-SEC/LENGTH2

STATION	DISTANCE	DISPLACEMENT	PHASE	SLOPE	PHASE	SHEAR STRESS
1	0.	0.	0.	1.0603E-06	325.89	1.0274E+02
2	100.00	2.9873E-01	325.71	5.8253E-03	325.61	1.0282E+02
3	200.00	1.1389E+00	325.51	1.0862E-02	325.29	1.0322E+02
4	300.00	2.4512E+00	325.30	1.5298E-02	324.95	1.0387E+02
5	400.00	4.1626E+00	325.08	1.9260E-02	324.62	1.0445E+02
6	500.00	6.2907E+00	324.87	2.2852E-02	324.29	1.0459E+02
7	600.00	8.7443E+00	324.66	2.6192E-02	323.99	1.1381E+02
8	700.00	1.1521E+01	324.47	2.9299E-02	323.71	1.1268E+02
9	800.00	1.4596E+01	324.28	3.2184E-02	323.45	1.1102E+02
10	900.00	1.7953E+01	324.10	3.4946E-02	323.20	1.2184E+02
11	1000.00	2.1580E+01	323.93	3.7565E-02	322.97	1.1910E+02
12	1100.00	2.5459E+01	323.77	4.0004E-02	322.77	1.1560E+02
13	1200.00	2.9577E+01	323.61	4.2362E-02	322.58	1.2695E+02
14	1300.00	3.3926E+01	323.47	4.4586E-02	322.42	1.2170E+02
15	1400.00	3.8487E+01	323.34	4.6623E-02	322.27	1.1563E+02
16	1500.00	4.3246E+01	323.21	4.8578E-02	322.14	1.2678E+02
17	1600.00	4.8195E+01	323.10	5.0382E-02	322.02	1.1906E+02
18	1700.00	5.3313E+01	322.99	5.1966E-02	321.92	1.1037E+02
19	1800.00	5.8583E+01	322.89	5.3444E-02	321.84	1.2047E+02
20	1900.00	6.3994E+01	322.80	5.4742E-02	321.77	1.0971E+02
21	2000.00	6.9522E+01	322.71	5.5789E-02	321.71	7.7975E+01
22	2100.00	7.5146E+01	322.63	5.6714E-02	321.66	1.0635E+02
23	2200.00	8.0856E+01	322.56	5.7446E-02	321.61	9.2715E+01
24	2300.00	8.6625E+01	322.50	5.7917E-02	321.58	7.8036E+01
25	2400.00	9.2435E+01	322.44	5.8278E-02	321.56	8.3880E+01
26	2500.00	9.8274E+01	322.39	5.8470E-02	321.54	6.7016E+01
27	2600.00	1.0412E+02	322.34	5.8476E-02	321.53	4.9129E+01
28	2700.00	1.0996E+02	322.30	5.8380E-02	321.52	5.1929E+01
29	2800.00	1.1579E+02	322.26	5.8241E-02	321.51	3.2081E+01
30	2900.00	1.2160E+02	322.22	5.8007E-02	321.51	1.1183E+01
31	3000.00	1.2740E+02	322.19	5.7882E-02	321.51	9.3438E-02

STATION	DISTANCE	BENDING MOMENT	PHASE	SHEAR FORCE	PHASE	BENDING STRESS
1	0.	1.0603E+08	329.89	1.6921E+05	329.16	1.0060E+03
2	100.00	9.1021E+07	325.28	1.6934E+05	329.07	8.6358E+02
3	200.00	7.9399E+07	324.53	1.6999E+05	328.60	7.5331E+02
4	300.00	7.0667E+07	323.71	1.7106E+05	327.75	6.7047E+02
5	400.00	6.3376E+07	322.91	1.7201E+05	326.78	6.0130E+02
6	500.00	5.8154E+07	322.22	1.7225E+05	325.93	5.5175E+02
7	600.00	5.4915E+07	321.65	1.8743E+05	325.17	5.2102E+02
8	700.00	5.0292E+07	321.04	1.8557E+05	324.72	4.7716E+02
9	800.00	4.7405E+07	320.53	1.8284E+05	324.28	4.4976E+02
10	900.00	4.6246E+07	320.18	2.0065E+05	323.72	4.3877E+02
11	1000.00	4.2428E+07	319.73	1.9614E+05	323.25	4.0254E+02
12	1100.00	4.0227E+07	319.47	1.9037E+05	322.84	3.8156E+02
13	1200.00	3.9722E+07	319.43	2.0906E+05	322.52	3.7687E+02
14	1300.00	3.5701E+08	319.14	2.0042E+05	322.30	3.3872E+02
15	1400.00	3.3412E+07	319.00	1.9042E+05	322.09	3.1700E+02
16	1500.00	3.2936E+07	319.08	2.0880E+05	321.89	3.1249E+02
17	1600.00	2.8294E+07	318.80	1.9607E+05	321.67	2.6844E+02
18	1700.00	2.5528E+07	318.76	1.8176E+05	321.47	2.4220E+02
19	1800.00	2.4755E+07	319.00	1.9840E+05	321.41	2.3487E+02
20	1900.00	1.9442E+07	318.66	1.8068E+05	321.34	1.8446E+02
21	2000.00	1.6274E+07	318.50	1.6135E+05	321.27	1.5440E+02
22	2100.00	1.5357E+07	318.77	1.7514E+05	321.25	1.4571E+02
23	2200.00	9.7605E+06	317.87	1.5269E+05	321.12	9.2605E+01
24	2300.00	6.6020E+06	317.26	1.2852E+05	320.98	6.2638E+01
25	2400.00	6.0217E+06	318.09	1.3814E+05	321.04	5.7132E+01
26	2500.00	9.7165E+05	306.53	1.1037E+05	321.03	9.2187E+00
27	2600.00	1.2736E+06	149.06	8.0910E+04	321.01	1.2084E+01
28	2700.00	4.5710E+05	154.56	8.5521E+04	321.13	4.3368E+00
29	2800.00	3.6982E+06	142.30	5.2833E+04	321.00	3.5087E+01
30	2900.00	3.6089E+06	141.70	1.8417E+04	320.60	3.4240E+01
31	3000.00	1.1347E+03	90.00	1.6211E+02	107.76	1.0766E-02

STATIC FORCE

SECTION	FORCE	FOR GRADIENT	MOMENT	MOMENT GRADIENT
1	4.0765E+02	3.0511E-01	0.	0.
2	4.9919E+02	-4.2797E-01	0.	0.
3	3.7080E+02	-4.7611E-01	0.	0.
4	2.2797E+02	-3.2823E-01	0.	0.
5	1.2950E+02	-1.9135E-01	0.	0.
6	7.2093E+01	-1.0384E-01	0.	0.
7	4.0942E+01	-5.5014E-02	0.	0.
8	2.4438E+01	-2.9285E-02	0.	0.
9	1.5652E+01	-1.5940E-02	0.	0.
10	1.0870E+01	-8.9521E-03	0.	0.

STATIC FORCE

SECTION	FORCE	FOR GRADIENT	MOMENT	MOMENT GRADIENT
1	4.0763E+02	3.0511E-01	0.	0.
2	4.9919E+02	-4.2797E-01	0.	0.
3	3.7080E+02	-4.7611E-01	0.	0.
4	2.2797E+02	-3.2823E-01	0.	0.
5	1.2950E+02	-1.9135E-01	0.	0.
6	7.2093E+01	-1.0384E-01	0.	0.
7	4.0942E+01	-5.5014E-02	0.	0.
8	2.4438E+01	-2.9285E-02	0.	0.
9	1.5652E+01	-1.5940E-02	0.	0.
10	1.0870E+01	-8.9521E-03	0.	0.

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STATIC RESPONSE SOLUTIONS

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	STATION	DEFLECTION	SLOPE	MOMENT	SHEAR FORCE	BENDING STRESS	SHEAR STRES
1	0.	0.	-1.3228E-06	-1.3228E+08	4.3062E+05	-1.2550E+03	2.6148E+02
2	100.00	3.5194E-01	-6.6547E-03	-9.3527E+07	3.8833E+05	-8.8736E+02	2.3580E+02
3	200.00	1.2624E+00	-1.1249E-02	-6.2678E+07	3.4299E+05	-5.9467E+02	2.0827E+02
4	300.00	2.5480E+00	-1.4227E-02	-3.8882E+07	2.9460E+05	-3.6890E+02	1.7833E+02
5	400.00	4.0664E+00	-1.5959E-02	-2.0467E+07	2.4682E+05	-1.9418E+02	1.4987E+02
6	500.00	5.7087E+00	-1.6759E-02	-7.3187E+06	2.0332E+05	-6.9437E+01	1.2346E+02
7	600.00	7.3966E+00	-1.6913E-02	1.4348E+06	1.7443E+05	1.3613E+01	1.0592E+02
8	700.00	9.0758E+00	-1.6599E-02	8.6307E+06	1.3974E+05	8.1885E+01	8.4849E+01
9	800.00	1.0705E+01	-1.5949E-02	1.2845E+07	1.0980E+05	1.2187E+02	6.6670E+01
10	900.00	1.2260E+01	-1.5122E-02	1.4683E+07	9.3860E+04	1.3931E+02	5.6993E+01
11	1000.00	1.3726E+01	-1.4189E-02	1.6509E+07	7.2704E+04	1.5663E+02	4.4147E+01
12	1100.00	1.5095E+01	-1.3194E-02	1.6313E+07	5.4831E+04	1.5951E+02	3.3294E+01
13	1200.00	1.6366E+01	-1.2218E-02	1.5931E+07	4.7706E+04	1.5113E+02	2.8968E+01
14	1300.00	1.7540E+01	-1.1278E-02	1.5640E+07	3.5713E+04	1.4839E+02	2.1686E+01
15	1400.00	1.8623E+01	-1.0378E-02	1.4596E+07	2.5634E+04	1.3848E+02	1.5565E+01
16	1500.00	1.9619E+01	-9.5586E-03	1.2965E+07	2.3309E+04	1.2301E+02	1.4153E+01
17	1600.00	2.0537E+01	-8.8146E-03	1.2057E+07	1.6616E+04	1.1440E+02	1.0091E+01
18	1700.00	2.1384E+01	-8.1364E-03	1.0757E+07	1.0967E+04	1.0206E+02	6.6590E+00
19	1800.00	2.2167E+01	-7.5450E-03	9.1442E+06	1.0963E+04	8.6757E+01	6.6571E+00
20	1900.00	2.2895E+01	-7.0293E-03	8.2076E+06	7.1443E+03	7.7871E+01	4.3381E+00
21	2000.00	2.3575E+01	-6.5762E-03	7.0391E+06	3.8753E+03	6.6785E+01	2.3531E+00
22	2100.00	2.4213E+01	-6.1983E-03	5.6763E+06	4.9438E+03	5.3855E+01	3.0019E+00
23	2200.00	2.4817E+01	-5.8836E-03	4.9110E+06	2.6464E+03	4.6594E+01	1.6070E+00
24	2300.00	2.5391E+01	-5.6191E-03	3.9856E+06	6.4193E+02	3.7814E+01	3.8979E-01
25	2400.00	2.5942E+01	-5.4137E-03	2.9189E+06	2.2382E+03	2.7694E+01	1.3591E+00
26	2500.00	2.6476E+01	-5.2555E-03	2.3945E+06	7.5269E+02	2.2718E+01	4.5704E-01
27	2600.00	2.6995E+01	-5.1321E-03	1.7473E+06	-5.7344E+02	1.6578E+01	-3.4820E-01
28	2700.00	2.7503E+01	-5.0505E-03	9.8852E+05	1.3459E+03	9.3787E+00	8.1723E-01
29	2800.00	2.8006E+01	-4.9984E-03	7.5340E+05	3.0361E+02	7.1481E+00	1.8435E-01
30	2900.00	2.8504E+01	-4.9631E-03	4.2133E+05	-6.4914E+02	3.9974E+00	-3.9417E-01
31	3000.00	2.8999E+01	-4.9501E-03	-3.0518E-05	5.9605E-03	-2.8954E-10	3.6193E-11

END.

Day File for Cost of the Run

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12.40.44$JOBBEAM,CM10000,T100.
12.40.44$AC2500J310001,          )A
12.40.44. 11/08/78.LH3DGDV
12.40.44.GET,DYNAMPY,INPUT=DATIN.
12.40.45.READY -   DYNAMPY
12.40.45.READY -   DATIN
12.40.45.RFL,100000.
12.40.45$FL    4096     0.001        0        0,
12.40.45$FI       0         2
12.40.46.TSRUN(D,DYNAMPY)
12.40.55.DBEAM   --066000
12.40.55$FL   32768     4.023      107       25
12.50.38.RFL,10000.
12.50.38$FL   27648    13.506      489      322,
12.50.38$FI       0         1
12.50.39.REWIND,OUTPUT.
12.50.39.SAVE,OUTPUT=BEAMOUT.
12.50.40.READY -   BEAMOUT
12.50.40.COST.
12.50.40$FL    4096    13.506        0        0,
12.50.40$FI       0         1
12.50.41.          SERV. UNITS-1 =     53
12.50.41.          JOB COST=$      15.90
12.50.42.DFD,BEAMDAY,R.
12.50.42$FL   12288    13.519        6        5
```

This indicates that this run costs $15.90.

B.5.2 Input/Output for Example 2

Input

```
   RESPONSE DUE TO  CURRENT
10,1.
1,0.,0.,0.,518400.,0.
0.,1.9905,2.9347,0.,0.
10,1,1,2,3,0,0,0,0
0.0001,0.005,0.
1,300.,0.,2.88E+08,0.3
0.,0.,0.,30.,0.2,0.
1,300.,0.,2.88E+08,0.3
0.,0.,0.,30.,0.2,0.
1,300.,0.,2.88E+08,0.3
0.,0.,0.,30.,0.2,0.
1,300.,0.,2.88E+08,0.3
0.,0.,0.,30.,0.2,0.
1,300.,0.,2.88E+08,0.3
0.,0.,0.,30.,0.2,0.
1,300.,0.,2.88E+08,0.3
0.,0.,0.,30.,0.2,0.
1,300.,0.,2.88E+08,0.3
0.,0.,0.,30.,0.2,0.
1,300.,0.,2.88E+08,0.3
0.,0.,0.,30.,0.2,0.
1,300.,0.,2.88E+08,0.3
0.,0.,0.,30.,0.2,0.
1,0.,1.0E+14,0.,0.
7,0
0.1,4.,0.9,0.0023,0.0012,0.002
```

Output Listing

```
*****************************************************
 FLEXURAL VIBRATION OF A COLD-WATER PIPE
*****************************************************

  RESPONSE DUE TO  CURRENT


VELOCITY OF INTERNAL WATER FLOW =    0.        LENGTH/SECOND

NO. OF SECTIONS =        10
NO. OF LUMPED STATIONS =         1
NO. OF INSPAN BOUNDARY CONDITIONS =         0
```

CROSS-SECTIONAL PROPERTIES OF THE COLD-WATER PIPE

SECTION	LENGTH	MOD. OF ELAS.	MO. INERTIA	MASS DENSITY
1	3.000000E+02	2.880000E+08	2.078539E+03	2.831682E+03
2	3.000000E+02	2.880000E+08	2.078539E+03	2.831682E+03
3	3.000000E+02	2.880000E+08	2.078539E+03	2.831682E+03
4	3.000000E+02	2.880000E+08	2.078539E+03	2.831682E+03
5	3.000000E+02	2.880000E+08	2.078539E+03	2.831682E+03
6	3.000000E+02	2.880000E+08	2.078539E+03	2.831682E+03
7	3.000000E+02	2.880000E+08	2.078539E+03	2.831682E+03
8	3.000000E+02	2.880000E+08	2.078539E+03	2.831682E+03
9	3.000000E+02	2.880000E+08	2.078539E+03	2.831682E+03
10	3.000000E+02	2.880000E+08	2.078539E+03	2.831682E+03

SECTION	OUTSIDE DIAM	WALL THICKNESS
1	3.000000E+01	2.000000E-01
2	3.000000E+01	2.000000E-01
3	3.000000E+01	2.000000E-01
4	3.000000E+01	2.000000E-01
5	3.000000E+01	2.000000E-01
6	3.000000E+01	2.000000E-01
7	3.000000E+01	2.000000E-01
8	3.000000E+01	2.000000E-01
9	3.000000E+01	2.000000E-01
10	3.000000E+01	2.000000E-01

SECTION	ELAS. FDN	ROT. ELAS. FDN	SHEAR AREA	POISSON RATIO
1	0.	0.	0.	3.000000E-01
2	0.	0.	0.	3.000000E-01
3	0.	0.	0.	3.000000E-01
4	0.	0.	0.	3.000000E-01
5	0.	0.	0.	3.000000E-01
6	0.	0.	0.	3.000000E-01
7	0.	0.	0.	3.000000E-01
8	0.	0.	0.	3.000000E-01
9	0.	0.	0.	3.000000E-01
10	0.	0.	0.	3.000000E-01

SECTION	AXIAL FORCE	RADIUS OF GYRATN	THERMAL MOMENT	TH MOMENT GRAD.
1	-1.719263E+06	0.	0.	0.
2	-1.547336E+06	0.	0.	0.
3	-1.375410E+06	0.	0.	0.
4	-1.203484E+06	0.	0.	0.
5	-1.031558E+06	0.	0.	0.
6	-8.596314E+05	0.	0.	0.
7	-6.877051E+05	0.	0.	0.
8	-5.157788E+05	0.	0.	0.
9	-3.438525E+05	0.	0.	0.
10	-1.719263E+05	0.	0.	0.

CONCENTRATED PARAMETERS

STATION	MASS	LINEAR SPRING	ROT SPRING	RADIUS GYRATN
1	0.	0.	1.000000E+14	0.

LEFT END BOUNDARY CONDITION

.....BOUNDARY SIMPLY SUPPORTED

RIGHT END BOUNDARY CONDITION

.....BOUNDARY FREE

CURRENT PROFILE

VO	VS	A1	A2	K1	K2
1.0000E-01	4.0000E+00	9.0000E-01	2.3000E-03	1.2000E-03	2.0000E-03

STATIC FORCE

SECTION	FORCE	FOR GRADIENT	MOMENT	MOMENT GRADIENT
1	3.8218E+02	2.8604E-01	0.	0.
2	4.6799E+02	-4.0122E-01	0.	0.
3	3.4762E+02	-4.4636E-01	0.	0.
4	2.1372E+02	-3.0771E-01	0.	0.
5	1.2140E+02	-1.7939E-01	0.	0.
6	6.7588E+01	-9.7347E-02	0.	0.
7	3.8383E+01	-5.1576E-02	0.	0.
8	2.2911E+01	-2.7455E-02	0.	0.
9	1.4674E+01	-1.4944E-02	0.	0.
10	1.0191E+01	-8.3926E-03	0.	0.

****

STATIC RESPONSE SOLUTIONS

****

	STATION	DEFLECTION	SLOPE	MOMENT	SHEAR FORCE	BENDING STRESS	SHEAR STRESS
1	0.	0.	-1.3324E-06	-1.3324E+08	4.0466E+05	-6.6774E+03	1.2168E+03
2	100.00	1.0056E+00	-1.9086E-02	-9.6462E+07	3.6501E+05	-4.8342E+03	1.0976E+03
3	200.00	3.6321E+00	-3.2613E-02	-6.6578E+07	3.2250E+05	-3.3366E+03	9.6974E+02
4	300.00	7.3797E+00	-4.1682E-02	-4.3015E+07	2.7713E+05	-2.1557E+03	8.3332E+02
5	400.00	1.1852E+01	-4.7247E-02	-2.4495E+07	2.3234E+05	-1.2276E+03	6.9863E+02
6	500.00	1.6740E+01	-5.0140E-02	-1.0897E+07	1.9156E+05	-5.4612E+02	5.7600E+02
7	600.00	2.1816E+01	-5.1119E-02	-1.4676E+06	1.6352E+05	-7.3548E+01	4.9170E+02
8	700.00	2.6917E+01	-5.0679E-02	6.2054E+06	1.3099E+05	3.1099E+02	3.9368E+02
9	800.00	3.1918E+01	-4.9207E-02	1.0986E+07	1.0292E+05	5.5055E+02	3.0948E+02
10	900.00	3.6733E+01	-4.7139E-02	1.3430E+07	8.7371E+04	6.7306E+02	2.6272E+02
11	1000.00	4.1333E+01	-4.4689E-02	1.5621E+07	6.7537E+04	7.8283E+02	2.0308E+02
12	1100.00	4.5668E+01	-4.2004E-02	1.6293E+07	5.0781E+04	8.1654E+02	1.5270E+02
13	1200.00	4.9733E+01	-3.9312E-02	1.5769E+07	4.3816E+04	7.9029E+02	1.3175E+02
14	1300.00	5.3533E+01	-3.6675E-02	1.5655E+07	3.2573E+04	7.8455E+02	9.7943E+01
15	1400.00	5.7071E+01	-3.4124E-02	1.4774E+07	2.3123E+04	7.4042E+02	6.9529E+01
16	1500.00	6.0364E+01	-3.1772E-02	1.3292E+07	2.0894E+04	6.6614E+02	6.2825E+01
17	1600.00	6.3432E+01	-2.9619E-02	1.2422E+07	1.4622E+04	6.2254E+02	4.3966E+01
18	1700.00	6.6294E+01	-2.7645E-02	1.1152E+07	9.3230E+03	5.5887E+02	2.8034E+01
19	1800.00	6.8969E+01	-2.5911E-02	9.5595E+06	9.4230E+03	4.7908E+02	2.8334E+01
20	1900.00	7.1483E+01	-2.4391E-02	8.5898E+06	5.8425E+03	4.3048E+02	1.7568E+01
21	2000.00	7.3854E+01	-2.3054E-02	7.3863E+06	2.7778E+03	3.7017E+02	8.3526E+00
22	2100.00	7.6101E+01	-2.1934E-02	5.9867E+06	3.9748E+03	3.0003E+02	1.1952E+01
23	2200.00	7.8247E+01	-2.1000E-02	5.1676E+06	1.8210E+03	2.5897E+02	5.4757E+00
24	2300.00	8.0306E+01	-2.0217E-02	4.1912E+06	-5.8213E+01	2.1004E+02	-1.7504E-01
25	2400.00	8.2296E+01	-1.9608E-02	3.0766E+06	1.6857E+03	1.5419E+02	5.0683E+00
26	2500.00	8.4232E+01	-1.9140E-02	2.5084E+06	2.9303E+02	1.2571E+02	8.8110E-01
27	2600.00	8.6127E+01	-1.8776E-02	1.8228E+06	-9.5022E+02	9.1348E+01	-2.8573E+00
28	2700.00	8.7992E+01	-1.8536E-02	1.0307E+06	1.1216E+03	5.1652E+01	3.3727E+00
29	2800.00	8.9837E+01	-1.8384E-02	7.7596E+05	1.4451E+02	3.8867E+01	4.3452E-01
30	2900.00	9.1670E+01	-1.8282E-02	4.2993E+05	-7.4869E+02	2.1546E+01	-2.2513E+00
31	3000.00	9.3496E+01	-1.8245E-02	-7.6294E-06	3.3528E-08	-3.8235E-10	1.0081E-10

Day File

```
11.41.14$JOBBEAM,CM10000,T100.
11.41.14$AC                    )A
11.41.14. 11/03/78.LH3IFNZ
11.41.14.GET,CWPFLX ,INPUT=DATIN1.
11.41.15.READY -   CWPFLX
11.41.16.READY -   DATIN1
11.41.16.RFL,100000.
11.41.16$FL    4096     0.001        0        0,
11.41.16$FI       0         2
11.41.16.TSRUN(0,       )
11.41.31.DBEAM   --066000
11.41.31$FL   32768     4.187      107       25
11.41.32.RFL,10000.
11.41.32$FL   27648     4.402       18       12
11.41.32.REWIND,OUTPUT.
11.41.32.SAVE,OUTPUT=BEAMOUT.
11.41.32.READY -   BEAMOUT
11.41.33.COST.
11.41.33$FL    4096     4.403        0        0,
11.41.33$FI       0         1
11.41.33.          SERV. UNITS-1 =     17
11.41.33.          JOB COST=$       5.10
11.41.34.DFD,BEAMDAY,R:
11.41.34$FL   12288     4.417        6        5
```

B.5.3 Input/Output for Example 3

Input

```
   RESPONSE DUE TO  CURRENT
10,1
1,0.,0.,0.,518400.,0.
0.,1.9905,2.9347,0.,0.
10,1,1,2,3,0,0,0,0
0.0001,0.005,0.
1,300.,0.,2.88E+08,0.3
0.,0.,0.,30.,0.2,0.
1,300.,0.,2.88E+08,0.3
0.,0.,0.,30.,0.2,0.
1,300.,0.,2.88E+08,0.3
0.,0.,0.,30.,0.2,0.
1,300.,0.,2.88E+08,0.3
0.,0.,0.,30.,0.2,0.
1,300.,0.,2.88E+08,0.3
0.,0.,0.,30.,0.2,0.
1,300.,0.,2.88E+08,0.3
0.,0.,0.,30.,0.2,0.
1,300.,0.,2.88E+08,0.3
0.,0.,0.,30.,0.2,0.
1,300.,0.,2.88E+08,0.3
0.,0.,0.,30.,0.2,0.
1,300.,0.,2.88E+08,0.3
0.,0.,0.,30.,0.2,0.
1,0.,1.0E+14,0.,0.
7,0
0.1,4.,0.9,0.,0.,0.
```

Output Listing

```
*****************************************************
 FLEXURAL VIBRATION OF A COLD-WATER PIPE
*****************************************************

  RESPONSE DUE TO  CURRENT


 VELOCITY OF INTERNAL WATER FLOW =    0.        LENGTH/SECOND

 NO. OF SECTIONS =        10
 NO. OF LUMPED STATIONS =        1
 NO. OF INSPAN BOUNDARY CONDITIONS =        0
```

CROSS-SECTIONAL PROPERTIES OF THE COLD-WATER PIPE

SECTION	LENGTH	MOD. OF ELAS.	MO. INERTIA	MASS DENSITY
1	3.000000E+02	2.880000E+08	2.078539E+03	2.831682E+03
2	3.000000E+02	2.880000E+08	2.078539E+03	2.831682E+03
3	3.000000E+02	2.880000E+08	2.078539E+03	2.831682E+03
4	3.000000E+02	2.880000E+08	2.078539E+03	2.831682E+03
5	3.000000E+02	2.880000E+08	2.078539E+03	2.831682E+03
6	3.000000E+02	2.880000E+08	2.078539E+03	2.831682E+03
7	3.000000E+02	2.880000E+08	2.078539E+03	2.831682E+03
8	3.000000E+02	2.880000E+08	2.078539E+03	2.831682E+03
9	3.000000E+02	2.880000E+08	2.078539E+03	2.831682E+03
10	3.000000E+02	2.880000E+08	2.078539E+03	2.831682E+03

SECTION	OUTSIDE DIAM	WALL THICKNESS
1	3.000000E+01	2.000000E-01
2	3.000000E+01	2.000000E-01
3	3.000000E+01	2.000000E-01
4	3.000000E+01	2.000000E-01
5	3.000000E+01	2.000000E-01
6	3.000000E+01	2.000000E-01
7	3.000000E+01	2.000000E-01
8	3.000000E+01	2.000000E-01
9	3.000000E+01	2.000000E-01
10	3.000000E+01	2.000000E-01

SECTION	ELAS. FDN	ROT. ELAS. FDN	SHEAR AREA	POISSON RATIO
1	0.	0.	0.	3.000000E-01
2	0.	0.	0.	3.000000E-01
3	0.	0.	0.	3.000000E-01
4	0.	0.	0.	3.000000E-01
5	0.	0.	0.	3.000000E-01
6	0.	0.	0.	3.000000E-01
7	0.	0.	0.	3.000000E-01
8	0.	0.	0.	3.000000E-01
9	0.	0.	0.	3.000000E-01
10	0.	0.	0.	3.000000E-01

SECTION	AXIAL FORCE	RADIUS OF GYRATN	THERMAL MOMENT	TH MOMENT GRAD.
1	-1.719263E+06	0.	0.	0.
2	-1.547336E+06	0.	0.	0.
3	-1.375410E+06	0.	0.	0.
4	-1.203484E+06	0.	0.	0.
5	-1.031558E+06	0.	0.	0.
6	-8.596314E+05	0.	0.	0.
7	-6.877051E+05	0.	0.	0.
8	-5.157788E+05	0.	0.	0.
9	-3.438525E+05	0.	0.	0.
10	-1.719263E+05	0.	0.	0.

CONCENTRATED PARAMETERS

STATION	MASS	LINEAR SPRING	ROT SPRING	RADIUS GYRATN
1	0.	0.	1.000000E+14	0.

LEFT END BOUNDARY CONDITION

.....BOUNDARY SIMPLY SUPPORTED

RIGHT END BOUNDARY CONDITION

.....BOUNDARY FREE

CURRENT PROFILE

VO	VS	A1	A2	K1	K2
1.0000E-01	4.0000E+00	9.0000E-01	0.	0.	0.

STATIC FORCE

SECTION	FORCE	FOR GRADIENT	MOMENT	MOMENT GRADIENT
1	3.8218E+02	0.	0.	0.
2	3.8218E+02	0.	0.	0.
3	3.8218E+02	0.	0.	0.
4	3.8218E+02	0.	0.	0.
5	3.8218E+02	0.	0.	0.
6	3.8218E+02	0.	0.	0.
7	3.8218E+02	0.	0.	0.
8	3.8218E+02	0.	0.	0.
9	3.8218E+02	0.	0.	0.
10	3.8218E+02	0.	0.	0.

****

STATIC RESPONSE SOLUTIONS

****

	STATION	DEFLECTION	SLOPE	MOMENT	SHEAR FORCE	BENDING STRESS	SHEAR STRESS
1	0.	0.	-3.6853E-06	-3.6853E+08	7.4367E+05	-1.8469E+04	2.2362E+03
2	100.00	2.8812E+00	-5.5742E-02	-3.0102E+08	7.0546E+05	-1.5086E+04	2.1212E+03
3	200.00	1.0803E+01	-1.0127E-01	-2.4602E+08	6.6724E+05	-1.2329E+04	2.0063E+03
4	300.00	2.2861E+01	-1.3854E-01	-2.0193E+08	6.2902E+05	-1.0120E+04	1.8914E+03
5	400.00	3.8292E+01	-1.6906E-01	-1.6481E+08	5.9080E+05	-8.2597E+03	1.7765E+03
6	500.00	5.6489E+01	-1.9406E-01	-1.3580E+08	5.5258E+05	-6.8057E+03	1.6616E+03
7	600.00	7.6963E+01	-2.1484E-01	-1.1413E+08	5.5106E+05	-5.7199E+03	1.6570E+03
8	700.00	9.9334E+01	-2.3194E-01	-9.1707E+07	5.1284E+05	-4.5959E+03	1.5421E+03
9	800.00	1.2324E+02	-2.4581E-01	-7.5221E+07	4.7462E+05	-3.7697E+03	1.4271E+03
10	900.00	1.4842E+02	-2.5739E-01	-6.4296E+07	4.8036E+05	-3.2222E+03	1.4444E+03
11	1000.00	1.7465E+02	-2.6684E-01	-4.9740E+07	4.4214E+05	-2.4927E+03	1.3295E+03
12	1100.00	2.0172E+02	-2.7427E-01	-4.0014E+07	4.0393E+05	-2.0053E+03	1.2146E+03
13	1200.00	2.2946E+02	-2.8047E-01	-3.4922E+07	4.1361E+05	-1.7501E+03	1.2437E+03
14	1300.00	2.5777E+02	-2.8539E-01	-2.4672E+07	3.7539E+05	-1.2364E+03	1.1288E+03
15	1400.00	2.8650E+02	-2.8893E-01	-1.8675E+07	3.3717E+05	-9.3593E+02	1.0138E+03
16	1500.00	3.1554E+02	-2.9186E-01	-1.6828E+07	3.4880E+05	-8.4337E+02	1.0488E+03
17	1600.00	3.4484E+02	-2.9396E-01	-9.0484E+06	3.1058E+05	-4.5346E+02	9.3389E+02
18	1700.00	3.7430E+02	-2.9510E-01	-5.2247E+06	2.7236E+05	-2.6184E+02	8.1897E+02
19	1800.00	4.0385E+02	-2.9592E-01	-5.3024E+06	2.8468E+05	-2.6573E+02	8.5601E+02
20	1900.00	4.3347E+02	-2.9624E-01	8.8725E+05	2.4646E+05	4.4465E+01	7.4110E+02
21	2000.00	4.6307E+02	-2.9584E-01	3.2617E+06	2.0825E+05	1.6346E+02	6.2618E+02
22	2100.00	4.9263E+02	-2.9536E-01	1.8482E+06	2.2047E+05	9.2625E+01	6.6294E+02
23	2200.00	5.2214E+02	-2.9459E-01	6.7667E+06	1.8225E+05	3.3912E+02	5.4802E+02
24	2300.00	5.5153E+02	-2.9331E-01	7.9190E+06	1.4404E+05	3.9686E+02	4.3310E+02
25	2400.00	5.8080E+02	-2.9215E-01	5.3151E+06	1.5571E+05	2.6637E+02	4.6821E+02
26	2500.00	6.0996E+02	-2.9091E-01	8.9493E+06	1.1749E+05	4.4850E+02	3.5329E+02
27	2600.00	6.3897E+02	-2.8937E-01	8.8113E+06	7.9276E+04	4.4158E+02	2.3838E+02
28	2700.00	6.6765E+02	-2.8817E-01	4.9004E+06	9.0273E+04	2.4559E+02	2.7144E+02
29	2800.00	6.9661E+02	-2.8712E-01	7.0709E+06	5.2055E+04	3.5436E+02	1.5653E+02
30	2900.00	7.2527E+02	-2.8602E-01	5.4390E+06	1.3837E+04	2.7258E+02	4.1608E+01
31	3000.00	7.5384E+02	-2.8552E-01	7.6294E-06	0.	3.8235E-10	0.

END.

APPENDIX C

USER'S MANUAL FOR THE COMPUTER PROGRAM CWPEXT FOR THE STRUCTURAL ANALYSIS OF OTEC COLD WATER PIPES

EXTENSION AND TORSION PROGRAM

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C.1 General Background

This program is for the calculation of the responses of the CWP to axial loads or to vertical motion of the OTEC platform. The CWP is treated as a general bar with up to 50 sections having different properties. All the sections can be connected by joints with specified axial stiffness.

Since the differential equations for the torsional responses of CWP are similar to those for extension, this program can also be used for calculation of CWP torsional responses. Sections can be connected by joints with specified torsional stiffness.

C.2 Program Capabilities

C.2.1 Extension - For extension or longitudinal motions of the CWP, the program has the capability of treating the following cases.

- Static analysis of arbitrary longitudinal loads.
- Dynamic analysis of arbitrary longitudinal loads.
- Dynamic analysis of CWP longitudinal motions due to vertical motion of OTEC platform.

C.2.2 Torsion - For torsion at or yawing motions of the CWP, the program has the capability of treating the following cases:

Static analysis of the arbitrary static torsional loads.
Dynamic analysis of arbitrary torsion loads.
Dynamic analysis of CWP torsional motion due to platform yawing or CWP rotation.

C.3 Description of Inputs to "CWPEXT" Program

	Format	Entry	Variable in Program
Card or Line 1			
Title card	A	Title or any other information e.g. problem number or brief description. (Column 1-72)	TITLE
Card or Line 2			
Control card	2I5	Type of member 1 = torsion 2 = extension	NCØN
		Type of analysis 1 = static 2 = unit heave 3 = dynamic	NFTYPE
Card or Line 3			
Control card	I5	1, a control number.	IC
	I5	Type of response 1 = static 2 = steady state 3 = free vibration	ID
	I5	Number of sections. The number of sections is one less than the number of stations. A station is a location of an occurrence, e.g., change in cross section, concentrated parameter, or abrupt change in	

	Format	Entry	Variable in Program
Card 3 (cont'd)		distributed load. Each end of the CWP is considered as a station. A section occurs between two successive stations. (max. 50).	
	I5	Number of stations with concentrated parameters (e.g. lumped masses, concentrated forces or torques). (max. 50).	NCP
	I5	Number of natural frequencies desired for free vibration. 0 if ID $\neq$ 3 (static or steady state).	NF
	I5	Boundary conditions (top-bottom) 1 = fixed-fixed 2 = fixed-free 3 = free-free 4 = free-fixed Ends with applied loads are treated as free boundaries since the loads are entered as applied loadings and not as boundary conditions. Similarly, ends with concentrated masses or spring stiffnesses are also treated as being free.	NB

	Format	Entry	Variable in Program
Card 3 (cont'd)	I5	1-for mode shapes printout for free vibrations. 0-for static or steady state or if no mode shape printout for free vibrations.	NM
	I5	0	ND
	I5	1-to print trace of frequency search. A characteristic determinant is searched for its root. 0-for static, steady state or no trace of frequency search for free vibration.	NP
	I5	Number of points for printing out results between stations.	NA
Card or Line 4 Control card, not needed for static problem (ID=1).	I10	5, a control number.	IC
	F10.2	Estimate in cps of first natural frequency desired for free vibration (ID=3). Choose a value less than the actual frequency. Value of frequency of applied loading for steady state (ID=2).	SP

	Format	Entry	in Program
Card 4 (cont'd)	F10.2	Frequency increment for natural frequency search (ID=3). 0. for steady state (ID=2).	DETE

Card or Line 5a

Section card, one card needed for each section.
The deck should be arranged with cards 5a, b for the first section followed by 5a, b for the second section, and so on. Move from top to bottom along the CWP with the first section beginning at the top.

I5	2, a control number	IC
I5	1 = elastic section 2 = rigid or lumped (spring or massless bar represented by a spring constant) section. 3 = section with transfer matrix supplied by user.	NR(I)
F10.2	Polar moment of inertia (length) for torsion of elastic section (NR=1). Cross-sectional area (length) for extension of elastic section (NR=1). 0. otherwise, including lumped section (NR=2).	A(I)

	Format	Entry	Variable in Program
Card 5a (cont'd)	F10.2	Modulus of elastic foundation (force-length/length for torsion, force/length^2 for extension). 0. if no foundation or for lumped section.	XK(I)
	F10.2	Length of section. In the case of a lumped section this "artificial" length serves as a coordinate that will identify the response at the right end of the section.	XL(I)
	F10.2	Set to 0.	DT(I)
	F10.2	Modulus of elasticity (force/length^2). G for torsion, E for extension, 0. for lumped section.	EY(I)
	F10.2	0.	PI(I)
Card 5b Section card, one card needed for each section.	I10	2, a control number	IC
	F10.2	Uniformly distributed applied torque (force-length/length) for torsion problem (NCON=1). Using the right hand rule, a torque is positive if it points toward the bottom of the CWP.	F(I)

	Format	Entry	Variable in Program
Card 5b (cont'd)		Uniformly distributed axial force (force/length) for extension problem (NCON=2), positive toward the bottom.	
	F10.2	Gradient of linearly verying applied distributed torque (force-length/length^2) for torsion. Positive if the magnitude of applied positive torque increases from top to bottom along the section.	F1(I)
		Gradient of linearly varying applied distributed force (force/length^2) for extension. Positive if the magnitude of applied positive axial force increases from top to bottom along the section.	
	F10.2	For free vibration (ID=3) or steady state (ID=2): ρr_p^2 (mass-length^2/length) for torsion. ρ= mass per unit length, r_p = polar radius of gyration. For circular cross section $\rho r_p^2 = \rho^* J$, where J is the polar moment of inertia and ρ^* is the mass density (mass/length^3).	DM(I)

	Format	Entry	Variable in Program
Card 5b (cont'd)		(mass/length) for extension. 0. for static problem, lumped section, or otherwise.	
	F10.2	Coefficient of thermal expansion (length/length-degree), required if there is thermal loading for extension problem. 0. for torsion or no thermal loading.	ALFA(I)

Card or Line 5c

Sections cards, a set of cards defining a user-supplied transfer matrix is needed for each appropriate section. No cards are needed if transfer matrices are not supplied by user. (max. 50).

The following card is employed for each row of the transfer matrix. Begin with row 1 and end with row 2.

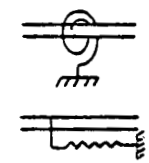
F10.2	Angle of twist (axial displacement) element of transfer matrix for torsion (extension).	S(I,J,1)
F10.2	Twisting moment (axial force) element of transfer matrix for torsion (extension).	S(I,J,2)
F10.2	Loading element of transfer matrix.	S(I,J,3) I=Ith section J=Jth row of the input transfer matrix.

Format	Entry	in Program

Card or Line 6

Concentrated parameter card. One card needed for each concentrated parameter station. No number 6 cards are required if there is no concentrated parameters. The deck should be arranged with card 6 for the first concentrated parameter station followed by 6 for the second such parameter station and so on. (max. 50).

I5	3, a control number.	IC
I5	Station number of lumped parameter. Each station should be given a number from top to bottom along the pipe. The top end is station number 1. There can be more than one lumped parameter at a station.	LNCP(I)
F10.2.	Torsional spring stiffness (force-length/radian). Stiffness of extension spring (force/length). These are lumped section entries that refer to shaft sections and springs that occur just above this station.	CK(I)
F10.2	Branch spring constant (force-length for torsion, force/length for extension).	BK(I)
F10.2	Value of polar mass moment of inertia for torsion (mass-	CM(I)



	Format	Entry	Variable in Program
Card 6 (cont'd)		length^2). Value of concentrated mass (mass) for extension.	
	F10.2	Value of concentrated torque (force-length) for torsion. Positive if it points toward the bottom using the right hand rule. Value of concentrated force (force) for extension. Positive toward the bottom.	CN(I)
Card or Line 7a Control card, required only for torsion problems (NCON=1)	I10	Use NG = 0	NG
	F10.2	Radius of CWP	RAD

C.4 Example of Input Preparation

The step-by-step procedure for input preparation is given in Section C.3. For illustration purposes the cold water pipe for Example 1 in Appendix B is used as an example.

C.4.1 Example 4 - Find the response of the CWP in Example 1 of Appendix B due to unit yawing of the OTEC platform.

From the data in Example 1 we have

J, The polar moment of inertia = 23397.8 ft^4.
I_p, Mass polar moment of inertia = 61770 lb-sec^2.
G, Shear modulus of elasticity = 5.54×10^7 psf.

Input Data (in unformatted form)

```
 COLD WATER PIPE RESPONSE DUE UNIT YAWING OF THE PLATFORM
1,2
1,2,10,0,0,2,0,0,0,1
5,0.1591549,0.
2,1,23397.8,0.,300.,0.,.554E+08,0.3
2,0.,0.,61770.0,0.
2,1,23397.8,0.,300.,0.,.554E+08,0.3
2,0.,0.,61770.0,0.
2,1,23397.8,0.,300.,0.,.554E+08,0.3
2,0.,0.,61770.0,0.
2,1,23397.8,0.,300.,0.,.554E+08,0.3
2,0.,0.,61770.0,0.
2,1,23397.8,0.,300.,0.,.554E+08,0.3
2,0.,0.,61770.0,0.
2,1,23397.8,0.,300.,0.,.554E+08,0.3
2,0.,0.,61770.0,0.
2,1,23397.8,0.,300.,0.,.554E+08,0.3
2,0.,0.,61770.0,0.
2,1,23397.8,0.,300.,0.,.554E+08,0.3
2,0.,0.,61770.0,0.
2,1,23397.8,0.,300.,0.,.554E+08,0.3
2,0.,0.,61770.0,0.
2,1,23397.8,0.,300.,0.,.554E+08,0.3
2,0.,0.,61770.0,0.
0,16.
```

COLD WATER PIPE RESPONSE DUE UNIT YAWINGOF THE PLATFORM

FORCED VIBRATION

SECTION PROPERTIES AND FORCES

LENGTH	ELASTIC FDN	POSSON'S RATIO	TEMPERATURE	COEF.OF EXPSN
3.0000E+02	0.	3.0000E-01	0.	0.
3.0000E+02	0.	3.0000E-01	0.	0.
3.0000E+02	0.	3.0000E-01	0.	0.
3.0000E+02	0.	3.0000E-01	0.	0.
3.0000E+02	0.	3.0000E-01	0.	0.
3.0000E+02	0.	3.0000E-01	0.	0.
3.0000E+02	0.	3.0000E-01	0.	0.
3.0000E+02	0.	3.0000E-01	0.	0.
3.0000E+02	0.	3.0000E-01	0.	0.
3.0000E+02	0.	3.0000E-01	0.	0.

POLAR MOMENT OF INERTIA	SHEAR MODULUS OF ELASTICITY	UNIFORM TORQUE	TORQUE GRAD.	MASS MOMENT OF INERTIA
2.3398E+04	5.5400E+07	0.	0.	6.1770E+04
2.3398E+04	5.5400E+07	0.	0.	6.1770E+04
2.3398E+04	5.5400E+07	0.	0.	6.1770E+04
2.3398E+04	5.5400E+07	0.	0.	6.1770E+04
2.3398E+04	5.5400E+07	0.	0.	6.1770E+04
2.3398E+04	5.5400E+07	0.	0.	6.1770E+04
2.3398E+04	5.5400E+07	0.	0.	6.1770E+04
2.3398E+04	5.5400E+07	0.	0.	6.1770E+04
2.3398E+04	5.5400E+07	0.	0.	6.1770E+04
2.3398E+04	5.5400E+07	0.	0.	6.1770E+04

BOUNDARY FIXED-FREE

****

COLD WATER PIPE TORSION PROBLEM

EXCITATION FRQUENCY = 1.0000E+00RAD./SEC

STATION	LOCATION	ANGLE	MOMENT	SHEAR STRESS
1	0.	-1.00000E+00	2.17301E+08	1.03192E+03
2	1.50000E+02	-9.75395E-01	2.07921E+08	9.87370E+02
3	3.00000E+02	-9.51888E-01	1.98317E+08	9.41767E+02
4	4.50000E+02	-9.29504E-01	1.88502E+08	8.95153E+02
5	6.00000E+02	-9.08269E-01	1.78484E+08	8.47580E+02
6	7.50000E+02	-8.88204E-01	1.68274E+08	7.99099E+02
7	9.00000E+02	-8.69331E-01	1.57885E+08	7.49760E+02
8	1.05000E+03	-8.51670E-01	1.47326E+08	6.99618E+02
9	1.20000E+03	-8.35240E-01	1.36609E+08	6.48726E+02
10	1.35000E+03	-8.20059E-01	1.25745E+08	5.97138E+02
11	1.50000E+03	-8.06143E-01	1.14747E+08	5.44910E+02
12	1.65000E+03	-7.93506E-01	1.03626E+08	4.92098E+02
13	1.80000E+03	-7.82164E-01	9.23938E+07	4.38758E+02
14	1.95000E+03	-7.72127E-01	8.10625E+07	3.84948E+02
15	2.10000E+03	-7.63406E-01	6.96442E+07	3.30725E+02
16	2.25000E+03	-7.56011E-01	5.81513E+07	2.76148E+02
17	2.40000E+03	-7.49950E-01	4.65960E+07	2.21274E+02
18	2.55000E+03	-7.45229E-01	3.49908E+07	1.66164E+02
19	2.70000E+03	-7.41853E-01	2.33481E+07	1.10875E+02
20	2.85000E+03	-7.39826E-01	1.16803E+07	5.54672E+01
21	3.00000E+03	-7.39150E-01	-9.53674E-07	-4.52879E-12

STOP.

RDY

Explanation of Input Data

The user should have no problem in understanding the above input which follows Section B.3.

C.4.2 Example 5 - Find the response of the CWP of example 1, Appendix B due to unit heave of the OTEC platform.

Because of the similarity between the torsion and the extension problems, the same program is used for the analysis of both problems. From the data in Example 1 we have

A, The sectional area = 98.0 ft^2.

m_p, The mass per unit length = 258.44 $lb\text{-}sec^2/ft^2$

E, The modulus of elasticity = 1.44×10^8 psf.

Input Data.

```
  COLD WATER PIPE RESPONSE DUE UNIT HEAVE OF THE PLATFORM
2,2
1,2,10,0,0,2,0,0,0,1
5,0.1591549,0.
2,1,98.,0.,300.,0.,1.44E+08,0.3
2,0.,0.,258.44,0.
2,1,98.,0.,300.,0.,1.44E+08,0.3
2,0.,0.,258.44,0.
2,1,98.,0.,300.,0.,1.44E+08,0.3
2,0.,0.,258.44,0.
2,1,98.,0.,300.,0.,1.44E+08,0.3
2,0.,0.,258.44,0.
2,1,98.,0.,300.,0.,1.44E+08,0.3
2,0.,0.,258.44,0.
2,1,98.,0.,300.,0.,1.44E+08,0.3
2,0.,0.,258.44,0.
2,1,98.,0.,300.,0.,1.44E+08,0.3
2,0.,0.,258.44,0.
2,1,98.,0.,300.,0.,1.44E+08,0.3
2,0.,0.,258.44,0.
2,1,98.,0.,300.,0.,1.44E+08,0.3
2,0.,0.,258.44,0.
```

****

COLD WATER PIPE RESPONSE DUE UNIT HEAVE OF THE PLATFORM

FORCED VIBRATION

SECTION PROPERTIES AND FORCES

LENGTH	ELASTIC FDN	POSSON'S RATIO	TEMPERATURE	COEF. OF EXPSN
3.0000E+02	0.	3.0000E-01	0.	0.
3.0000E+02	0.	3.0000E-01	0.	0.
3.0000E+02	0.	3.0000E-01	0.	0.
3.0000E+02	0.	3.0000E-01	0.	0.
3.0000E+02	0.	3.0000E-01	0.	0.
3.0000E+02	0.	3.0000E-01	0.	0.
3.0000E+02	0.	3.0000E-01	0.	0.
3.0000E+02	0.	3.0000E-01	0.	0.
3.0000E+02	0.	3.0000E-01	0.	0.
3.0000E+02	0.	3.0000E-01	0.	0.

CROSS-SECTIONAL AREA	MODULAS OF ELASTICITY	UNIFORM FORCE	FORCE GRADIENT	MASS
9.8000E+01	1.4400E+08	0.	0.	2.5844E+02
9.8000E+01	1.4400E+08	0.	0.	2.5844E+02
9.8000E+01	1.4400E+08	0.	0.	2.5844E+02
9.8000E+01	1.4400E+08	0.	0.	2.5844E+02
9.8000E+01	1.4400E+08	0.	0.	2.5844E+02
9.8000E+01	1.4400E+08	0.	0.	2.5844E+02
9.8000E+01	1.4400E+08	0.	0.	2.5844E+02
9.8000E+01	1.4400E+08	0.	0.	2.5844E+02
9.8000E+01	1.4400E+08	0.	0.	2.5844E+02
9.8000E+01	1.4400E+08	0.	0.	2.5844E+02

BOUNDARY FIXED-FREE

****

COLD WATER PIPE EXTENSION PROBLEM

EXCITATION FREQUENCY = 1.0000E+00RAD./SEC

	LOCATION	EXTENSION	AXIAL FORCE	STRESS
1	0.	-1.00000E+00	8.20924E+05	5.81720E+01
2	1.50000E+02	-9.91481E-01	7.81991E+05	5.54132E+01
3	3.00000E+02	-9.83377E-01	7.42737E+05	5.26316E+01
4	4.50000E+02	-9.75692E-01	7.03176E+05	4.98282E+01
5	6.00000E+02	-9.68430E-01	6.63326E+05	4.70044E+01
6	7.50000E+02	-9.61592E-01	6.23202E+05	4.41611E+01
7	9.00000E+02	-9.55182E-01	5.82822E+05	4.12997E+01
8	1.05000E+03	-9.49203E-01	5.42201E+05	3.84213E+01
9	1.20000E+03	-9.43657E-01	5.01357E+05	3.55270E+01
10	1.35000E+03	-9.38546E-01	4.60306E+05	3.26181E+01
11	1.50000E+03	-9.33872E-01	4.19066E+05	2.96957E+01
12	1.65000E+03	-9.29638E-01	3.77653E+05	2.67611E+01
13	1.80000E+03	-9.25844E-01	3.36085E+05	2.38155E+01
14	1.95000E+03	-9.22493E-01	2.94378E+05	2.08601E+01
15	2.10000E+03	-9.19587E-01	2.52549E+05	1.78961E+01
16	2.25000E+03	-9.17125E-01	2.10617E+05	1.49247E+01
17	2.40000E+03	-9.15109E-01	1.68598E+05	1.19471E+01
18	2.55000E+03	-9.13541E-01	1.26509E+05	8.96465E+00
19	2.70000E+03	-9.12420E-01	8.43684E+04	5.97849E+00
20	2.85000E+03	-9.11748E-01	4.21929E+04	2.98986E+00
21	3.00000E+03	-9.11523E-01	-3.72529E-09	-2.63980E-13

STOP.

Day File

```
07.56.46$JOBSEAM,T100,CM10000.
07.56.46$AC XXXXXXX                    )A
07.56.46. 11/15/78.LH3TANZ
07.56.46.GET,CWPEXT,INPUT=DAT.
07.56.46.READY -   CWPEXT
07.56.47.READY -   DAT
07.56.47.RFL,100000.
07.56.47$FL    4096     0.002        0        0,
07.56.47$FI       0         2
07.56.47.TSRUN(0,
07.56.52.CWPIPE  --017100
07.56.52$FL   32768     1.184       34        8-
07.56.53.RFL,10000.
07.56.53$FL    7744     1.255       10        8
07.56.53.REWIND,OUTPUT.
07.56.53.SAVE,OUTPUT=BEAMOUT.
07.56.53.READY -   BEAMOUT
07.56.53.COST.
07.56.53$FL    4096     1.255        0        0,
07.56.53$FI       0         1
07.56.54.          SERV. UNITS-1 =      4
07.56.54.          JOB COST=$       1.20
07.56.54.DFD,BEAMDAY,R.
07.56.54$FL   12288     1.270        6        5
```

This run costs $1.20.

APPENDIX D

USER'S MANUAL FOR THE COMPUTER PROGRAM "COTEC" FOR CALCULATION OF PLATFORM SECTIONAL HYDRODYNAMIC FORCES

D.1 General Background

Program "COTEC" is used in conjunction with program "XOTEC" for all slender, floating and submerged hulls. Program "COTEC" generates the hydrodynamic forces (added mass, damping and wave exciting forces) for specified hull sections and stores these forces in a file which is accessed by program "XOTEC" (see Appendix E), which uses the values to determine hydrodynamic forces for the complete hull.

Program "COTEC" uses the close-fit method developed by Frank (22), as described in Section 5. This method permits consideration of rather arbitrary section geometries.

D.2 Program Capabilities

Program "COTEC" can be used to compute section added mass, damping and wave exciting forces for heave, sway and roll for sections having rather arbitrary geometry defined in one of two ways:

- The section beam, draft and section area coefficient (section area divided by beam times draft) are specified and the program uses a Lewis form or a bulb form to describe section shape.
- A set of x and y coordinates for the section are specified.

For normal section shapes it is recommended that the section be represented by a Lewis form. This saves considerable time in generating required input data. For unusual section shapes it is desirable to specify a series of section coordinates.

Added mass and damping depend only on frequency while wave exciting forces depend on frequency and wave heading angle. Up to 30 frequencies and 10 wave heading angles can be con-

sidered for any section. Heave and pitch forces for the hull are determined in program "XOTEC" from heave values; sway and yaw forces are determined from sway values. Program "COTEC" does not calculate any forces for surge.

As it is possible to simultaneously store data for a large number of sections in the data file, it is generally possible to simultaneously store sectional data characterizing several hulls in the file. The number of sections for which data can be stored is given by

$$N_s = 200/ N_\omega N_\beta$$

where

N_s is the number of sections.
N_ω is the number of wave frequencies (20 or less).
N_β is the number of wave heading angles (10 or less).

Each section is assigned a section number, and this section number is used by program "XOTEC" to access the data generated by "COTEC".

D.3 Program Organization

Program "COTEC" calls a number of subroutines, whose functions are outlined in Figure D-1. The program calls these subroutines in the order shown in the Figure. All subroutines are called once, except for subroutine GELG, which solves the equations for pressure distributions on the section. Program GELG is called three times, once each for heave, sway and roll.

D.4 Program Output

The program output is divided into two basic parts. The first describes the section geometry and includes:

- Section offsets (calculated or input).
- A plot of the section shape (useful for checking accuracy of input data).

The second part describes, for each specified frequency and corresponding wave length, LAMBDA, and wave number, K, the calculated dimensional added mass, damping and wave exciting forces, where:

A is added mass.
B is hydrodynamic damping.
ZDV is heave wave exciting force.
ZDA is sway wave exciting force.
ZDR is roll wave exciting moment.

and where the subscripts 2, 3 and 4 refer to sway, heave and roll as described in Section 5 of the report. Thus A_{33} is heave added mass due to heave motion, B_{24} is sway damping due to roll motion, etc. The wave exciting forces are given for all specified wave heading angles, and consist of the in-phase (real) part, given first, and the out-of-phase (imaginery) part. Phase is defined, unlike the definition used in program "XOTEC", with respect to wave slope.

D.5 Inputs to Program "COTEC"

The required inputs to the program are described below. The total number of input lines or cards depends on the means used to specify the section shapes. The total number of cards are:

Lewis or hull forms - $5 + 2 \times N_s$
Detailed section offsets - $5 + 2 \times N_s \times N_o$

where N_s and N_o are the numbers of different sections and the number of offsets per section, respectively. The specific inputs required are:

	Format	Entry	Variable in Program
Card or Line 1	3I5	Number of wave frequencies (maximum of 20)	NK
		Number of wave heading angles (maximum of 10).	NENC

	Format	Entry	Variable in Program
Card or Line 1 (cont.)		Number of non-zero stations	NSTA
		Number of ship speeds (enter "1")	NSPD
Card or Line 2	3F10.6	Computational tolerance (use 0.001).	TOL 1
		Computational tolerance (use 0.001).	TOL 2
		Computational tolerance (use 0.001).	TOL 3
Card or Line 3 (up to four cards)	8F10.4	Frequencies (maximum of 30 values).	OMEGA
Card or Line 4 Up to 2 cards	8F10.4	Wave Heading angles (maximum of 10 values)	BETA
Card or Line 5	Blank	Reserved for future use with forward speed.	
Card or Line 6 (number of cards or lines equal to NSTA	2I5 17A4	Section number	ISTA
		Number of section offset points.	NO
		Alphanumeric identification 18A4 (Columns 11-80)	XNAME
Note:		N = 0 Lewis form is used.	
		N = 1 Bulb form is used.	
		N > 1 Section offsets are used.	
Card or Line 7	3F10.4	If: N = 0 or 1, one card 7 for each card 6	
		- Section Beam	B
		- Section Draft	T
		- Section Area Coefficient	SIG

Cards or Lines 6 and 7 are repeated as required.

Format	Entry	Variable in Program
	If: N > 1, NO cards 7 for each card 6	
	Half beam ordinate	ZZ(I)
	XI = *R* (ZZ(I))	
	Depth ordinate	
	YI = *I* (ZZ(I))	
	(for first card XI = -B/2, YI = 0, for last card - XI and YI are for the point nearest but <u>not</u> at the keel, where XI = 0, YI = -T. Other offsets are given in the proper sequence from the first point at water line to the last point which is the point nearest the keel.	

D.6 Sample Input and Output

Tables D1 and D2 show typical input data and output for program "COTEC". These data are for the APL modular experiment plant which is used as an example in Section 8. The basic input data, as contained in data cards or lines 1 - 7, are given in Table D1. The calculated output for the single hull section, as described by data line 7, are given in Table D2. These output follow the description given in Section D.4.

TABLE D-1 INPUT DATA FOR PROGRAM COTEC

```
****************  COTEC - OUTPUT  ******************
NK NENC NSTA NSPD NPCH
 20    2    1    0    0
TOL1=  .0010000 , TOL2=  .0010000 , TOL3=  .0010000
```

Printed by Program

FREQUENCIES

0.2 0.25 0.30 0.35 etc.

WAVE HEADING ANGLES

180. 90.

Not Printed by Program

```
STATION   10        APL OTEC PILOT PLANT
      BEAM       DRAFT      SIGMA
   121.0000   60.0000      .9900
```

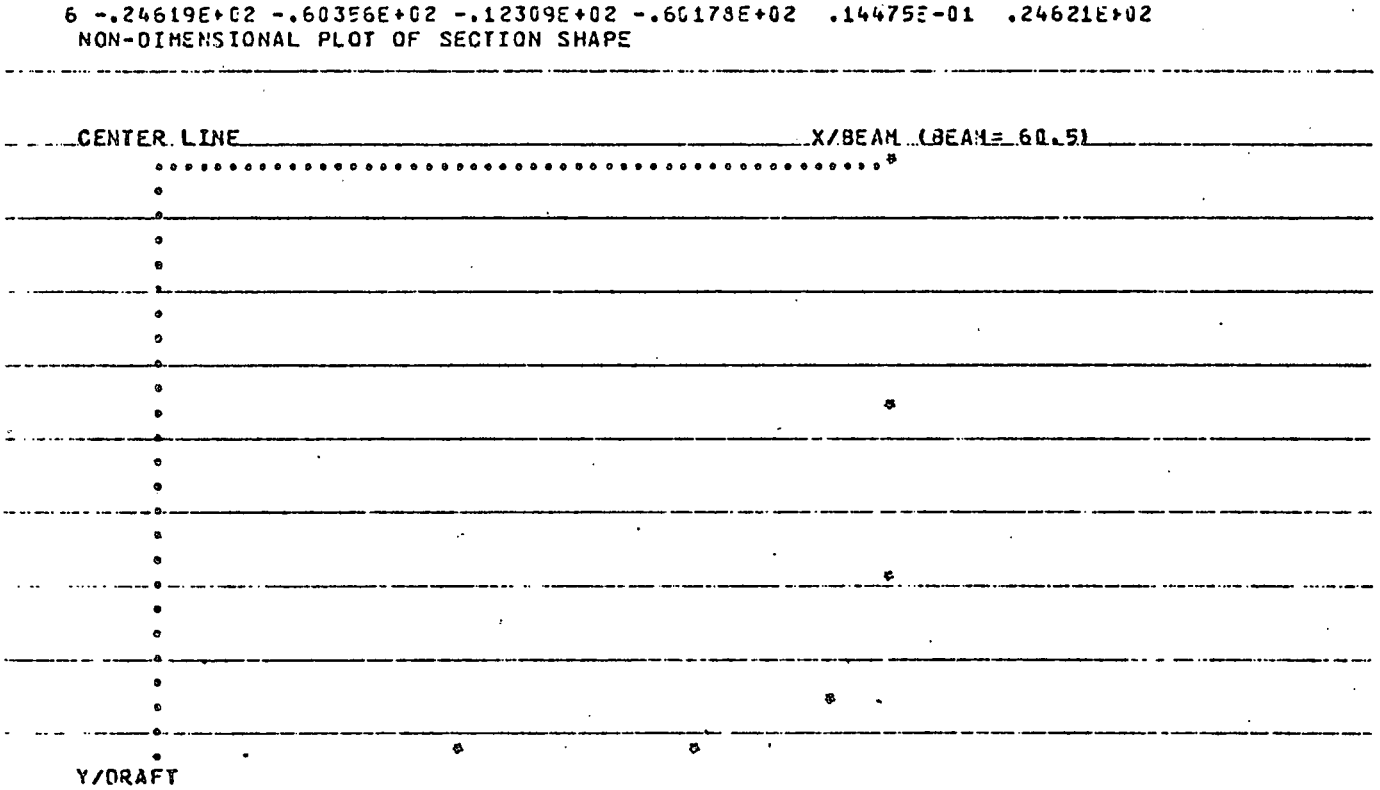
Printed by Program

TABLE D-2 TYPICAL COMPUTED OUTPUT OF PROGRAM COTEC

BODY COORDINATES

	ZETA		Z		AL	DS
1	-.60500E+02	0.	-.60670E+02	-.12245E+02	-.15847E+01	.24491E+02
2	-.60839E+02	-.24489E+02	-.60634E+02	-.34202E+02	-.15496E+01	.19429E+02
3	-.60428E+02	-.43914E+02	-.58163E+02	-.49729E+02	-.11994E+01	.12482E+02
4	-.55398E+02	-.55545E+02	-.50031E+02	-.57770E+02	-.36249E+00	.12550E+02
5	-.44164E+02	-.59995E+02	-.34392E+02	-.60176E+02	-.18495E-01	.19549E+02
6	-.24619E+02	-.60356E+02	-.12309E+02	-.60178E+02	.14475E-01	.24621E+02

NON-DIMENSIONAL PLOT OF SECTION SHAPE



CALL COFC

K	LAMBDA	OMEGA
.0012	5053.8791	.2000

CALL NVEL
CALL COF1
CALL COUT1

A33	B33	A22	B22	A44	B44	A24	B24
.1991E+05	.4063E+04	.1827E+05	.1507E+03	.7654E+07	.2520E+05	.2745E+06	.1938E+04

EXCITING FORCES

BETA	UK	OMEGA	ZDV		ZDH		ZDR	
180.0	.0	.2000	.755E+03	.646E+04	.151E-01	.346E-03	.194E+00	.445E-02
90.0	.0	.2000	.817E+03	.642E+04	.124E+04	.285E+02	.160E+05	.367E+03

TABLE D-2 (Continued)

```
      K        LAMBDA    OMEGA

    .0019 3234.4826      .2500
 CALL NVEL
 CALL COF1
 CALL COUT1

    A33          B33          A22          B22          A44          B44          A24          B24

  .1642E+05  .4405E+04  .1973E+05  .4769E+03  .7972E+07  .8254E+05  .2958E+06  .6242E+04

EXCITING FORCES

   BETA      UK      OMEGA          ZDV                          ZDH                          ZDR

   180.0      .0     .2500      .982E+03  .599E+04  .240E-01  .133E-02  .314E+00  .174E-01
    90.0      .0     .2500      .111E+04  .592E+04  .197E+04  .109E+03  .258E+05  .143E+04

*****************************************************************************************
      K        LAMBDA    OMEGA

    .0024 2673.1261      .2750
 CALL NVEL
 CALL COF1
 CALL COUT1

    A33          B33          A22          B22          A44          B44          A24          B24

  .1510E+05  .4489E+04  .2050E+05  .7804E+03  .8142E+07  .1376E+06  .3073E+06  .1031E+05

EXCITING FORCES

   BETA      UK      OMEGA          ZDV                          ZDH                          ZDR

   180.0      .0     .2750      .107E+04  .575E+04  .293E-01  .236E-02  .387E+00  .311E-01
    90.0      .0     .2750      .126E+04  .566E+04  .240E+04  .193E+03  .318E+05  .255E+04

*****************************************************************************************
      K        LAMBDA    OMEGA

    .0028 2246.1685      .3000
 CALL NVEL
 CALL COF1
 CALL COUT1

    A33          B33          A22          B22          A44          B44          A24          B24

  .1401E+05  .4519E+04  .2121E+05  .1219E+04  .8312E+07  .2191E+06  .3183E+06  .1626E+05

EXCITING FORCES

   BETA      UK      OMEGA          ZDV                          ZDH                          ZDR

   180.0      .0     .3000      .115E+04  .550E+04  .350E-01  .395E-02  .468E+00  .527E-01
    90.0      .0     .3000      .139E+04  .540E+04  .287E+04  .322E+03  .383E+05  .429E+04

*****************************************************************************************
```

APPENDIX E

USER'S MANUAL FOR THE COMPUTER PROGRAM "XOTEC" FOR CALCULATION OF THE COUPLED MOTIONS AND STRUCTURAL LOADS OF AN OTEC PLATFORM AND COLD WATER PIPE

E.1 General Background

Program "XOTEC" calculates the coupled responses of OTEC platform and Cold Water Pipe (CWP) to regular and irregular waves. The response amplitude operators (RAO)s for platform motions and CWP motions, shears and bending moments for the coupled platform/CWP system are first computed. Standard seakeeping spectral techniques are then used to determine the system response in one or several random seaways from these RAOs.

Program "XOTEC" requires, as input, transfer functions describing the response at the top of the CWP to unit translation of the pipe attachment point, unit rotation of the pipe attachment point and a unit amplitude wave. These functions are generated by Program "CWPFLX" described in Appendix B and stored by "CWPFLX" in a file named CWPTF (TAPE8 in CWPFLX, TAPE11 in XOTEC). Therefore, before executing "XOTEC", "CWPFLX" must always be executed, even when no CWP is to be used.

Program "XOTEC" also requires, as input, data describing the hydrodynamic forces for the OTEC platform alone. If the platform is composed of a slender floating or submerged hull or twin hulls, program "COTEC", described in Appendix D, is used to compute the sectional added mass, damping and wave excitation. The two-dimensional data for a variety of sections from different platforms may be stored simultaneously and selected from the data file by XOTEC. Strip theory is used by "XOTEC" to compute the three-dimensional hydrodynamic properties of the platform from the sectional data. If the platform is axisymmetric three-dimensional hydrodynamic data are read as input by "XOTEC". These axisymmetric data can be obtained from a number of computer programs including those of Garrison (8) and Bai (16).

E.2 Program Capabilities

Program "XOTEC" can treat the following cases:

1. Four general platform configurations can be treated. These are ship-like hulls, submarines, semi-submersibles and axisymmetric bodies.
2. Any CWP which can be analysed using program CWPFLX is allowed.
3. Arbitrary pipe attachment stiffnesses in surge, sway, heave, pitch and roll are allowed.
4. Up to 30 arbitrary regular wave frequencies, up to six combinations of significant wave heights and frequency for peak wave energy and up to 10 wave heading angles are allowed.

E.3 Program Organization

Figure E-1 presents a brief flow chart for program "XOTEC". Each line or card of input data is printed immediately after it is read so that any input error can be readily detected and corrected.

Subroutines "INPUT", FORC2", and "OUTP2" read input data from files previously created and stored by programs "COTEC" and/or "CWPFLX". Program "COTEC", described in Appendix D, stores sectional hydrodynamic data in a random file with a record number which depends on the station label, the number of headings, and the number of frequencies. All section hydrodynamic data stored by "COTEC" must, therefore, have the same number of frequencies, and heading angles, and the number of frequencies and headings used in "XOTEC" must be the same as that used in "COTEC". In addition, the number and values of the frequencies, used in "CWPFLX" must be identical to the scaled frequencies printed out by "XOTEC". These scaled frequencies are equal to the input frequencies divided by the square root of the scale ratio. Usually the scale ratio will be one and the input and scaled frequencies will be equal.

The function of other subroutines used by "XOTEC" are described in Figure E-1.

E.4 Program Output

Program XOTEC prints out the following information:

1. All input data read from cards or a terminal.
2. CWP transfer functions at the top of the CWP for all frequencies.
3. For each frequency, platform added mass, damping, and stiffness matrices and the combined platform response matrix.
4. For each frequency the responses of CWP and platform of a unit amplitude wave are printed.
5. For each sea state the significant (average of one-third highest) amplitude of platform motions and CWP motions, loads and stresses.

E.5 Description of Input

The required input for each data card or line of keyboard input are:

	Format	Entry	Variable in Program
Card or Lines 1	20A4	Title or any other information, e.g. problem number or description. (Repeat 2 lines or cards)	TITL1 TITL2
Card or Line 2	7I5	Number of frequencies (max. 30).	NOM
		Number of headings (max. 10). NENC = 1 for NSTA = 1	NENC
		Number of stations on hulls set (max. 25). NSTA = 1 if platform is axisymmetric.	NSTA
		Number of surface piercing legs of semi-submersible or submarine type platform. NL = 0 if	NL

	Format	Entry	Variable in Program
		platform is ship shape or axisymmetric (max. 6).	
		Number of points on platform at which motions are desired. (max. 4).	NMOT
		Flag for output of CWP loads and motions. Set ≠ 0 if and only if output of CWP loads and motions at each CWP segment boundary given in CWPFLX program are desired.	NZMOM
		Number of sea states (max. 6).	NH13
Card or Line 3 (up to 2 cards)	8F10	Heading angles in degrees. 0° is stern seas 180° is head seas (max. 10).	BETA
Card or Line 4 (up to 4 cards)	8F10	Wave exciting frequencies in radians per second. (max. 30).	OM
Card or Line 5 (up to 4 cards depending on value of NSTA)	8F10	Distance from amidships to each station (positive Fwd). Enter bow station first and proceed to stern. Use blank card or line if platform is axisymmetric (max. 25).	XSTA
Card or Line 6 (up to 2 cards depending on value of NSTA	16I5	Station labels assigned in input to program COTEC. Program COTEC stores each station by its label. The label is an interger which indicates the stored location of the section hydrodynamic	NST

	Format	Entry	Variable in Program
		data. Labels are repeated if the same section reappears along the ship as in the case of parallel midbody. Labels are input in the same order as the longitudinal locations. A zero station lable automatically denotes a station with zero for all hydrodynamic properties as at the ends of the platform. Use a blank card if platform is axisymmetric. (max. 25).	
Card or Line 7 (up to 4 cards depending on value of NSTA)	8F10.4	Station section area for each station lable. Input zero for stations labeled zero. Use blank card if platform is axisymmetric. (max. 25).	SA
Card or Line 8 (up to 4 cards depending on value of NSTA)	8F10.4	Station beam for each station given a label. Include zero for stations with a label of zero. Enter platform diameter if platform axisymmetric.	BEAM
Card or Line 9 (NL cards)	8F10.2	Include one card of type 9 for each vertical, surface piercing leg of submarine or semi-submersible. Omit card if NL, number of legs, equals zero. Enter:	
		diameter of leg at surface	DL
		submerged length of leg	XLL

	Format	Entry	Variable in Program
		longitudinal location of leg	XXL
		transverse location of leg.	YYL
Card or Line 10	2F10.2	Parameters describing the semi-submersible or submarine hull . Enter hull diameter	DS
		and separation between hulls.	SEP
		If separation is zero a single-hull submarine configuration is assumed. If separation is greater than DS a twin hulled semi-submersible is assumed. If SEP is greater than zero and less than DS incorrect results are obtained. If NL = 0 omit this card.	
Card or Line 11	E10.3, 7F10.3	Hull parameters. If platform is a semi-submersible use properties for the entire platform including vertical columns. Enter platform mass (slugs),	XMASS
		Radii of gyration about x, y and z axes respectively.	RXX,RYY, RZZ
		Height of vertical center of gravity above waterline (positive up).	VCG
		Location of longitudinal center of gravity measured from midships (positive Fwd).	XLCG
		Estimated transverse metocentric height.	GM

	Format	Entry	Variable in Program
		Hull block coefficient (one hull if semi). Note: The program uses a GM calculated from the station beams, input value is for comparison purposes only.	CB
Card or Line 12	6F10.3		
	E10.3	Hull parameters:	
		Length between perpendiculars.	XLBP
		Beam (set equal to zero for semi-submersible).	B
		Draft.	DRAFT
		Height of center of buoyancy above water surface (positive up).	VCB
		Linear scale ratio relative to that for which the two-dimensional sectional properties were computed and frequencies specified.	SCALE
		Current velocity (not used).	VCUR
		Linear empirical viscous roll damping coefficient.	B44V
Card or Line 13	3E10.3	CWP attachment stiffness in heave. (Force per unit displacement)	XKP1
		CWP attachment stiffness in rotation (moment per radian).	XKP2
		Youngs Modulus of pipe material (PSI)	YMOD
Card or Line 14	8F10.4	CWP parameters:	
		CWP diameter.	DP

	Format	Entry	Variable in Program
		CWP length.	XLP
		Mass density of CWP material	RHOP
		Wall thickness	TP
		Semi-submersible or submarine.	XKD
		Linear normal vicous drag coefficient (lb/ft). Drag = $XKD\omega\rho(DS)^2 2\pi$	
		Linear pipe heave drag coefficient Drag = $XKD7\rho\omega^2$	XKD7
Card 15	8F10.4	Location of pipe attachment X,Y,Z	ATACH(I) (I = 1,3)
Card 16	8F10.4	Location of pipe top X, Y, Z	PTOP(I)
Card or Line 17 (up to 4 cards or lines depending on value of NMOT)	3F10.2	Locations on platform at which motions are desired. One card required for each locations. Enter longitudinal location - XMOT transverse location - YMOT vertical location. -A2MOT	XMOT YMOT
Card or Line 18	8F10.8	Significant wave heights - feet Omit this card if no sea states, NH13 = 0 in Card 2)	XH13
Card or Line 19	8F10.8	Peak energy frequencies of wave spectra - radians per second. (Omit this card if no sea states, NH13 = 0 in Card 2).	OMP
Card or Line 20	3F10.5 I5	The program calculates the waterplane area, GM_L and GM_T based on the beams read from	

Format	Entry	Variable in Program
	Card 8. The presence of a moon pool or other free flooding areas in the hull may require reductions to the computed waterplane area and moment. The computed area or moment is multiplied by the appropriate correction factor to yield the area or moment consistent with the presence of the moon pool. Enter:	
	Waterplane area correction factor.	WPF33
	Transverse inertia correction factor.	WPF44
	Longitudinal inertia correction factor.	WPF55
	If NVCB is zero the computed vertical center of byouancy is used. If NVCB is greater than zero the VCB read from Card 12 is used.	NVCB
	If NSTA = 1 the program assumes that the platform is axisymmetric. "COTEC" cannot compute accurate hydrodynamic data for an axisymmetric shape; therefore, the three-dimensional hydrodynamic coefficients must be entered. A 6 x 6 added mass matrix and 6 x 6 damping matrix is required for each frequency.	

		Format	Entry	
Repeat once for each frequency	Card or Line 21	6E13.6	Enter six cards containing added mass matrix, six data items per card or line.	
	Card or Line 22	6E13.6	Enter six cards containing damping matrix, six data items per card or line.	B
	Card or Line 23	6E13.6	Wave-exciting forces on axisymmetric hull. Each wave-exciting force is a complex quantity (2E10.2). One card or line is required for each frequency. Enter:	
			Wave induced horizontal force.	ZX
			Wave induced vertical force.	Z7
			Wave induced pitching moment.	ZM

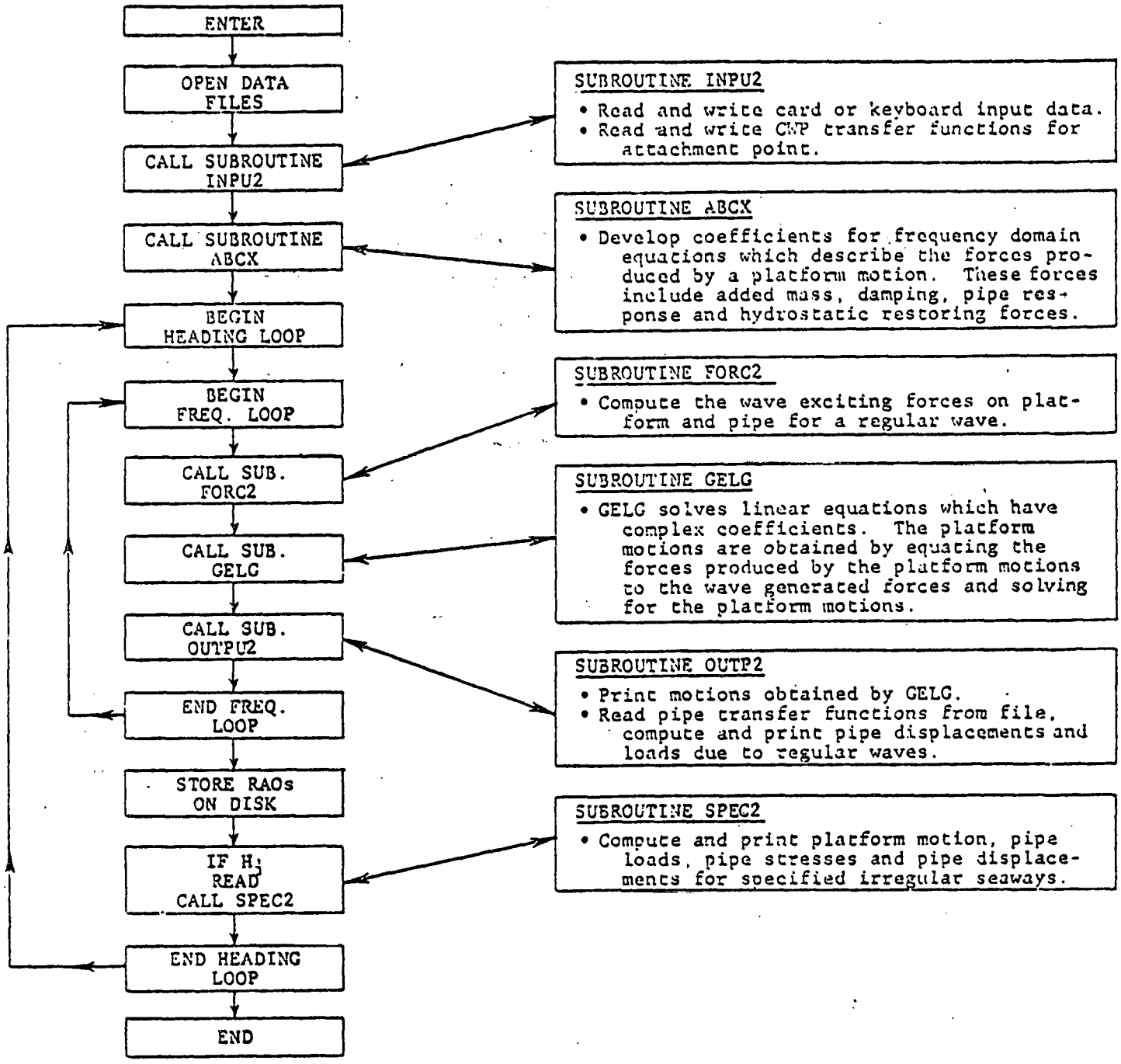


Figure E-1 FLOW CHART OF PROGRAM "XOTEC"

APPENDIX F

CWP Notes 1-4:

Revisions and Updates to NOAA/DOE Code

F.1 BACKGROUND

After receiving and implementing the code in January 1979, ORI, Inc. identified a number of areas in which the code could be improved, both from a standpoint of operational efficiency, and also from the point of view of making the program applicable to a broader range of CWP analysis cases. "CWP Notes" 1 through 4 were developed as addenda to the user's manual (Appendices A through E). These documents follow, and address the points which ORI identified as problem areas during the operational implementation of the code.

CWP NOTES #1

The following changes or additions are for improvement in the operational efficiency of the NOAA/DOE Code. (revised 5-1-79)

MAIN.DBEAM (.CWPFLX)

Line 61 --

Change:

```
BMM1(10)
```

To:

```
BMM1(50)
```

Reason: Erroneous dimension. Pipe with more than 10 sections will overwrite into next array.

Line 137 --

Replace:

```
905 XC = 0.
```

With:

```
905 XC = ZP
```

Line 139 --

Insert:

```
IF (XC .LT. DRAFT) VI=0.
```

After:

```
VI = VZ * VS + VS * ...
```

Line 141 --

Insert:

```
IF (VI .EQ. 0.) VF=0.
```

After:

```
VF = VZ * VS + VS * ...
```

Reason: The preceeding three changes take into account that the top of the pipe may not be located at the water surface and sets the current force equal to zero if the top section of the pipe is located inside the platform.

Lines 292-294 --

Delete:

```
IF (LRØØT .EQ. 0) GØ TØ 9002
IF (DADA - DABS(D)) 9001,9002,9002
9001 DEL = DEL/2
```

Reason: These statements seem to be left over from a binary search algorithm and do not belong in the present straight line search algorithm.

SUB.ØUT

Lines 58-59 --

No change; should remain as follows:

```
115 IF (ID-2) 116,116,209
116 IF (D) 209,117,209
```

Reason: Program should proceed to statement 209 (error message and program kickout) only if ID is less than 2 (static case) and D (motion matrix determinant) is not equal to zero.

SUB.HDFØRCE

Lines 75-76 --

Insert:

```
     IF (ZI .LT. DRAFT) VI=0.
```

After:

```
     VI = VS * (VZ + AZ1 * DEXP ...)
```

Insert:

```
     IF (VI .EQ. 0.) VF=0.
```

After:

```
     VF = VS * (VZ + AZ1 * DEXP ...)
```

Reason: Same as lines 137-141

MAIN.CØTEC

All file manipulations must be changed to conform to the user's specific computer configuration.

MAIN.ØTEC (.XØTEC)

SUB.INPU2

After line 152 (XM(2,4) = -XM(1,5)) --

Insert:

```
     XM(2,6) = XMASS * XLCG
```

Before line 159 (100 FØRMAT ...) --

Insert:

```
     XM(4,6) = XM(3,5) * VCG
     XM(6,4) = XM(4,6)
```

SUB.FØRC2

Lines 111-112 --

Replace:

```
     ZST1(I) = ZST1(I)/CMPLX(XSTA(I),0.)
     IF (XSTA(I) .EQ. 0.) ZST1(I)=(0.,0.)
```

With:

```
     ZST1(I) = (0.,0.)
     IF [redacted] .NE. 0.) ZST1(I) = ZST1(I) / CMPLX (XSTA(I),0.)
```

Reason: Prevents possible divide-by-zero.

IMPROVEMENTS TO PROGRAM XØTEC

1. The following insertions will allow the designer to input a longitudinal spring at the bottom of the CWP. This configuration, which was not previously available, permits bottom mounted pipes with heave compensation devices or the Gibbs & Cox tension-moored SPAR platform to be modelled. Since many of the proposed CWP configurations contain some form of tension mooring, this addition greatly increases the flexibility of the program.

MAIN.ØTEC (.XØTEC)

SUB.INPU2

Insert:

```
     CØMMØN[redacted]XKPBØT
```

Line 119 --

Replace:

```
     READ(IR,114) XKP1,XKP2,YMØD
```

With:

```
     READ(IR,114) XKP1,XKP2,YMØD,XKPBØT
```

Where: XKPBØT is the spring stiffness in force per unit length.

After line 120 --

Insert:

```
     WRITE (IW,301) XKPBØT
 301 FØRMAT(/,1X,'AXIAL BØTTØM MØØR SPRING STIFFNESS',
    1' (FØRCE/LENGTH)=', E12.5)
```

SUB.ABCX

Insert:

```
     CØMMØN[redacted] XKPBØT
```

Line 169 --

Replace:

```
     ZLHS(7,7) = CMPLX(XKP1-ØM(IØM)**2*XM77*XLP,XKD7*RHØ*
```

With:

```
     ZLHS(7,7) = CMPLX(XKP1 + XKPBØT - ØM(IØM)**2 * XM77 * XLP , XKD7 * RHØ *
```

2. The following changes will permit the designer to run a specific platform without the CWP attached. This type of analysis would be applicable to any case where the CWP would be disconnected during extreme storm conditions or maintainance operations and there would be a need to know ship motions without the pipe. It would also be of importance to the definition of ship motions during initial CWP installation planning and to validating model test results for various barge or SPAR designs.

MAIN.ØTEC (.XØTEC)

SUB.INPU2

Insert:

```
     CØMMØ[redacted] KEYCWP
```

Line 40 --

Replace:

```
     READ(IR,100) NØM,NENC,NSTA,NL,NMØT,NZMØM,NH13
```

With:

```
     READ(IR,100) NØM,NENC,NSTA,NL,NMØT,NZMØM,NH13,KEYCWP
```

Note: If KEYCWP is anything other than zero, the program will treat it as if there is no pipe.

After line 40 --

Insert:

```
     IF (KEYCWP .NE. 0) GØ TØ 12
```

After line 60 (DØ 10 ...) --

Insert:

```
     IF (KEYCWP .NE. 0) GØ TØ 303
```

Before line 75 (10 CØNTINUE) --

Insert:

```
     GØ TØ 10
 303 CØNTINUE
     ZFP(IØM) = 0.
     ZMP(IØM) = 0.
     ZFPP(IØM) = 0.
     ZMPP(IØM) = 0.
     ZFPW(IØM) = 0.
     ZMPW(IØM) = 0.
```

SUB.FØRC2

Insert:

```
     CØMMØN[redacted] KEYCWP
```

After line 23 (I11 = ...) --

Insert:

```
      IF (KEYCWP .NE. 0) GØ TØ 66
```

Before line 37 (C CALL DATSS ...) --

Insert:

```
      IF( KEYCWP .EQ. 0) GØ TØ 67
   66 CØNTINUE
      ZFP(IØM) = 0.
      ZMP(IØM) = 0.
      ZFPP(IØM) = 0.
      ZMPP(IØM) = 0.
      ZFPW(IØM) = 0.
      ZMPW(IØM) = 0.
   67 CØNTINUE
```

SUB.ØUTP2

Insert:

```
      CØMMØN [redacted] KEYCWP
```

After line 19 (I11 = ...) --

Insert:

```
      IF (KEYCWP .NE. 0) GØ TØ 66
```

Before line 39 (WRITE(IW,103)) --

Insert:

```
      IF (KEYCWP .EQ. 0) GØ TØ 67
   66 CØNTINUE
      ZFP(IØM) = 0.
      ZMP(IØM) = 0.
      ZFPP(IØM) = 0.
      ZMPP(IØM) = 0.
      ZFPW(IØM) = 0.
      ZMPW(IØM) = 0.
   67 CØNTINUE
```

After line 113 (C PIPE MØTIØNS AND LØADS) --

Insert:

```
      IF (KEYCWP .NE. 0) GØ TØ 68
      IF (NZMØM .EQ. 0) GØ TØ 68
```

After line 137 (10 CØNTINUE) --

Insert:

```
   68 CØNTINUE
```

CWP NOTES #2

ERRATA TO USER'S MANUALS

The following changes to the User's Manual and discussion of CWPFLX were forwarded to ORI on 28 March by Dr. Chirasak Thasanatorn of Hydronautics, Inc.

"Addenda and Errata to Report 7825-2"
(03/28/1979)

Technical Report 7825-2 Vol. I

The following corrections should be made to the original report (dated November 1978):

Page 53, right-hand side of equation [43]. Should read

"$1.1\ e^{-\frac{kD_p}{2}}$....." instead of "$1.1\ e^{-kD_p}$....."

Page 85, Table 7-2, line 2 of shear results. Should read

"0.013 0.013" instead of "0.13 0.13".

Technical Report 7825-2 Vol. II

Page B-6, input in card 8 should read:

```
LNCP(I),CK(I),BK(I),CM(I),CN(I),HSP(I)
(I10,4F10.2)
```

instead of

```
LNCP(I),CK(I),BK(I),CM(I),CN(I),SHP(I),
 RLHSP(I) (I10,5F10.2)
```

Page B-9, line 3 from top. Should read k_1 instead of k_1k_2.
line 8 from top. Definition of current velocity profile should read "$\ldots\ldots+a_2z\ e^{-k_2z}$" instead of "$\ldots\ldots+a\ ze^{-k_2z}$".

Comments on "CWPFLX"

In order to improve the accuracy of a shear result in a vicinity of the pipe attachment, shear forces in an upper one-quarter of the pipe length are obtained by directly integrating the equation of motion taking into account only distributed pipe characteristics and transverse (horizontal) distributed forces. Therefore, any concentrated parameters, i.e., lumped masses, concentrated forces, any spring supports (mooring lines), are not permitted in the upper one-quarter of the pipe. However, the program can easily be modified to allow the concentrated parameters in this portion of the pipe.

At line number 111 in the main program, "NSEG = RNS/4." where RNS = total number of CWP sections, and NSEG - number of CWP sections (range of integration) from pipe top which shear results are obtained by integration. This range of integration or NSEG should be decreased such that any concentrated parameters are outside this range. For example, if the integration is to be performed in the upper one-sixth of the total number pipe sections, line 111 should be changed to "NSEG = RNS/6." instead of "NSEG = RNS/4."

Note on Limitations on CWP Configurations

Due to the mathematical approach used in the NOAA/DOE model, it is impossible to analyze certain Cold Water Pipe (CWP) configurations. In particular, a number of neutrally buoyant cases will result in either unstable or neutrally stable solutions. This is due to the fact that the solution technique relies on the determination of natural frequencies. For neutrally buoyant pipes, natural frequencies cannot be computed for cases such as the following:

- Neutrally buoyant, simply supported pipe with no hinge stiffness at attachment point. (Pipe will be in equilibrium at any angle to the vertical.)
- Neutrally buoyant, hinged pipe with no hinge stiffness.
- Negatively buoyant pipe, simply supported or hinged, axial force including internal water flow is upward.

Note that in each of these cases, the solution could be made stable by adding a downward tension, extra weight or reduced buoyancy, non-zero hinge spring stiffness or mooring lines.

Obviously, the ultimate goal of the design being to minimize deflections, one or more of these solutions will naturally be incorporated into the design. The three cases noted above are not feasible designs. We bring attention to these configurations only because one of the users attempted to analyze one of these situations and encountered the obvious problems.

Change to Program XOTEC

The following change increases the generality of program XOTEC. As presently programmed, the code will handle only the case of XCG (Center of Gravity) equal to zero. By making the following change, a non-zero XCG for the platform may be implemented. The change noted alters the generalized mass matrix to account for this case.

Subroutine INPU2

Line 153	Replace:	XM(3,5)=-XM(2,6)
	With:	XM(2,6)=XMASS*XLCG
Line 158	Insert:	XM(4,6)=XM(3,5)*VCG
		XM(6,4)=XM(4,6)
	After:	XM(6,2)=XM(2,6)

CWP NOTES #3

Attached is the most recent listing of the NOAA/DOE computer code for programs CWPFLX and XOTEC. All of the changes that have been made to the originally publshed code have been delineated and brief comments have been placed near the altered lines. A number of changes have been made to correct logic or FORTRAN related errors, but several improvements to the code have also been added. The following summaries contain information pertaining to these modeling changes.

Program CWPFLX

Improved natural frequency search algorithm: The original search routine was a false position search. This type of search may cause numerical instabilities or oscillations, preventing a solution or greatly decreasing the efficiency of the routine. The improved false position search will prevent these instabilities as long as suitable search increments are used. Recommended initial increments are about 1/2 the value of the estimated first modal frequency.

Frequency search bypass: The option will now be available to bypass the frequency. If the pipe modal frequencies are already known (ie., the identical pipe has previously been analyzed), the frequency search can be bypassed by reading in the natural frequencies as input. This option saves considerable computation of time and money. See user's guide update (last page of this document) for details. When the iterative damping scheme presently being developed by Hydronautics, Inc. is implemented, this bypass will no longer by necessary.

Inclusion of concentrated parameters in subroutine CORREC: Subroutine CORREC recomputes the shear force by integrating the pipe response. The original subroutine could not handle segments that contained attached springs or concentrated masses. This deficiency has now been corrected. See user's guide update. Shear stress is now computed after CORREC is called, not before.

Current force on pipe inside platform: Current forces on pipe segments inside the platform moon pool are now set to zero.

Bottom mounted pipe: Setting the lower end boundary condition to simply supported results in a bottom mounted pipe. Previous errors resulting in motion of the bottom end have been corrected and the present code produces no lateral motion at a simply supported bottom mount.

Shape factor for bottom mounted or hinged platform/pipe correction: The analytic approach to pipe bending analysis assumes rigid body motion for computing hydrodynamic loads on the pipe. The approach also necessitates adding an offset to the state vector to transform the bending response from the pipe coordinate system to the inertial frame of reference. In the bottom mounted case, the offset is computed by assuming a static pipe shape based on the boundary conditions and the pipe material and geometry. The freely hung case with a top hinge is analyzed dynamicaly as a rigid body-spring system with damping. This modification corrects the previous asssumption that the pipe rotated one radian in response to a unit platform rotation for all top boundary conditions. This assumption is only true for fixed connections. The corrected response now results in zero pipe motion due to platform rotation for a pure hinged correction and increasing response as the spring constant is increased. In the limit, an infinite spring does reduce to the fixed case.

Diameter and thickness added to transfer file: The diameter and thickness at each segment have been added to the transfer file. This change is necessary so that XOTEC will properly compute pipe stresses for non-prismatic pipes.

PROGRAM XOTEC

No-Pipe options: An option to run the platform without a pipe has been added to allow the user to run XOTEC without having to run CWPFLX for a zero pipe case. See user's guide update for details on input.

XMASS computation: Corrections have been made to the mass matrix computation to properly handle cases when the longitudinal and vertical centers of gravity are non-zero. Transverse center of gravity is assumed to be on the centerline.

Bottom pipe axial spring: A variable has been added to simulate a bottom axial mooring line by reading in its spring constant. This effect can also be included in CWPFLX by assuming an average tension and estimating the transverse restoring force due to the axial spring. See user's guide update for details.

Stress in pipe segments: Individual pipe section diameters and thicknesses are passed from CWPFLX via the transfer file to ensure proper computation of stresses. This change is necessary to properly handle non-prismatic pipes.

User's Manual Corrections
(Input Data Cards)

CWPFLX

Card 2 - NTERM, NLOADS,NWRITE,NOSRCH (4I5)

NWRITE = 0 - no debug output
1 - debug output
NOSRCH = 0 - use frequency search
1 - read in known natural frequencies

Card 2A- if NOSRCH = 1, read NTERM cards with natural frequencies in increasing order (magnitude)

FQN(I)- natural frequency in cycles/sec (E22.14)

XOTEC

Card 2- (8I5) - NOM,NENC,NSTA,NL,NMOT,NZMOM,NH13,KEYCWP

Set NZMOM=0 and KEYCWP = 1 if no pipe

Card 13-(4F10.3)XKP1,XKP2,YMOD, XKPBOT

XKPBOT is an axial bottom spring stiffness, lb/ft

Card 14- RHOP is the mass density of pipe materials, including effect of average density lowering due to internal bouyancy pods. (RHOP x pipe volume x 32.2 = total weight of pipe in air)

CWP NOTES #4

USER'S GUIDE CHANGES/ADDITIONS

The following changes or additions apply to the most recent version of the NOAA/DOE Code.

PROGRAM CWPFLX

Page B-1 Card 2 - Read NTERM, NLOADS, NWRITE, NOSRCH (4I5)

NWRITE = 0, no debug output
1, debug output

NOSRCH = 0, perform frequency search
1, do not perform search, use read-in frequencies

Card 2A - natural frequencies, one to a card, lowest to highest, cycles/sec, at least 8 significant digits, NTERM cards (E20.10)

Page B-5 Card 76 - Read XK(I), RK(I), RG(I), DIAM(I), TH(I), FA(I), CDSTAT(I) (7F10.2)

CDSTAT(I) = Steady drag coefficient for section. If less than .0001, uses default value of .8.

PROGRAM XOTEC

Page E-3 Card 2 - Read NOM, NENC, NSTA, NL, NMOT, NZMOM, NH13, KEYCWP (8I5)

KEYCWP = 0, platform with pipe
1, platform without pipe

If no pipe, set NZMOM=0, DP=.1, XLP=.1, TP=.01, RHOP=2. CWPFLX need not be run.

Page E-8 Variable RHOP is the average mass density of the pipe (not necessarily equal to the pipe material density if the pipe contains buoyancy chambers). RHOP·pipe volume·32.17= pipe weight in air.

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