AN ABSTRACT OF THE THESIS OF

Ong-In Shin for the degree of Master of Ocean Engineering in Civil Engineering presented on August 4th, 1987.

Title: Wave Forces on Concrete Pipes and Plates Used as Seabed Artificial Reef Units.

Abstract approved:

Charles K. Sollitt

Wave forces acting on concrete pipes and plates intended for use as artificial reef units are examined. Large scale experiments with a prototype to model ratio of 2:1 were conducted at O.H. Hinsdale Wave Research Laboratory at Oregon State University in Corvallis, Oregon. Test wave conditions ranged from shallow to deep water with wave heights from 0.3 to 4.7 feet and wave periods from 1.3 to 10.6 seconds at water depths of 11.5 and 9.0 feet.

Simulated flanged concrete pipe units, 15.3-inches in diameter and 46.3-inches long, were examined in both horizontal and vertical orientations. Horizontal plates, 25.5 x 30.0-inch wide and 4.25-inch thick, simulating hollow core concrete floor slabs, were examined in open stacked arrays with unit void ratios.

Drag and inertia force coefficients were determined utilizing the Morison equation. Wave heights, currents and forces were measured, and the water kinematics were predicted by linear wave theory. The force coefficients based on both measured and predicted kinematics were

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determined by the least square method, Fourier method and the maximum value method. The maximum force coefficient and the lift force coefficients were also determined. The center of force on the pipe model and the phase lags of measured velocities and forces were examined.

The drag and inertia coefficients were found to depend both on the Reynolds number and the Keulegan-Carpenter parameter in ranges of $0.1 \times 10^5$ to $5.0 \times 10^5$ and $0.1$ to $12$, respectively. The drag coefficients varied from approximately $0.1$ to $15.0$ for the vertical pipe, $1.0$ to $17.0$ for the horizontal pipe and $2.0$ to $50.0$ for the plates. The inertia coefficients ranged from $1.5$ to $2.8$. The maximum force coefficients and lift force coefficients decreased from $100.0$ to $1.0$ exponentially with increasing Keulegan-Carpenter parameter values. The center of force along the vertical pipe was within seven percent of the pipe centroid. Phase lags of drag, inertia, and total forces displayed monotonic trends when compared to the water depth and wave length parameter.

Results of this study may be used directly by designers to determine the stability of similar materials in wave and current environments. The results also may be used to quantify ballast requirements for extreme wave and current conditions.
WAVE FORCES ON CONCRETE PIPES AND PLATES
USED AS SEABED ARTIFICIAL REEF UNITS

by

Ong-In Shin

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# TABLE OF CONTENTS

1. **INTRODUCTION**
   - 1.1 Motivation ........................................... 1
   - 1.2 Research Scope ...................................... 4

2. **THEORETICAL BACKGROUND** .................................. 6
   - 2.1 Wave Forces ........................................... 6
   - 2.2 Governing Parameters ................................. 10

3. **EXPERIMENTAL APPARATUS & PROCEDURES** .................. 14
   - 3.1 Research Facilities ................................... 14
   - 3.2 Experiments ............................................ 16
   - 3.3 Models .................................................. 24
   - 3.4 Measurements .......................................... 28

4. **DATA ANALYSIS** ............................................ 41
   - 4.1 Procedures ............................................. 41
   - 4.2 Data Smoothing ........................................ 43
   - 4.3 Force Coefficients ..................................... 50
   - 4.4 Center of Force ........................................ 59
   - 4.5 Phase Lag ............................................... 62

5. **RESULTS PART I : VERTICAL PIPE** ......................... 64
   - 5.1 Introduction ........................................... 64
   - 5.2 Measurements .......................................... 65
   - 5.3 Drag & Inertia Force Coefficients ..................... 71
   - 5.4 Center of Force ........................................ 76
   - 5.5 Maximum Force Coefficient ............................. 80
   - 5.6 Phase Lag ................................................ 80
   - 5.7 Comparison with Long Vertical Cylinder ............... 83
## LIST OF FIGURES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>3-1</td>
<td>Wave Channel Plan &amp; Profile</td>
<td>15</td>
</tr>
<tr>
<td>3-2</td>
<td>Vertical Pipe and the Wave Board in the back</td>
<td>21</td>
</tr>
<tr>
<td>3-3</td>
<td>Vertical Pipe and the Beach</td>
<td>21</td>
</tr>
<tr>
<td>3-4</td>
<td>Horizontal Pipe view from the Beach</td>
<td>22</td>
</tr>
<tr>
<td>3-5</td>
<td>Horizontal Pipe View from the Wave Board</td>
<td>22</td>
</tr>
<tr>
<td>3-6</td>
<td>Four Layers Setup (Top View)</td>
<td>25</td>
</tr>
<tr>
<td>3-7</td>
<td>Three Layers Setup</td>
<td>25</td>
</tr>
<tr>
<td>3-8</td>
<td>Pipe Model</td>
<td>27</td>
</tr>
<tr>
<td>3-9</td>
<td>Plate Model</td>
<td>27</td>
</tr>
<tr>
<td>3-10</td>
<td>Sonic Profiler Head &amp; Cover</td>
<td>29</td>
</tr>
<tr>
<td>3-11</td>
<td>Sonic Profiler attached to the Bridge</td>
<td>29</td>
</tr>
<tr>
<td>3-12</td>
<td>Marsh McBirney current Meter Set</td>
<td>30</td>
</tr>
<tr>
<td>3-13</td>
<td>Current Meter In Place</td>
<td>30</td>
</tr>
<tr>
<td>3-14</td>
<td>Larger Dynamometer attached to Vertical Pipe</td>
<td>31</td>
</tr>
<tr>
<td>3-15</td>
<td>Smaller Dynamometer in Place</td>
<td>31</td>
</tr>
<tr>
<td>3-16</td>
<td>Instruments in Position for Pipe Model</td>
<td>33</td>
</tr>
<tr>
<td>3-17</td>
<td>Instruments in Position for Plate Model</td>
<td>33</td>
</tr>
<tr>
<td>3-18</td>
<td>Measurements Sample</td>
<td>34</td>
</tr>
<tr>
<td>4-1</td>
<td>Data Analysis Procedure</td>
<td>42</td>
</tr>
<tr>
<td>4-2</td>
<td>Data Smoothing Procedure</td>
<td>44</td>
</tr>
<tr>
<td>4-3</td>
<td>Center of Force for Vertical Pipe</td>
<td>61</td>
</tr>
<tr>
<td>4-4</td>
<td>Center of Force for Horizontal Pipe</td>
<td>61</td>
</tr>
<tr>
<td>5-1</td>
<td>Max. Horizontal Force vs. h/Lo</td>
<td>69</td>
</tr>
<tr>
<td>Page</td>
<td>Title</td>
<td>Reference</td>
</tr>
<tr>
<td>------</td>
<td>----------------------------------------------------------------------</td>
<td>-----------</td>
</tr>
<tr>
<td>6-13</td>
<td>Center of Force Location vs. h/L₀</td>
<td>99</td>
</tr>
<tr>
<td>6-14</td>
<td>CL vs. K-C : LWT Kinematics</td>
<td>101</td>
</tr>
<tr>
<td>6-15</td>
<td>CL vs. K-C : Measured Kinematics</td>
<td>101</td>
</tr>
<tr>
<td>6-16</td>
<td>CF vs. Re : LWT Kinematics</td>
<td>103</td>
</tr>
<tr>
<td>6-17</td>
<td>CF vs. K-C : Measured Kinematics</td>
<td>103</td>
</tr>
<tr>
<td>6-18</td>
<td>Time Series Phase Angle vs. h/L₀</td>
<td>104</td>
</tr>
<tr>
<td>7-1</td>
<td>CD vs. Re : LSQ &amp; LWT Kinematics</td>
<td>110</td>
</tr>
<tr>
<td>7-2</td>
<td>CD vs. K-C : FORI &amp; LWT Kinematics</td>
<td>110</td>
</tr>
<tr>
<td>7-3</td>
<td>CI vs. Re : LSQ &amp; LWT Kinematics</td>
<td>111</td>
</tr>
<tr>
<td>7-4</td>
<td>CI vs. K-C : MXVL &amp; LWT Kinematics</td>
<td>111</td>
</tr>
<tr>
<td>7-5</td>
<td>CD vs. Re : MXVL &amp; Measured Kinematics</td>
<td>113</td>
</tr>
<tr>
<td>7-6</td>
<td>CD vs. K-C : MXVL &amp; Measured Kinematics</td>
<td>113</td>
</tr>
<tr>
<td>7-7</td>
<td>CD &amp; CI Relationships of Different Methods (LWT)</td>
<td>114</td>
</tr>
<tr>
<td>7-8</td>
<td>CI vs. Re : FORI &amp; Measured Kinematics</td>
<td>115</td>
</tr>
<tr>
<td>7-9</td>
<td>CI vs. K-C : LSQ &amp; Measured Kinematics</td>
<td>115</td>
</tr>
<tr>
<td>7-10</td>
<td>CL vs. K-C : LWT Kinematics</td>
<td>117</td>
</tr>
<tr>
<td>7-11</td>
<td>CL vs. Re : LWT Kinematics</td>
<td>117</td>
</tr>
<tr>
<td>7-12</td>
<td>CL vs. K-C : Measured Kinematics</td>
<td>118</td>
</tr>
<tr>
<td>7-13</td>
<td>CL vs. K-C : Measured Kinematics</td>
<td>118</td>
</tr>
<tr>
<td>7-14</td>
<td>CF vs. K-C : LWT Kinematics</td>
<td>120</td>
</tr>
<tr>
<td>7-15</td>
<td>CF vs. K-C : Measured Kinematics</td>
<td>120</td>
</tr>
<tr>
<td>7-16</td>
<td>Time Series Phase Angle vs. h/L</td>
<td>121</td>
</tr>
<tr>
<td>Table</td>
<td>Page</td>
<td></td>
</tr>
<tr>
<td>-------</td>
<td>------</td>
<td></td>
</tr>
<tr>
<td>3-1</td>
<td>17</td>
<td></td>
</tr>
<tr>
<td>3-2</td>
<td>19</td>
<td></td>
</tr>
<tr>
<td>3-3</td>
<td>20</td>
<td></td>
</tr>
<tr>
<td>3-4</td>
<td>32</td>
<td></td>
</tr>
<tr>
<td>3-5</td>
<td>39</td>
<td></td>
</tr>
<tr>
<td>4-1</td>
<td>48</td>
<td></td>
</tr>
<tr>
<td>4-2</td>
<td>51</td>
<td></td>
</tr>
<tr>
<td>4-3</td>
<td>51</td>
<td></td>
</tr>
<tr>
<td>4-4</td>
<td>52</td>
<td></td>
</tr>
<tr>
<td>5-1</td>
<td>66</td>
<td></td>
</tr>
<tr>
<td>5-2</td>
<td>68</td>
<td></td>
</tr>
<tr>
<td>6-1</td>
<td>86</td>
<td></td>
</tr>
</tbody>
</table>

**Table**

- **3-1** Experiment Parts
- **3-2** Experimental Wave Conditions I (h=11.5 ft)
- **3-3** Experimental Wave Conditions II (h= 9.0 ft)
- **3-4** Measurement Channel Identification
- **3-5** Instruments Calibration Coefficient
- **4-1** Variance Coefficients of Measurements: Part II
- **4-2** Elevation Conversion Factor for Velocity
- **4-3** Time Constant of Current Meter
- **4-4** Force Coefficients Determination
- **5-1** Variance Coefficients of Measurements: Part I Vertical Pipe (h=9.0 ft)
- **5-2** Kinematics Results: Part I Vertical Pipe (h=11.5 ft)
- **6-1** Variance Coefficients of Measurements: Part II Horizontal Pipe (h=9.0 ft)
WAVE FORCES ON CONCRETE PIPES AND PLATES
USED AS SEABED ARTIFICIAL REEF UNITS

1. INTRODUCTION

1.1 Motivation

In the past three decades in the United States, the population migration from inland areas to the coast has been significant. Growing coastal populations have been accompanied by a corresponding increase in recreational activities such as saltwater sport fishing. Limited fish populations in nearshore waters have become a concern for the tourism industry as well as local and federal governments.

Fishermen and scientists have known for many years the value of natural reefs as fish habitats. However, many offshore areas off the coastline of the United States lack natural geologic or coral structures which serve as spawning areas, shelter, and feeding grounds for marine plants and animals. In the past, mankind has successfully demonstrated its ability to supplement nature through scientific and technological advancement. From this capacity, extensive irrigation networks have turned arid lands throughout the world into productive farms. From the same capacity constructed artificial reefs have been developed.

Artificial reefs have been developed at selected
underwater sites to provide habitats for fisheries, thereby increasing the population of selected species. The inter-relationships among economic, biological, chemical, and technological aspects play important roles in the successful development of artificial reefs. Major concerns are with target species, site selection, material types, unit design and stability, construction cost, and the effectiveness of the reefs.

Japan, with its great demand for sea food, is the most advanced nation in the world in artificial reef technology. In Japan, artificial reefs have been employed to enhance commercial fisheries production for more than 200 years, and the national government has actively supported reef programs in recent years. Increased funding has accelerated reef research and development and has resulted in mass production and placement of carefully designed artificial reefs (Sheehy 1981).

Artificial reef development in the United States has proceeded at a slower pace. The demand for improved fisheries comes from the recreational sector rather than commercial fisheries. Accordingly, financial resources, as well as technical assistance from state or federal agencies, have been limited. Under these circumstances, scrap and surplus objects such as old vessels, tires, and concrete pipes, or rocks and wood have been most widely used as artificial reef materials. Recently, the U.S. Army Corps of Engineers and some scientists have shown their
interests in designed artificial reefs (Federal Research Report 1986; Grace 1987).

The factors considered in selecting reef materials are their availability, stability, cost, ease of assembling, handling and transporting, and impact on the environment. In a survey of the 167 reefs in Florida priority materials are vessels (30%), concrete products (17%), unique single items such as oil rigs (8%), and tires (6%), while the rest are mixtures of two or more materials (Seaman et al. 1985). The trend has been away from shorter-lived or less dense materials to durable and dense items. Surplus concrete products, which are abundant throughout the United States, are desirable as artificial reef units because they are inert and durable in sea water and relatively dense. Surplus concrete products which are readily available are pipes, hollow-core planks, and construction blocks.

The stability of deployed reef units deployed is a major concern in artificial reef development to provide assurances that the structure will remain at the prescribed site. The Waianae Artificial Reef off leeward Oahu in Hawaii was started in 1963 and received 3,802 metric tons of concrete pipe over the next nine years. Recent scuba surveys show that the concrete pipes at the Waianae site have been widely dispersed due to wave action and currents. Many of them have probably been swept into deeper waters (Brock et al. 1984). The movement of reef
units is generally accompanied by reef damage as well as destruction of plants and shells already settled on the reef surface.

Engineers must be able to evaluate the hydrodynamic forces on reef units in order to determine their stability. Several researchers have provided guidance in predicting wave forces on long, sealed pipes near the sea floor (Grace et al. 1979; Sarpkaya and Issacson 1981; Shaw 1979). However, short and open-ended pipes have not been examined in detail. To the same extent, little information for calculating wave loads on flat plates is available. Consequently, there is a definite need for wave force studies on concrete pipes and plates to determine their stability as artificial reef units.

1.2 Research Scope

This research examines wave-induced water kinematics and dynamics on two common concrete products, pipes and hollow core floor slabs, placed on the seabed. This research focuses on the behavior of an individual concrete pipe placed on the seabed, and the behavior of a concrete slab placed as the top layer of an open-stacked structures. The models are set up perpendicular to the incoming waves to induce the maximum accountable force coefficients.

Large pipe and plate models were built and examined to quantify various force coefficients for the products.
A 15 inch diameter by 46 inch long pipe model was examined in vertical and horizontal orientations. A four-inch thick by 25 inch wide plate was examined on top of a three and four layer open stack. Experiments were conducted at large scale ratios at the O.H. Hinsdale Wave Research Laboratory at Oregon State University. Water depths of 9.0 and 11.5 feet were included in the tests as well as wave periods from 1.3 to 10.6 seconds.

The wave-induced horizontal and vertical forces on the models were measured by strain gauge dynamometers during the experiment. Wave surface profiles and water particle velocities in the vicinity of the models were also measured. In addition, water kinematics were predicted from the measured wave height using linear wave theory.

With the measured and predicted inputs, the drag and inertia force coefficients were determined by the least square, Fourier, and the maximum value method using the Morison equation. Maximum force coefficients were also evaluated. The relationships between the force coefficients determined and the governing parameters, the Reynolds number and the Keulegan-Carpenter parameter, were investigated. The center of force and the phase lags of current and forces relative to the surface wave profile were also studied. Graphical and tabular results are presented to facilitate the design of prototype artificial reef structures.
2. THEORETICAL BACKGROUND

2.1 Wave Forces

The interaction of waves with an object may be divided into two different types of wave force problems. One is called "wave forces on small bodies" and is based on the assumption that the kinematics of the flow in the region near the object remain relatively unaffected. This phenomenon is observed when the ratio of the object dimension in the direction of wave propagation to wave length is small. In small bodies, the viscosity of the fluid is important and the loading behavior is characterized by skin friction drag and the pressure gradient caused by flow separation. The other type of interaction is known as "wave forces on large bodies." This phenomenon generally occurs when a structure spans more than about a fifth of the incident wave length. Significant scattering and diffraction of the incident waves are observed and the fluid is treated as inviscid. The wave forces on concrete pipes and plates studied in this research are treated as small body problems.

There are two subjects which are worth reviewing for a better understanding of wave loading on small bodies. One is the fundamental fluid mechanics of steady and unsteady flows past bodies. The other is concerned with wave theories which are used to predict the kinematics of fluid motion due to waves.
In steady flow, where the fluid velocity at any point remains constant, the in-line flow-induced force on a body is the drag force. The drag force consists of form drag and the skin friction drag and may be defined as:

\[ F_D = \rho \, C_D \, A \, U \, \frac{|U|}{2} \]  

(2.1)

where

- \( F_D \) = drag force
- \( C_D \) = drag coefficient
- \( \rho \) = mass density of fluid
- \( A \) = projected area normal to velocity
- \( U \) = velocity of fluid

In unsteady flow, where the fluid accelerates, the flow field is modelled as an inviscid ideal fluid. In the absence of viscosity, theoretically, no shear stress is developed by fluid passing a body. Also, no net pressure force can be expected in steady flow if the flow does not separate to form a wake. However, a hydrodynamic force, called an inertia force, is exerted on a body held in uniformly accelerating ideal fluid. This force is proportional to the acceleration and may be expressed as:

\[ F_I = \rho \, C_I \, V \, \frac{dU}{dt} \]  

(2.2)

where

- \( F_I \) = inertia force
- \( C_I \) = inertia coefficient
The inertia force consists of two forces. One is the buoyancy-like force due to the pressure gradient between upstream and downstream surfaces in an accelerating fluid. The force is equal to the product of the displaced mass and the fluid acceleration. The other force is due to the distortion of the flow around the body and is known as the added mass effect. Since both component forces are dependent on the mass, the inertia coefficient $C_I$ can be defined as $C_I = C_M + 1$, in which $C_M$ denotes the added mass coefficient. Added mass coefficients can be analytically determined by integrating the predicted pressure distribution over the surface of the body. Analytically, the added mass coefficient for an infinitely long cylinder is 1.0 and a sphere is 0.5.

The flow under waves is unsteady and oscillatory. A submerged body experiences acceleration of the flow around the body over a wave cycle. Initially, the fluid travels along the surface of the body and the separation of flow does not occur. As the fluid continues to flow with an acceleration for a period of time, a boundary layer develops and flow separation occurs. Since the flow under waves is oscillatory, the above process is reversed with each wave cycle. This reversal velocity creates an
interruption in flow around the body and the inertia of this disturbance may cause the observed phase lag in force measurements.

Morison et al. (1950) proposed a method of calculating wave forces on small bodies. The Morison equation defines that the force acting on a section of a pile due to wave motion is the sum of the drag and inertia force components. The drag force is exerted on a body subjected to a steady flow of a real fluid and the inertia force is due to uniformly accelerated flow of an ideal fluid. The Morison equation is expressed as:

\[ F = F_D + F_I \]  
\[ F = \rho C_D A U \frac{|U|}{2} + \rho C_I V \frac{du}{dt} \]

where \( F = \) total force on the body

Wave motion is an unsteady and oscillating flow of viscous fluid and therefore Equation 2.4 does not exactly reproduce the actual phenomenon. The drag and inertia coefficients, \( C_D \) and \( C_I \), in the equation are not necessarily constant throughout the wave cycle. However, the force coefficients are assumed constant and determined experimentally. To determine the coefficients \( C_D \) and \( C_I \), the measured wave induced forces on an object are related with either measured or calculated water particle velocities and acceleration of the flow around the object.
Various wave theories can be used to predict the water kinematics from a given wave height, wave period, and water depth. Since the Morison equation has two unknowns and one equation, special methods, which are described in Section 4.3, have been developed to quantify the coefficients.

The development of a theoretical description of surface wave behavior began with the introduction of linear wave theory by Airy in 1845 (Ippen 1966). Stokes later introduced a perturbation procedure for obtaining higher order theories which are the Stokes finite amplitude wave theories (Stokes 1847, 1880). Solitary wave theory and conoidal wave theory were also developed (Ippen 1966). With increased numerical work requiring a computer, significant advances have been made in the last two decades. The properties of a regular wave train can now be predicted with considerable accuracy utilizing stream function theory (Dean 1974). In this research linear wave theory is used to predict water kinematics because other studies have shown that peak velocities and pressures at the seabed are predicted equally well by finite amplitude and linear wave theories (Dean 1974).

2.2 Governing Parameters

The wave force on a unit length of cylinder may be expressed as a function of five wave, cylinder and fluid properties according to
\[ F = f (T, U_m, D, \rho, \nu) \]  \hspace{1cm} (2.3)

where

- \( F \) = force per unit length of cylinder
- \( T \) = wave period
- \( U_m \) = maximum horizontal velocity
- \( D \) = cylinder diameter
- \( \rho \) = mass density of fluid
- \( \nu \) = kinematic viscosity of fluid

Using \( \rho, D, \) and \( T \) for the repeating variables of mass, length, and time, respectively, dimensional analysis reduces the number of dimensionless variables to two (five characteristic parameters minus three basic dimensions).

\[
\frac{F}{\rho U_m^2 D} = f \left( \frac{U_m T}{D}, \frac{U_m D}{\nu} \right) \hspace{1cm} (2.4)
\]

where

- \( \frac{U_m T}{D} \) = Keulegan-Carpenter parameter (KC)
- \( \frac{U_m D}{\nu} \) = Reynolds number (Re)

Combining with the Morison equation yields

\[ C_D = f_1 (KC, Re) \]  \hspace{1cm} (2.5)

\[ \frac{C_I}{KC} = f_2 (KC, Re) \]  \hspace{1cm} (2.6)

The relationship between the force coefficients and the
dimensionless parameters can be extended to the lift force and expressed as:

\[ (C_D, C_I, C_L, \ldots) = f(KC, Re) \] (2.7)

Keulegan and Carpenter (1958) first related \( C_D \) and \( C_I \) as functions of \( KC \) and \( Re \) using experimental data from a cylinder placed at the node point of a standing wave where the fluid motion was sinusoidal and horizontal. Sarpkaya (1975) used a U-tube oscillator and plotted the force coefficients as functions of the period parameter.

Sarpkaya (1981) showed that the maximum force coefficient, which is determined by the absolute maximum force and the velocity within a wave cycle (see Sec. 4.3), is closely related to the \( KC \) parameter. Sarpkaya also stated that the drag force coefficient behaves in a similar fashion to the maximum force coefficient in the drag-dominated region. Grace (1979) carried out a field experiment where a cylinder was placed on the ocean bottom and the maximum horizontal forces and velocities were measured. He used a measured parameter, \( \Phi \), which is defined by

\[ \Phi = \frac{U_m^2}{D \frac{dU}{dt}} \] (2.8)

For simple harmonic oscillations, \( \Phi \) is the \( KC \) number divided by \( 2\pi \). The results of Sarpkaya and Grace show that
the measured maximum force coefficients are strongly
dependent on the KC number and vary inversely.

Little research has been conducted on wave forces on
three-dimensional objects lying on the seabed. Kim et al.
(1981) conducted large scale experiments at the O.H.
Hinsdale Laboratory to determine force coefficients for
three-dimensional tire configurations which are intended
for use as artificial reefs. The results showed that the
force coefficients depend both on the Reynolds number and
the Keulegan-Carpenter parameter with a more definitive
dependence on the period parameter. The maximum force
coefficients exponentially decreased as the period para-
meter increased and inertia forces dominated for all tire
configurations.
3. EXPERIMENTAL APPARATUS & PROCEDURES

3.1 Research Facilities

The concrete wave channel at the O.H. Hinsdale Wave Research Laboratory is 342 feet long, 12 feet wide, and 15 feet deep. The channel deepens to 18 feet at the wave board and shoals on a sloped beach at the opposite end of the channel. Three and one-half feet of channel wall freeboard extends above the ground level. On the forward side of the wave board, a sloping beach composed of 12-foot-square concrete panels can be built with varying slopes and beach lengths. For this research a beach of a constant slope of one on twelve and 120 feet long was built. The location of the model installation was 113 feet from the wave board and 60 feet from the toe of the beginning point of the beach. During the experiment the null zone of this particular beach configuration was identified at about 18-24 feet ahead of the beach (see Fig. 3-1). The null zone is a spot on the wave channel floor where light drifting particles experience zero net drift under the influence of continuous wave action.

The wave board is a 5-ton aluminum weldment that is 18 feet high and 12 feet wide. The board is hinged at the bottom of the channel and operates with water on one side only. Polypropylene wipers on the board sliding against the stainless steel plates of the wall seal the sides. A knife seal is located at the base of the board. On the
Fig. 3-1. Wave Channel Plan & Profile
dry side of the board a servo-controlled hydraulic actuator built by MTS Corporation of Minneapolis, Minnesota, is pin connected at 10 feet from the bottom. The actuator is powered by a 150 hp electrically-driven hydraulic pump that generates 3,000 psi and 76 gallons per minute. This system is controlled by a voltage signal generated by a periodic function generator or by a Program Data Processor (PDP) 11/23 computer of Digital Equipment Corporation at the laboratory. The function generator is used for periodic wave generation and the computer for random waves. The system is powerful enough to make waves up to five feet high and can generate a wave period up to 10 seconds long.

Data is collected in digital form by the PDP 11/23 and stored on nine track magnetic tape. Up to 64 channels of data can be collected. The data are transferred to IBM-AT floppy disks for further analysis.

3.2 Experiments

The experiment took place at the O.H. Hinsdale Wave Research Laboratory at Oregon State University from June to October of 1985. The experiment was in four parts: two with the pipe model and two with the plate model. With an exception for Part III, each part consisted of two experiments with the same setup but at different water depths. A summary of the experiments is shown in Table 3-1.
Table 3-1. Experiment Parts

<table>
<thead>
<tr>
<th>Parts</th>
<th>Water Depth</th>
<th>Run No.</th>
<th>Experiment Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>Part I</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pipe Model</td>
<td>11.5 ft</td>
<td>001-016</td>
<td>8/19/85</td>
</tr>
<tr>
<td>(Vertical Orientation)</td>
<td>9.0 ft</td>
<td>017-030</td>
<td>8/21/85</td>
</tr>
<tr>
<td>Part II</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pipe Model</td>
<td>9.0 ft</td>
<td>031-048</td>
<td>9/06/85</td>
</tr>
<tr>
<td>(Horizontal Orientation)</td>
<td>11.5 ft</td>
<td>049-064</td>
<td>9/06/85</td>
</tr>
<tr>
<td>Part III</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Plate Model</td>
<td>11.5 ft</td>
<td>065-083</td>
<td>10/07/85</td>
</tr>
<tr>
<td>(Four Layers)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Part IV</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Plate Model</td>
<td>11.5 ft</td>
<td>084-100</td>
<td>10/09/85</td>
</tr>
<tr>
<td>(Three Layers)</td>
<td>9.0 ft</td>
<td>101-114</td>
<td>10/09/85</td>
</tr>
</tbody>
</table>

Notes:

- There are 10 wave periods per run.
- There are 256 data points per wave period.
- There are 9 channels of data.
- There are 256 pre-run zero values per channel.
The tested wave conditions were the Dean's Stream Function cases identified in Tables 3-2 and 3-3. Wave periods ranged from 1.3 to 10.6 seconds and the predicted wave heights from 0.4 to 5.4 feet. A total of 114 test runs were completed. Each experiment was subjected to 14 or as many as 19 runs depending on the number of repeated runs which were carried out in the occasions of instrumental problems. Each run recorded measurements for ten consecutive waves.

The water temperature ranged from 50°-58°F throughout the experiment. The average temperature of 54°F is used in determining the fluid property constants. The kinematic viscosity of water at 54°F is $1.25 \times 10^{-5}$ ft$^2$/sec and the density is 1.939 slugs/ft$^3$.

**Part I: Vertical Pipe**

The model pipe sits vertically with its flange side on the wave channel floor as in Figures 3-2 and 3-3. The pipe was pin connected at three locations by the force measuring dynamometers; two near the bottom and one near the top. The bottom clearance between the pipe and the floor was kept at a minimum (approximately $\frac{1}{4}$ inches).

**Part II: Horizontal Pipe**

The model pipe lay on the floor with the centerline in parallel with the incoming wave crests as shown in Figures 3-4 and 3-5. The pipe was held by the force
<table>
<thead>
<tr>
<th>Dean's Stream Function Case No.</th>
<th>$h/L_0$</th>
<th>$L_0$</th>
<th>$T$</th>
<th>$H/h$</th>
<th>$H/h(H/h)$</th>
<th>$f$</th>
</tr>
</thead>
<tbody>
<tr>
<td>4-A</td>
<td>0.02</td>
<td>575.0</td>
<td>10.60</td>
<td>0.195</td>
<td>2.24</td>
<td>0.094</td>
</tr>
<tr>
<td>5-A</td>
<td>0.05</td>
<td>230.0</td>
<td>6.70</td>
<td>0.195</td>
<td>2.24</td>
<td>0.149</td>
</tr>
<tr>
<td>5-B</td>
<td>0.05</td>
<td>230.0</td>
<td>6.70</td>
<td>0.390</td>
<td>4.49</td>
<td>0.149</td>
</tr>
<tr>
<td>6-A</td>
<td>0.10</td>
<td>115.0</td>
<td>4.74</td>
<td>0.183</td>
<td>2.11</td>
<td>0.211</td>
</tr>
<tr>
<td>6-B</td>
<td>0.10</td>
<td>115.0</td>
<td>4.74</td>
<td>0.366</td>
<td>4.21</td>
<td>0.211</td>
</tr>
<tr>
<td>7-A</td>
<td>0.20</td>
<td>57.5</td>
<td>3.35</td>
<td>0.156</td>
<td>1.80</td>
<td>0.298</td>
</tr>
<tr>
<td>7-B</td>
<td>0.20</td>
<td>57.5</td>
<td>3.35</td>
<td>0.313</td>
<td>3.59</td>
<td>0.298</td>
</tr>
<tr>
<td>7-C</td>
<td>0.20</td>
<td>57.5</td>
<td>3.35</td>
<td>0.469</td>
<td>5.39</td>
<td>0.298</td>
</tr>
<tr>
<td>8-A</td>
<td>0.50</td>
<td>23.0</td>
<td>2.12</td>
<td>0.084</td>
<td>0.97</td>
<td>0.472</td>
</tr>
<tr>
<td>8-B</td>
<td>0.50</td>
<td>23.0</td>
<td>2.12</td>
<td>0.168</td>
<td>1.93</td>
<td>0.472</td>
</tr>
<tr>
<td>8-C</td>
<td>0.50</td>
<td>23.0</td>
<td>2.12</td>
<td>0.252</td>
<td>2.90</td>
<td>0.472</td>
</tr>
<tr>
<td>9-A</td>
<td>1.0</td>
<td>11.5</td>
<td>1.50</td>
<td>0.043</td>
<td>0.49</td>
<td>0.667</td>
</tr>
<tr>
<td>9-B</td>
<td>1.0</td>
<td>11.5</td>
<td>1.50</td>
<td>0.085</td>
<td>0.98</td>
<td>0.667</td>
</tr>
<tr>
<td>9-C</td>
<td>1.0</td>
<td>11.5</td>
<td>1.50</td>
<td>0.128</td>
<td>1.47</td>
<td>0.667</td>
</tr>
<tr>
<td>9-D</td>
<td>1.0</td>
<td>11.5</td>
<td>1.50</td>
<td>0.170</td>
<td>1.95</td>
<td>0.667</td>
</tr>
</tbody>
</table>

$h = \text{water depth}$

$L_0 = \text{wave length in deep water}$

$T = \text{wave period}$

$H = \text{wave height}$

$f = \text{frequency}$
Table 3-3. Experimental Wave Conditions II (h=9.0 feet)

<table>
<thead>
<tr>
<th>Dean's Stream Function Case No.</th>
<th>$h$</th>
<th>$L_0$</th>
<th>$11.5\frac{h}{L_0}$</th>
<th>$\sqrt{\frac{L_0}{5.12}}$</th>
<th>$H$</th>
<th>$h(H/h)$</th>
<th>$1/T$</th>
</tr>
</thead>
<tbody>
<tr>
<td>4-A</td>
<td>0.02</td>
<td>450.0</td>
<td>9.375</td>
<td>0.195</td>
<td>1.76</td>
<td>0.107</td>
<td></td>
</tr>
<tr>
<td>5-A</td>
<td>0.05</td>
<td>180.0</td>
<td>5.929</td>
<td>0.195</td>
<td>1.76</td>
<td>0.169</td>
<td></td>
</tr>
<tr>
<td>5-B</td>
<td>0.05</td>
<td>180.0</td>
<td>5.929</td>
<td>0.390</td>
<td>3.51</td>
<td>0.169</td>
<td></td>
</tr>
<tr>
<td>6-A</td>
<td>0.10</td>
<td>90.0</td>
<td>4.193</td>
<td>0.183</td>
<td>1.65</td>
<td>0.238</td>
<td></td>
</tr>
<tr>
<td>6-B</td>
<td>0.10</td>
<td>90.0</td>
<td>4.193</td>
<td>0.366</td>
<td>3.30</td>
<td>0.238</td>
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</tr>
<tr>
<td>7-A</td>
<td>0.20</td>
<td>45.0</td>
<td>2.965</td>
<td>0.156</td>
<td>1.41</td>
<td>0.337</td>
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<tr>
<td>7-B</td>
<td>0.20</td>
<td>45.0</td>
<td>2.965</td>
<td>0.313</td>
<td>2.81</td>
<td>0.337</td>
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</tr>
<tr>
<td>7-C</td>
<td>0.20</td>
<td>45.0</td>
<td>2.965</td>
<td>0.469</td>
<td>4.22</td>
<td>0.337</td>
<td></td>
</tr>
<tr>
<td>8-A</td>
<td>0.50</td>
<td>18.0</td>
<td>1.875</td>
<td>0.084</td>
<td>0.76</td>
<td>0.533</td>
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</tr>
<tr>
<td>8-B</td>
<td>0.50</td>
<td>18.0</td>
<td>1.875</td>
<td>0.168</td>
<td>1.51</td>
<td>0.533</td>
<td></td>
</tr>
<tr>
<td>8-C</td>
<td>0.50</td>
<td>18.0</td>
<td>1.875</td>
<td>0.252</td>
<td>2.27</td>
<td>0.533</td>
<td></td>
</tr>
<tr>
<td>9-A</td>
<td>1.0</td>
<td>9.0</td>
<td>1.326</td>
<td>0.043</td>
<td>0.38</td>
<td>0.754</td>
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</tr>
<tr>
<td>9-B</td>
<td>1.0</td>
<td>9.0</td>
<td>1.326</td>
<td>0.085</td>
<td>0.77</td>
<td>0.754</td>
<td></td>
</tr>
<tr>
<td>9-C</td>
<td>1.0</td>
<td>9.0</td>
<td>1.326</td>
<td>0.128</td>
<td>1.15</td>
<td>0.754</td>
<td></td>
</tr>
</tbody>
</table>

$h$ = water depth

$L_0$ = wave length in deep water

$T$ = wave period

$H$ = wave height

$f$ = frequency
Fig. 3-2. Vertical Pipe and the Wave Board in the back

Fig. 3-3. Vertical Pipe and the Beach
Fig. 3-4. Horizontal Pipe View from the Beach

Fig. 3-5. Horizontal Pipe View from the Wave Board
dynamometers at three locations; two at the flange side and one at the other end. The clearance between the pipe and the floor was from \( \frac{1}{4} \) to \( \frac{1}{2} \) inches.

**Part III: Four Plate Layers**

Three layers of steel beams were open-stacked from the floor with unit void ratios, and they were firmly bolted down to the floor (see Fig. 3-6). This setup simulated a situation where hollow-core concrete slabs are stacked in arrays as artificial reefs. Each layer was four inches thick, 25 inches wide and the length was as long as the wave channel width. The fourth layer was built with 3/4-inch plywood with the middle section vacant for the plate model to be inserted. The total blocking area, including the gap between the layers, created by the four layers was 21.7 percent of the water cross-sectional area at the water depth of 11.5 feet. The center-placed plate model was pin-connected to the dynamometers. The gaps between the plate and the attached fourth layer were about \( \frac{1}{4} \) inches.

**Part IV: Three Plate Layers**

Experiment IV used the same setup as Experiment III except that the total number of layers was three instead of four (see Fig. 3-7). Hence, the plate model was placed 8 inches lower than in Experiment III. The purpose of the experiment was to investigate the significance of the
stack height on the upper plate forces. The total blocking areas imposed by this three-layer structure was 15.9 percent and 20.4 percent of the water cross-sectional area at water depths of 11.5 feet and 9.0 feet, respectively.

3.3 Models

Two common concrete products that can be used as artificial reef components are pipes and hollow core slabs. A survey of concrete pipe products reveals that the pipes are manufactured with various inside diameters, lengths, wall thickness and bell formations to meet the application of individual projects (Spec Industries, 1985). One common pipe size, 7.5 feet long and 2.0 feet in diameter, is selected as the prototype. A similar survey shows the thickness of hollow core slabs varying from 6 to 12 inches with the width of 48 inches (Cement & Concrete Products Industries of Hawaii, 1984). An eight inch thick slab is selected as the prototype. Considering the wave channel dimensions, a prototype to model ratio of approximately 2:1 is chosen for both pipe and slab. Note, however, that the scale ratio will be a function of the actual prototype product dimensions selected for a specific application. One pipe model and one plate model were constructed and non-dimensionalized relative to the model.

The natural frequency of the models attached to the dynamometer apparatus was about 13 Hertz in air, whereas
Fig. 3-6. Four Layers Setup (Top View)

Fig. 3-7. Three Layers Setup
wave frequencies tested ranged from 0.1 to 0.8 hertz. Resonance occurrence was not expected.

**Pipe Model**

The pipe model was made of two equal length but of different diameter heavy-duty PVC pipes with wall thicknesses of 0.28 inches. The smaller pipe was inserted into the larger pipe and the two pipes were held together by wood rings and spacers. In an effort to measure small forces, the model voids between the outer and inner walls were filled with closed-cell styrofoam so they would be neutrally buoyant when submerged in water during the experiments. The two layer method of constructed was used to provide the same geometry as concrete pipes while allowing a considerable reduction in weight. Thus, the dynamometers were designed to be sensitive to the wave induced load, rather than over designed to support the dead weight of the pipe. To provide extra stiffness to the model the dynamometers were connected at places where the plugs and spacers were inserted. A wooden bell, turned on a lathe, was attached at one end. The wood was treated with water sealant to prevent water penetration. The completed model is shown in Figure 3-8.

**Plate Model**

The plate model was made of 3/4-inch thick plywood. Two equal-sized plywood pieces were put together with a
Model to Prototype Scale: Approx. 1 to 2

Pipe length: 46.3 inches
Inside Diameter: 12.3 inches
Outside Diameter: 15.3 inches
Wall Thickness: 1.5 inches
Bell Diameter: 18.25 inches
Bell Depth: 2.0 inches
Projected Area: 5.03 sq. ft.
Enclosed Volume: 4.95 cu. ft.
Weight in Air: 68.0 lb.

Fig. 3-8. Pipe Model

Plate Thickness: 4.25 inches
Width (=diameter): 25.50 inches
Length: 30.00 inches
Projected Area: 0.89 sq.ft.
Enclosed Volume: 1.85 cu.ft.
Weight in Air: 75.0 lb.

Fig. 3-9. Plate Model
rigid wood frame in between. All wood materials were
treated with water sealant. The sides where the dynamome-
ter were to be connected were strengthened by attaching
steel angles. The completed model with dimensions is shown
in Figure 3-9.

3.4 Measurements

Three types of measurements, wave profile, current,
and force, were recorded using a sonic profiler (see Figs.
3-10 and 3-11), a current meter (Figs. 3-12 and 3-13), and
strain gauge dynamometers (Fig. 3-14 and 3-15). Data
collection required nine separate channels. One channel
was used for measuring the wave surface profile, two for
the horizontal and vertical velocity of the current, and
six for the force measurements (three horizontal and three
vertical). Table 3-4 identifies each instrument and its
channels. Figures 3-16 and 3-17 present the installation
layouts of the instruments. For each channel, a total 2560
data points were read per test run. This corresponds to
ten consecutive waves sampled at 256 data point per wave
cycle. A sample measurement is shown in Figure 3-18. In
addition, a 6-channel pen plotter was used to record water
surface, both velocities, and three horizontal forces for
a visual check of each experimental run. This record
became useful later in the data analysis as a reference to
check magnitudes and trends of the digital data recorded
by computer.
Fig. 3-10. Sonic Profiler Head & Cover

Fig. 3-11. Sonic Profiler attached to the Bridge
Fig. 3-12. Marsh McBirney Current Meter Set

Fig. 3-13. Current Meter Probe in Place
Fig. 3-14. Larger Dynamometer attached to Vertical Pipe

Fig. 3-15. Smaller Dynamometer in Place
Table 3-4. Measurement Channel Identification

<table>
<thead>
<tr>
<th>Ch #</th>
<th>Instrument</th>
<th>Measurements</th>
<th>Mounted</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ch #1</td>
<td>Dynamometer #1</td>
<td>Ver. Force</td>
<td>East side of model</td>
</tr>
<tr>
<td>Ch #2</td>
<td>Dynamometer #1</td>
<td>Hor. Force</td>
<td>East side of model</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>( For Pipe Model )</td>
</tr>
<tr>
<td>Ch #3</td>
<td>Dynamometer #2</td>
<td>Ver. Force</td>
<td>West side bottom</td>
</tr>
<tr>
<td>Ch #4</td>
<td>Dynamometer #2</td>
<td>Hor. Force</td>
<td>West side bottom</td>
</tr>
<tr>
<td>Ch #5</td>
<td>Dynamometer #3</td>
<td>Ver. Force</td>
<td>West side top</td>
</tr>
<tr>
<td>Ch #6</td>
<td>Dynamometer #3</td>
<td>Hor. Force</td>
<td>West side top</td>
</tr>
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<td></td>
<td></td>
<td></td>
<td>( For Plate Model )</td>
</tr>
<tr>
<td>Ch #3</td>
<td>Dynamometer #2</td>
<td>Ver. Force</td>
<td>West to wave board</td>
</tr>
<tr>
<td>Ch #4</td>
<td>Dynamometer #2</td>
<td>Hor. Force</td>
<td>West to wave board</td>
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<tr>
<td>Ch #5</td>
<td>Dynamometer #3</td>
<td>Ver. Force</td>
<td>East to beach</td>
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<tr>
<td>Ch #6</td>
<td>Dynamometer #3</td>
<td>Hor. Force</td>
<td>East to beach</td>
</tr>
<tr>
<td>Ch #7</td>
<td>Marsh Mcbirney</td>
<td>Ver. Current</td>
<td>East wall</td>
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<td>Marsh Mcbirney</td>
<td>Hor. Current</td>
<td>East wall</td>
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<tr>
<td>Ch #9</td>
<td>Sonic Profiler</td>
<td>Wave Profile</td>
<td>Over Bridge</td>
</tr>
</tbody>
</table>
Fig. 3-16. Instruments in Position for Pipe Model

Fig. 3-17. Instruments in Position for Plate Model
RUN.006   CASE 7-A

Part I Vertical Pipe (h=11.5ft)

T = 3.35 sec.

Volts 0.0
0.2
-0.2

Ver. Force

Volts 0.0
1.0
-1.0

Hor. Force

Volts 0.0
0.1
-0.1

Ver. Force

Volts 0.0
1.0
-1.0

Hor. Force

Fig. 3-18. Measurements Sample
Fig. 3-18. Measurements Sample (continued)
**Instrumentation**

Wave height was measured by a sonic profiler placed directly above the model and about five feet above the still water level. This instrument senses distance by measuring the delay time for a pulsed acoustic signal to propagate to the water surface and reflect back to the profiler. The measurements repeat at 60 hertz.

The water kinematics in the vicinity of the model were measured by a Marsh McBirney Model 115 electro-magnetic current meter. For the vertical pipe experiment, the current meter was placed as close to the geometric center elevation of the model as possible. In other parts of the experiment, the meter was placed up to 1.5 feet above the center elevation of the models. Later in data analysis, all the measured kinematics were extrapolated to the center of force elevation using linear wave theory.

Force measurements were done by three force dynamometers fabricated from aluminum rods. The specifications of the rods were determined for a design wave condition of a three-second period and a four-foot wave height. The maximum horizontal force predicted by the Morison equation with the drag coefficient of 1.2 and the inertia coefficient of 2.0 was about 48 pounds. Aluminum 6061-T6, which has the modulus of elasticity of 10,000 ksi and the yield strength of 26 ksi, was used. Each end of the rods was milled to four orthogonal faces spaced at 2.5 inches. Two
faces were used for vertical force measurement and two for horizontal forces. Strain gauges were glued to the faces and protected with a water proof coating. Force measurements are made by reading changes in voltage level across the strain gauges, responding to bending by external forces.

The models were fixed at three points by the force measuring rods; two smaller rods on one side and one larger rod on the other. The two smaller rods were attached to the model by moment-free spherical bearings and the other ends were bolted to the channel side wall. The larger rod was connected to the model by a horizontal rotation-free pillow block and the other end to the wall by a transverse movement-free device.

**Instrument Calibration**

The sonic profiler calibration is 64 inches per 10 volts which is equivalent to 0.5333 feet per one volt. The Marsh-McBirney current meter was calibrated immediately following the experiment by Ramsden (1987). The vertical current calibration was 1.79 feet per second per volt and the horizontal calibration was 1.83. The manufacturer's calibration of the meter is 2.0 feet per second per volt for both currents.

All three force measuring rods were calibrated in air using combinations of three-pound and five-pound weights. The calibration was done by increasing the weight in
increments of three and five pounds up to a total of 50 pounds, and then by decreasing back to zero. The increasing and decreasing slopes overlapped on a straight line. Except for Part III, the three dynamometers were pre- and post-calibrated. The average force measurement for the larger rod was 20.45 pounds per volt and 19.73 for the smaller rods. The post-calibration coefficients were used in data analysis. A summary of the instrument calibration is presented in Table 3-5.

Consistency of Force Measurement

The repeatability of the force measurements was tested many times. With the pipe model mounted in a vertical orientation, known forces of about 8, 16, and 25 pounds were applied horizontally at the center, the upper half, and the lower half locations, both toward the wave board and the beach directions. The same procedures were repeated with about 15 pounds of transverse load applied. The magnitude of the applied weights was compared with the total measured force by the dynamometers, and the elevation of the applied load was checked with the resultant force elevation. The vertical force measurement was examined by applying the same known weights to the top center of the pipe model. The results show that the horizontal force measurements in both directions were the same either with or without side loads. The resultant force elevation is predictable within two percent of the
Table 3-5. Instrument Calibration Coefficients

<table>
<thead>
<tr>
<th>Runs</th>
<th>Part I</th>
<th>Part II</th>
<th>Part III</th>
<th>Part IV</th>
</tr>
</thead>
<tbody>
<tr>
<td>001-030</td>
<td>031-064</td>
<td>065-083</td>
<td>084-114</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Vertical / Horizontal Forces (lb/volt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ch #1</td>
</tr>
<tr>
<td>Pre Cal</td>
</tr>
<tr>
<td>Post Cal</td>
</tr>
<tr>
<td>Ch #2</td>
</tr>
<tr>
<td>Pre Cal</td>
</tr>
<tr>
<td>Post Cal</td>
</tr>
<tr>
<td>Ch #3</td>
</tr>
<tr>
<td>Pre Cal</td>
</tr>
<tr>
<td>Post Cal</td>
</tr>
<tr>
<td>Ch #4</td>
</tr>
<tr>
<td>Pre Cal</td>
</tr>
<tr>
<td>Post Cal</td>
</tr>
<tr>
<td>Ch #5</td>
</tr>
<tr>
<td>Pre Cal</td>
</tr>
<tr>
<td>Post Cal</td>
</tr>
<tr>
<td>Ch #6</td>
</tr>
<tr>
<td>Pre Cal</td>
</tr>
<tr>
<td>Post Cal</td>
</tr>
</tbody>
</table>

Ch #7 Vertical Current 1.79 (fps/volt)

Ch #8 Horizontal Current 1.83 (fps/volt)

Ch #9 Surface Profile 0.53333 (ft/volt)

** Post calibration was not done due to time conflict with other experiments scheduled at the wave channel.
actual load point. The vertical measurement shows about
four percent less than the actual load. In general,
deviations of measured forces from actual loads were
greatest when the calibration loads were applied to the
upper quarter of the model. Deviations were greater when
the applied loads were smaller, and the post-calibration
coefficients produced better results than the pre-calibra-
tion coefficients. For this reason, the post-calibration
coefficients were used in the data analysis.
4. DATA ANALYSIS

4.1 Procedures

Data processing was accomplished as diagrammed in Figure 4-1. Input data included measured wave profile, current, and forces. The laboratory data was reduced and smoothed by an IBM-PC/AT with the methods described in Section 4.2. From the smoothed data, wave height was determined, and then the water kinematics were predicted from the wave height, water depth, and wave period using linear wave theory. The acceleration was determined by the slope of measured velocities. Depending on the smoothness of the velocity measurements, either three, five or seven data points can be used to compute the slope of the mid-data point. The five-point slope method is used in this study, wherein the acceleration of the third data point is calculated by the slope between the first and the fifth data point.

Drag and inertia force coefficients are determined by three different methods described in Section 4.3. The coefficients were calculated once using the predicted kinematics and again using the measured kinematics. Maximum force and lift force coefficients were calculated using measured kinematics and forces. The center of force for the pipe experiments was also determined. Finally, the phase lags of measured velocity and forces relative to the wave crest were examined.
Fig. 4-1. Data Analysis Procedure
4.2 Data Smoothing

The experimental data were initially recorded on disks by the PDP-11/23 minicomputer and then were transferred to digital magnetic tape. The data were subsequently transferred to IBM-PC/AT floppy disks for analysis. There were a total of 114 runs, where each run included nine channels of data for ten consecutive waves totaling 2560 data points per channel. The data also included 114 zero-reading references which were read before each run for all nine channels. Each zero references totaled 256 data points.

Much effort was spent converting the laboratory data into data which could be used by the software that was developed to interpret the data. The procedure is shown in the block diagram in Figure 4-2. Many computer programs and subroutines developed by D. R. Standley were used for data smoothing.

Bad Points

The initial task was to remove bad points recorded in water surface profile data caused by the acoustic signal going off-scale. The program BADPTS can correct most such errors, but some are transformed to other bad points, which could result in incorrect predictions of wave heights. The method adopted for the data interpretation is to correct the bad points by BADPTS first and then view
Laboratory Data
- Wave Profile, Current, Force
- 10 Waves per Run

Remove Bad Points from Surface Profile
- Use software FIXDTA

Noise Filtering by Fast Fourier Trans.
- Filter 8 Waves per Run
- From 3rd to 10th Wave

Wave Selection
- Check 6 Waves (3rd to 8th)
- Coefficient of Variance of Period and Amplitude of Wave Height, Velocity, Force
- Select 3 to 6 Best Consecutive Waves

Fig. 4-2. Data Smoothing Procedure
the data on the monitor to detect the remaining badpoints. These secondary bad points were fixed by the software FIXDTA which uses interpolation or cubic fit methods. This was necessary for only about six percent of the total runs.

Noise Frequency

All the data were filtered at 20 hertz at the time of recording, with the exception of the wave profile. However, the presence of lower frequency noise in the measurements of small magnitude made data analysis difficult. Filtering the noise from the surface profile and the measured velocity was essential because the maximum values and their phases were to be determined from data. The noise frequency can be expressed as:

\[ f_n = \frac{1}{\delta t} \cdot n \]  

(4.1)

where

- \[ f_n \] = noise frequency
- \[ \delta t \] = time increment
- \( n \) = noise constant

The noise frequency ranged from 1.2 to 4.8 hertz and the noise constant was about 0.02. The Fast Fourier Transform method was used to transform time domain data to frequency domain data to determine the noise frequency. Since the length of a time series must be a power of two,
a total of 2048 data points, equivalent to eight waves, were examined. Due to the reasons discussed in the next section, the two lead waves of the ten waves recorded were discarded and the rest, which began with the third wave and ended with the tenth wave, were filtered. All nine channels readings were filtered and then the results were inverted back to the time domain data.

Wave Selection

Although measurements for ten sequential waves were recorded, three to six waves were selected for data analysis. After reviewing data from several runs it became apparent that some of the lead waves were less consistent than the following waves in their wave height and period. It was also noticed that even when the surface profile became uniform, the velocity and force measurements near the models were not stabilized. The measurements of trailing waves also fluctuated for some records. Disruption of tailing waves was probably due to the wave channel back current. Both the lead and trailing wave consistency problems were less severe with the shallow and intermediate water wave conditions than with the deep water conditions. Considering these facts, the six consecutive waves in the middle, beginning with the third wave and ending with the eighth wave were used for data analysis.

Further effort was made to eliminate inconsistent
waves in the middle six. The coefficients of variation of measurements, which were obtained by dividing the standard deviation of magnitude and period of the three measurements (wave height, horizontal velocity, and horizontal force) by the mean values, were calculated for all runs. Any run data with the coefficient of variation of any kind greater than 0.05 was reevaluated to remove further inconsistent waves. The coefficients of variation of all possible combinations of three to six consecutive waves were determined. There are ten such combinations and the one with the lowest maximum coefficient value was selected for data analysis. Table 4-1 is a summary of waves selected for analysis for each run of Part I of the experiment. The coefficients of variation of the wave height, the maximum horizontal velocity, and the total horizontal force are also included in the table.

The main computer program, PRGM 8, was developed in Fortran language for the computation. The program, which is attached in Appendix B, includes several subroutines from LABTEST, a program used previously for data analysis of similar experiments conducted at the O.H. Hinsdale Wave Research Laboratory.

**Measured Velocity Modification**

The velocity measured by the current meter was modified twice. The first modification converted the measured velocity at the water depth of the current meter
<table>
<thead>
<tr>
<th>Run No.</th>
<th>Stream No.</th>
<th>T</th>
<th>H</th>
<th>No. of Waves Analyzed</th>
<th>Beginning Data Point</th>
<th>Wave Height</th>
<th>Variance Coefficient</th>
<th>Current Force</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>(sec)</td>
<td>(ft)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td>049</td>
<td>4</td>
<td>10.600</td>
<td>1.55</td>
<td>6</td>
<td>625</td>
<td>0.003</td>
<td>0.035</td>
<td>0.017</td>
</tr>
<tr>
<td>050</td>
<td>5</td>
<td>6.700</td>
<td>2.25</td>
<td>6</td>
<td>564</td>
<td>0.010</td>
<td>0.019</td>
<td>0.010</td>
</tr>
<tr>
<td>051</td>
<td>5</td>
<td>6.700</td>
<td>2.94</td>
<td>6</td>
<td>773</td>
<td>0.009</td>
<td>0.020</td>
<td>0.010</td>
</tr>
<tr>
<td>052</td>
<td>6</td>
<td>4.740</td>
<td>2.02</td>
<td>6</td>
<td>748</td>
<td>0.008</td>
<td>0.013</td>
<td>0.016</td>
</tr>
<tr>
<td>053</td>
<td>6</td>
<td>4.740</td>
<td>4.03</td>
<td>6</td>
<td>597</td>
<td>0.007</td>
<td>0.023</td>
<td>0.015</td>
</tr>
<tr>
<td>054</td>
<td>7</td>
<td>3.350</td>
<td>1.63</td>
<td>6</td>
<td>649</td>
<td>0.008</td>
<td>0.022</td>
<td>0.011</td>
</tr>
<tr>
<td>055</td>
<td>7</td>
<td>3.350</td>
<td>3.48</td>
<td>6</td>
<td>530</td>
<td>0.008</td>
<td>0.035</td>
<td>0.011</td>
</tr>
<tr>
<td>056</td>
<td>7</td>
<td>3.350</td>
<td>4.58</td>
<td>6</td>
<td>689</td>
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<td>0.015</td>
<td>0.022</td>
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<tr>
<td>057</td>
<td>8</td>
<td>2.120</td>
<td>1.00</td>
<td>6</td>
<td>547</td>
<td>0.017</td>
<td>0.033</td>
<td>0.011</td>
</tr>
<tr>
<td>058</td>
<td>8</td>
<td>2.120</td>
<td>1.86</td>
<td>4</td>
<td>903</td>
<td>0.010</td>
<td>0.020</td>
<td>0.010</td>
</tr>
<tr>
<td>059</td>
<td>8</td>
<td>2.120</td>
<td>2.79</td>
<td>3</td>
<td>980</td>
<td>0.002</td>
<td>0.009</td>
<td>0.013</td>
</tr>
<tr>
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<td>9</td>
<td>1.500</td>
<td>0.47</td>
<td>3</td>
<td>745</td>
<td>0.012</td>
<td>0.065</td>
<td>0.058</td>
</tr>
<tr>
<td>061</td>
<td>9</td>
<td>1.500</td>
<td>0.89</td>
<td>3</td>
<td>1263</td>
<td>0.025</td>
<td>0.029</td>
<td>0.015</td>
</tr>
<tr>
<td>062</td>
<td>9</td>
<td>1.500</td>
<td>1.27</td>
<td>3</td>
<td>577</td>
<td>0.018</td>
<td>0.015</td>
<td>0.011</td>
</tr>
<tr>
<td>063</td>
<td>9</td>
<td>1.500</td>
<td>1.45</td>
<td>3</td>
<td>1418</td>
<td>0.020</td>
<td>0.020</td>
<td>0.025</td>
</tr>
<tr>
<td>064</td>
<td>9</td>
<td>1.500</td>
<td>1.20</td>
<td>3</td>
<td>715</td>
<td>0.092</td>
<td>0.099</td>
<td>0.068</td>
</tr>
</tbody>
</table>

( ) = runs excluded in plots
< > = unaccepted values
to the predicted velocity at the water depth of the centroid of the tested model. The conversion factors used for various wave conditions were derived from the kinematics equations of linear wave theory (see Table 4-2).

The second modification involved the correction of amplitude attenuation and phase lag of the Marsh McBirney current meter, which was extensively investigated by Dibble (1981). In Dibble's report, the MMI current meter was defined as a first order instrument of which the velocity measurement can be expressed as:

$$\tau \frac{dU_0}{dt} + U_0 = KU_i$$  \hspace{1cm} (4.2)

where \( U_0 = \) measured velocity by current meter
\( U_i = \) actual velocity in field
\( \tau = \) time constant of current meter
\( K = \) static sensitivity (fps/volt)

The solution of Equation 4.2 in terms of the magnitude and the phase is

$$A_i = \frac{1}{K} A_0 \sqrt{(\sigma \tau)^2 + 1}$$  \hspace{1cm} (4.3)

$$\phi = \tan^{-1} (-\sigma \tau)$$  \hspace{1cm} (4.4)

where \( A_0 = \) measured velocity amplitude
\( A_i = \) actual velocity amplitude
\( \phi = \) phase angle
\[ \sigma = \text{angular frequency} \]

Ramsden (1987) most recently calibrated the MMI current meter used in this research and computed the time constants (see Table 4-3). Values from the pendulum test were used for the data analysis.

### 4.3 Force Coefficients

In this study, drag and inertia coefficients were determined by the least square method, Fourier method, and the maximum value method utilizing the Morison equation. The maximum force coefficient and the lift force coefficient were also evaluated. The parameters used in the computation were water depth, wave period, model dimensions, wave height, current, and forces. Table 4-4 shows inputs required for the determination of individual force coefficients. Wave height, current and forces were measured in the experiment and the acceleration was calculated from the numerical derivative of the measured velocity. Velocity and acceleration were also predicted by linear wave theory from wave height, frequency and water depth.

Two approaches were made to determine force coefficients of all the experimental runs. One was with the measured forces and the water kinematics predicted by the wave theory, and the other with the same forces but with the measured velocity and the calculated acceleration. In
Table 4-2. Elevation Conversion Factor for Velocity

<table>
<thead>
<tr>
<th>Wave Condition</th>
<th>$\frac{h}{L}$</th>
<th>Conversion Factor*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shallow Water</td>
<td>$&lt; 0.05$</td>
<td>1</td>
</tr>
<tr>
<td>Intermediate Water</td>
<td>$0.05 \leq \frac{h}{L} \leq 0.5$</td>
<td>$\frac{\cosh [2\pi \frac{E_F}{L}]}{\cosh [2\pi \frac{E_M}{L}]}$</td>
</tr>
<tr>
<td>Deep Water</td>
<td>$0.5 &lt; \frac{h}{L}$</td>
<td>$\frac{\frac{e^{2\pi(h-E_F)/L}}{e^{2\pi(h-E_M)/L}}}{e^{2\pi(h-E_M)/L}}$</td>
</tr>
</tbody>
</table>

* $E_F$ = Center of Force Elevation (distance from bottom)  
  $E_M$ = Current Meter Elevation (distance from bottom)

Table 4-3. Time Constant of Current Meter

<table>
<thead>
<tr>
<th>MM 115 Current Meter</th>
<th>Wave Test</th>
<th>Pendulum</th>
<th>Electronic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vertical</td>
<td>0.29</td>
<td>0.29</td>
<td>0.26</td>
</tr>
<tr>
<td>Horizontal</td>
<td>0.24–0.26</td>
<td>0.26</td>
<td>0.24</td>
</tr>
</tbody>
</table>

Source: Ramsden (1987)
Table 4-4. Force Coefficients Determination

<table>
<thead>
<tr>
<th>INPUT</th>
<th>METHOD</th>
<th>OUTPUT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Velocity, Acceleration, Force</td>
<td>Least Square</td>
<td>$C_D, C_I$</td>
</tr>
<tr>
<td>Max. Hor. Velocity, Force</td>
<td>Fourier</td>
<td>$C_D, C_I$</td>
</tr>
<tr>
<td>Max. Hor. Velocity, Force at the Velocity</td>
<td>Maximum Value</td>
<td>$C_D$</td>
</tr>
<tr>
<td>Max. Hor. Acceleration, Force at the Acceleration</td>
<td></td>
<td>$C_I$</td>
</tr>
<tr>
<td>Max. Hor. Force, Max. Hor. Velocity</td>
<td>Maximum Force</td>
<td>$C_F$</td>
</tr>
</tbody>
</table>
the following sections, the concept of each method used for drag and inertia coefficients, and the methodology for determining the maximum force and lift force coefficients are described further.

**Least Square Method**

The least square method, used by Dean and Aagaard (1970), is to minimize the mean square error, $\epsilon^2$, between measured and predicted forces. The coefficients are chosen for each group so that the minimum squared error is maintained.

$$\epsilon^2 = \frac{1}{I} \sum_{i=1}^{I} (F_{mi} - F_{pi})^2$$  \hspace{1cm} (4.5)

where $F_{pi} = \rho C_D A (U \frac{|U|}{2}) + \rho C_I V \frac{DU}{Dt}$

$F_{mi} = \text{measured force}$

$i = \text{number of time increments, } t$

$I = \text{total number of data points}$

Taking the derivative of Equation 4.5 with respect to $C_D$ and $C_I$ and setting them equal to zero results in two equations as:

$$\frac{\epsilon^2}{C_D} = \frac{2}{I} \sum_{i=1}^{I} (F_{mi} - F_{pi}) \frac{F_{pi}}{C_D} = 0$$  \hspace{1cm} (4.6)

$$\frac{\epsilon^2}{C_I} = \frac{2}{I} \sum_{i=1}^{I} (F_{mi} - F_{pi}) \frac{F_{pi}}{C_I} = 0$$  \hspace{1cm} (4.7)
Substituting
\[
\frac{F_{pi}}{C_D} = \frac{1}{2} \rho A (U |U|)_i
\]
\[
\frac{F_{pi}}{C_I} = \rho V (\frac{DU}{Dt})_i
\]

rearranging and multiplying Equation 4.6 and 4.7 by \( \frac{2 \, V}{A} \) provides
\[
\Sigma F_{mi} (U|U|)_i = C_D \Sigma \frac{1}{2} \rho A (U |U|)_i^2 + C_I \Sigma \rho V (\frac{DU}{Dt})_i (U |U|)_i \quad (4.8)
\]
\[
\frac{2V}{A} \Sigma F_{mi} (\frac{DU}{Dt})_i = C_D \Sigma \rho V (U |U|)_i (\frac{DU}{Dt})_i + C_I \Sigma \frac{2V}{A} \rho V (\frac{DU}{Dt})_i^2 \quad (4.9)
\]

which can be abbreviated as :

\[
D = J C_D + B C_I
\]
\[
G = B C_D + F C_I
\]

where

\[
D = \Sigma_{i=1}^I F_{mi} (U |U|)_i
\]
\[
J = \Sigma_{i=1}^I \frac{1}{2} \rho A (U |U|)_i^2
\]
\[
B = \Sigma_{i=1}^I \rho V (\frac{DU}{Dt})_i (U |U|)_i
\]
\[
G = \Sigma_{i=1}^I \frac{2V}{A} F_{mi} (\frac{DU}{Dt})_i
\]
\[ F = \sum_{i=1}^{I} \frac{2 \cdot V^2}{A} \left( \frac{DU}{DT} \right)_{i}^{2} \]

Eliminating unknowns yield

\[ C_D = \frac{G \cdot A - D \cdot F}{B^2 - J \cdot F} \quad (4.10) \]

\[ C_I = \frac{D \cdot B - G \cdot J}{B^2 - J \cdot F} \quad (4.11) \]

**Fourier Method**

Keulegan and Carpenter expressed the force on a cylinder in terms of a Fourier series as:

\[ \frac{F}{\rho U_m^2 D} = A_1 \sin \theta + A_3 \sin 3\theta + A_5 \sin 5\theta + \ldots + B_1 \cos \theta + B_3 \cos 3\theta + B_5 \cos 5\theta + \ldots \]

where \( U_m \) = maximum horizontal velocity

The velocity and acceleration may be given by

\[ U = -U_m \cos \omega t \]

\[ \frac{dU}{dt} = U_m \omega \sin \omega t \]

Upon substitution of \( U \), and \( \frac{dU}{dt} \), the Morison equation can be written as:

\[ \frac{F}{\rho U_m^2 D} = \frac{1}{2} C_D \ l \ \cos \omega t \ |\cos \omega t| - \frac{1}{4} C_I \ \frac{D \cdot \omega^2}{U_m} \ \omega \sin \omega t \quad (4.13) \]
Multiplying both sides of the Equation once with $\cos \omega t$ and integrating

$$C_D = -\frac{3}{4 \rho A_U m^2 D} \int_0^{2\pi} F \cos \omega t \, d(\omega t) \quad (4.14)$$

and again multiplying both sides by $\sin \omega t$ and integrating

$$C_I = \frac{2 T}{\pi^3 D^2 \rho A_U m} \int_0^{2\pi} F \sin \omega t \, d(\omega t) \quad (4.15)$$

**Maximum Value Method**

This method used by Morison et al. to obtain the values of $C_D$ and $C_I$ correlates forces with water kinematics at times when the velocities or accelerations are zero. At such instants either the drag or inertia term is zero leaving one unknown in the equation. For small amplitude waves of a single period, the horizontal velocity is maximum and the acceleration is zero at the wave crest. And the resulting drag force is maximum and the inertia force is zero. Accordingly, $C_D$ is given as:

$$C_D = \frac{F_{mv}}{\frac{1}{2} \rho A U_m^2} \quad (4.16)$$

where $F_{mv} =$ measured force at maximum velocity

$U_m =$ maximum horizontal velocity
Similarly, acceleration is maximum when the velocity is zero and $C_I$ is given as:

$$C_I = \frac{F_{ma}}{\frac{1}{2} \rho A \left(\frac{du}{dt}\right)_m^2} \quad (4.17)$$

where $F_{ma} = \text{measured force at maximum acceleration}$

$(\frac{du}{dt})_m = \text{maximum acceleration}$

In real fluid flow induced by waves, a phase lag between the drag force and the velocity exists because of the formation of wake at the downstream side of an object. As a result the drag force still has some value instead of zero when the inertia force is maximum. This phenomenon may introduce errors in the evaluation of the inertia coefficients.

**Maximum Force Coefficient**

Engineers seeking a static design are interested in the maximum force on an object under a given design wave condition. The maximum force occurs at the instant when the sum of the drag and inertia forces achieves an absolute maximum value within a wave cycle. However, the maximum force is evaluated relative to the maximum velocity only, under the assumption that the drag force relationship characterizes the dynamics.
The maximum force coefficient is then calculated using the maximum force measured and the maximum velocity, although the two quantities may be out of phase.

Lift Force Coefficient

Lift forces are transverse forces that act perpendicular to flow due to asymmetries in the velocity field. This asymmetric velocity and the consequent pressure distribution are generally caused by an adjacent boundary or vortex shedding. The lift force is an important part of wave induced forces in this research because the concrete pipes and plates used for artificial reefs will be placed on a seabed as units of a larger reef system. The horizontal pipe setup, which resembles a section of a pipeline on a seabed is subject to a lift force as the varying velocity above and below the pipe cause an inverse relationship with pressure via the Bernoulli equation. The top layer of the stacked plates, wherein the instrumented section is placed, is also expected to experience the maximum lift force due to the variation of velocities above the plate and the gap between the top two plates.

The lift force is defined in a form analogous to the
drag force equation as:

\[ F_L = \frac{1}{2} \rho C_L A U_m^2 \]  

(4.19)

where \( F_L \) = measured maximum lift force
\( C_L \) = lift force coefficient

The vertical force measured is used as the lift force and the horizontal maximum velocity as the maximum velocity. In this research, the lift force coefficient is determined for all experiments except the vertical pipe.

4.4 Center of Force

Reef unit stability is affected by the overturning moment, sliding force and lifting force. The pipe model is more susceptible to the overturning moment and sliding force, while the open-stacked horizontal layers are more vulnerable to the lifting force. In this research, the overturning stability of the pipe model is examined by evaluating the position of the center of force at the occurrence of the maximum moment.

The overturning moment is induced by the total horizontal force acting on an object at the center of force, a vertical distance from the bottom. The resisting moment is the net vertical force due to the object weight, which acts at a known horizontal distance from the rotation point of the object.
Static equilibrium (see Fig. 4-3 and 4-4) requires

\[ \Sigma M = 0 \]

\[ F_{HT} \cdot e_t = F_{H1} \cdot e_1 + F_{H2} \cdot e_2 + F_{H3} \cdot e_3 \]  \hspace{1cm} (4.20)

\[ \Sigma FH = 0 \]

\[ F_{HT} = F_{H1} + F_{H2} + F_{H3} \]  \hspace{1cm} (4.21)

where \( M \) = moment

\( FH \) = measured horizontal force

\( F_{HT} \) = resultant horizontal force

\( F_{H1}, F_{H2}, F_{H3} \) = individual horizontal force

\( e_t, e_1, e_2, e_3 \) = distance from floor

Then, the resultant force lever arm, \( e_t \), is determined by

\[ e_t = \frac{F_{H1} \cdot e_1 + F_{H2} \cdot e_2 + F_{H3} \cdot e_3}{F_{H1} + F_{H2} + F_{H3}} \]  \hspace{1cm} (4.23)

The absolute maximum moment, either towards the beach or towards the wave board, was determined from each run, and the corresponding center of force and the moment lever length was calculated. The length was converted to a distance from the centroid of the pipe model, and then it was non-dimensionalized by the vertical length of the pipe. For the horizontal pipe experiment, the pipe diameter was used for the vertical length. The center of force is quantified relative to the centroid.
Fig. 4-3. Center of Force for Vertical Pipe

Fig. 4-4. Center of Force for Horizontal Pipe
4.5 Phase Lag

Wave theories predict that the water surface profile is in phase with the horizontal water particle velocity. However, experimental results have shown that phase lags are present between surface profiles and measured bottom velocities. Hence, the measured maximum horizontal velocity and the wave crest do not occur at the same time as the wave theories predict.

The cause of this phase lag is probably due to real fluid effects and the existence of a back current in the wave channel. The wave channel described in Section 3.1 is a closed system in which the breaking waves on the beach cause a return flow that is confined near the bottom and proceeds towards the wave board.

The force coefficients determined using the predicted water kinematics ignore the velocity phase lag problem, because the predicted kinematics can be applied in phase with the surface profile. However, the consequences are significant in the force coefficient determination when the measured kinematics are used, because the time series velocity, acceleration and force measurements are matched to each other to determine force coefficients. Exceptions are with the maximum force and lift force coefficients, where individual maximum values are used. Therefore, the phase lag information is an important condition of the determined force coefficients.
In this study, the phase lags of velocity and force with respect to the wave crest are determined. The time difference in the phase angle between the wave crest and the absolute maximum velocity, either towards the beach or the wave board, was considered as the velocity phase, and also as the drag force phase. The maximum acceleration phase was also the inertia force phase. For the total and the lift force phases, the time lag between the wave crest and the respective maximum forces were used.
5. RESULTS PART I: VERTICAL PIPE

5.1 Introduction

The experimental results are presented in the following three chapters. The vertical pipe experiment is discussed first in this chapter and followed by the horizontal pipe experiment in Chapter 6. Finally, the results from the plate model, which includes the four layer and three layer experiments, are described in Chapter 7.

In the present discussions, wave conditions are frequently mentioned, which are defined by the ratio of water depth to wave length in deep water. The water wave conditions in this paper are defined as:

- Shallow Water: \( h/L_0 < 0.05 \)
- Intermediate Water: \( 0.05 < h/L_0 < 0.5 \)
- Deep Water: \( 0.5 < h/L_0 \)

Current and force measurements are presented with plus (+) or minus (-) signs. The plus sign indicates that the measurements are upward or in the direction of wave propagation (also referred as towards the beach). The minus sign symbolizes downward or opposed to the direction of wave propagation (towards the wave board).

Some representative data tables and graphs are presented in the discussions and a complete set of graphs and tables are attached in Appendix A.
In this chapter, the following topics on the vertical pipe experiment are presented in the order listed.

(1) The statistical variability of measurements required to quantify the experimental condition.

(2) Drag and inertia force coefficients determined by three methods for two different kinematic descriptions.

(3) Center of force location.

(4) Maximum force coefficient.

(5) Phase lag of velocity and force measurements.

(6) Comparison with the results of related previous experiments.

5.2 Measurements

Wave height, current and force measurements under wave conditions of shallow water and intermediate water are quite consistent and the variance coefficients of the middle six waves are within 0.05. However, the measurements are much less stable under deep water conditions, where the wave periods are shorter, and the magnitude of current and force measurements are smaller. Under such conditions current measurements show the greatest variability (see Table 5-1). Runs with coefficients of variance greater than 0.11 are excluded in the following discussions and graphs. The limiting value of 0.11 is selected so that as many experimental results as possible
Table 5-1. Variance Coefficients of Measurements: Part I Vertical Pipe (h= 9.0ft)

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>017</td>
<td>4-A</td>
<td>9.375</td>
<td>1.67</td>
<td>6</td>
<td>709</td>
<td>0.008</td>
<td>0.012</td>
<td>0.004</td>
</tr>
<tr>
<td>018</td>
<td>5-A</td>
<td>5.929</td>
<td>1.77</td>
<td>6</td>
<td>628</td>
<td>0.007</td>
<td>0.010</td>
<td>0.011</td>
</tr>
<tr>
<td>019</td>
<td>5-B</td>
<td>5.929</td>
<td>1.79</td>
<td>6</td>
<td>737</td>
<td>0.006</td>
<td>0.018</td>
<td>0.008</td>
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<td>020</td>
<td>6-A</td>
<td>4.193</td>
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<td>0.048</td>
<td>0.046</td>
<td>0.020</td>
</tr>
<tr>
<td>021</td>
<td>6-B</td>
<td>4.193</td>
<td>3.16</td>
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<td>0.024</td>
<td>0.046</td>
<td>0.025</td>
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<tr>
<td>022</td>
<td>7-A</td>
<td>2.965</td>
<td>1.37</td>
<td>6</td>
<td>753</td>
<td>0.011</td>
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<td>7-B</td>
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<td>2.87</td>
<td>6</td>
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<td>0.012</td>
<td>0.006</td>
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<td>7-C</td>
<td>2.965</td>
<td>4.27</td>
<td>6</td>
<td>649</td>
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<td>0.80</td>
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<td>1075</td>
<td>0.019</td>
<td>0.050</td>
<td>0.009</td>
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<td>026</td>
<td>8-B</td>
<td>1.875</td>
<td>1.40</td>
<td>4</td>
<td>976</td>
<td>0.019</td>
<td>0.044</td>
<td>0.005</td>
</tr>
<tr>
<td>027</td>
<td>8-C</td>
<td>1.875</td>
<td>1.95</td>
<td>3</td>
<td>565</td>
<td>0.000</td>
<td>0.011</td>
<td>0.010</td>
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<tr>
<td>(028)</td>
<td>9-A</td>
<td>1.326</td>
<td>0.36</td>
<td>3</td>
<td>1129</td>
<td>0.017</td>
<td>&lt;0.177&gt;</td>
<td>&lt;0.142&gt;</td>
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<td>9-B</td>
<td>1.326</td>
<td>0.81</td>
<td>3</td>
<td>580</td>
<td>0.010</td>
<td>0.103</td>
<td>0.023</td>
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<td>1.08</td>
<td>3</td>
<td>849</td>
<td>0.008</td>
<td>0.037</td>
<td>0.006</td>
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</tbody>
</table>

( ) = runs excluded in plots < > = unaccepted values
can be included, while eliminating misleading results.

In general, measured current values are less than linear wave theory predicted values under shallow and intermediate water wave conditions (see Table 5-2). Under deep water wave conditions the trend is reversed. In most runs, the maximum current towards the wave board is greater than that of the current towards the beach, demonstrating the presence of a return current in the wave channel.

Figure 5-1 is a graph showing the maximum horizontal forces of three different experiments at a water depth of 11.5 feet. The vertical pipe model encounters the maximum wave force under intermediate water wave conditions with h/L₀ values ranging from 0.1 to 0.2.

A summary of approximate maximum and minimum values of the measurements is

<table>
<thead>
<tr>
<th></th>
<th>(h = 11.5 ft)</th>
<th>(h = 9.0 ft)</th>
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</thead>
<tbody>
<tr>
<td>Wave height (ft)</td>
<td>Max. 4.7</td>
<td>Min. 0.5</td>
</tr>
<tr>
<td>Hor. Current(ft/sec)</td>
<td>Max. -2.2</td>
<td>Min. 0.2</td>
</tr>
<tr>
<td>Hor. Force (lb)</td>
<td>Max. -75.0</td>
<td>Min. -0.6</td>
</tr>
</tbody>
</table>

As expected the model under the 9.0 foot depth experiences higher wave forces than at a depth of 11.5 feet. It is noted that both maximum current and force occur in the direction opposite to that of wave propagation. A ratio of maximum drag force to maximum inertia force under different wave conditions are shown in Figure 5-2.
Table 5-2. Kinematics Results: Part I  Vertical Pipe (h=11.5ft)

<table>
<thead>
<tr>
<th>Run No.</th>
<th>Dean's Stream</th>
<th>T (sec)</th>
<th>H (ft)</th>
<th>h Avg.</th>
<th>Predicted Velocity (ft/sec)</th>
<th>Measured Velocity (ft/sec)</th>
<th>Acceleration (ft/sec²)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>No.</td>
<td></td>
<td></td>
<td></td>
<td>Maximum</td>
<td>Max.</td>
<td></td>
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<tr>
<td>001</td>
<td>4-A</td>
<td>10.600</td>
<td>1.55</td>
<td>0.020</td>
<td>1.24</td>
<td>1.31</td>
<td>1.38</td>
</tr>
<tr>
<td>002</td>
<td>5-A</td>
<td>6.700</td>
<td>2.24</td>
<td>0.050</td>
<td>1.68</td>
<td>1.27</td>
<td>1.37</td>
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<tr>
<td>003</td>
<td>5-B</td>
<td>6.700</td>
<td>2.96</td>
<td>0.050</td>
<td>2.22</td>
<td>1.66</td>
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<td>6-A</td>
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<td>2.02</td>
<td>0.100</td>
<td>1.35</td>
<td>1.23</td>
<td>1.23</td>
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<tr>
<td>005</td>
<td>6-B</td>
<td>4.740</td>
<td>3.99</td>
<td>0.100</td>
<td>2.66</td>
<td>2.13</td>
<td>2.03</td>
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<tr>
<td>006</td>
<td>7-A</td>
<td>3.350</td>
<td>1.63</td>
<td>0.200</td>
<td>0.81</td>
<td>0.81</td>
<td>0.76</td>
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<tr>
<td>007</td>
<td>7-B</td>
<td>3.350</td>
<td>3.50</td>
<td>0.200</td>
<td>1.76</td>
<td>1.54</td>
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<td>4.74</td>
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<td>009</td>
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<td>0.27</td>
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<td>0.47</td>
<td>0.36</td>
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<td>2.120</td>
<td>2.74</td>
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<td>(012)</td>
<td>9-A</td>
<td>1.500</td>
<td>0.45</td>
<td>0.998</td>
<td>0.01</td>
<td>0.04</td>
<td>0.05</td>
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<tr>
<td>(013)</td>
<td>9-B</td>
<td>1.500</td>
<td>0.91</td>
<td>0.998</td>
<td>0.01</td>
<td>0.05</td>
<td>0.00</td>
</tr>
<tr>
<td>014</td>
<td>9-C</td>
<td>1.500</td>
<td>1.30</td>
<td>0.998</td>
<td>0.02</td>
<td>0.11</td>
<td>-0.03</td>
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<tr>
<td>(015)</td>
<td>9-D</td>
<td>1.500</td>
<td>1.39</td>
<td>0.998</td>
<td>0.02</td>
<td>0.11</td>
<td>-0.07</td>
</tr>
<tr>
<td>016</td>
<td>9-D</td>
<td>1.500</td>
<td>1.37</td>
<td>0.998</td>
<td>0.02</td>
<td>0.14</td>
<td>-0.06</td>
</tr>
</tbody>
</table>

( ) = runs excluded in plots

**+(+) = maximum velocity towards beach**

**(-) = maximum velocity towards wave board**
Fig. 5-1. Max. Horizontal Force vs. $h / L_o$
Fig. 5-2. Drag Force / Inertia Force

- ○--Vertical Pipe
- △--Horizontal Pipe
- X--Three Layers

h = 11.5 ft

h/Lo
The drag force used in the ratio is the force at the maximum velocity and the inertia force is the force at the maximum acceleration. For the pipe model the drag force ranges from 15 to 55 percent of the inertia force. The ratio increases gradually as the ratio of water depth to wave length approaches shallow water conditions.

### 5.3 Drag & Inertia Force Coefficient

Drag and inertia force coefficients determined by three methods for two different kinematic descriptions are numerous. In order to systemize the discussion, the following guide is adopted. The results from kinematics predicted from linear wave theory are discussed first followed by results from measured kinematics. The drag force coefficient results are followed by the inertia coefficient results.

#### Results from Predicted Kinematics

The drag force coefficient, $C_D$, correlates well with both Reynolds number and Keulegan-Carpenter parameter. The approximate range of the Reynolds number is from 0.15 to $3.0 \times 10^5$ and that of the Keulegan-Carpenter (KC) parameter is from 0.2 to 12.0. The $C_D$ ranges from 0.5 to 11.0 decreasing with increasing Reynolds number. In Figure 5-3, $C_D$ determined by the Fourier method is graphed against the Reynolds number. In Figure 5-4, $C_D$ by the maximum value method is plotted versus the KC parameter. Among the three
Fig. 5-3. CD vs. Re : FORI & LWT Kinematics

Fig. 5-4. CD vs. Re : MXVL & LWT Kinematics
different methods, the maximum value results produce the curve with the least scatter. The coefficients determined by the least squares method are very close in magnitude with that of the Fourier method, while the results from the maximum value method vary from the other two methods (see Figure 5-5). The KC parameter correlates better with force coefficients than the Reynolds number. Except for the maximum value method results, the water depth has a significant effect on force coefficients when the predicted kinematics are used.

The inertia coefficient relationship to the governing parameters are shown in Figures 5-6 and 5-7. The $C_I$ value remains close to 2.0 dropping slightly with KC parameter values greater than 5.0. The inertia coefficients determined by the maximum value are higher value than the other two methods when the KC parameter is near 10.0 (see Fig. 5-5).

**Results from Measured Kinematics**

The results from the measured kinematics show less scatter graphed against the governing parameters than the results from the predicted kinematics. The ranges of both parameters are slightly narrower than that of predicted kinematics. The drag coefficients range from 0.6 to 15. In Figure 5-8, $C_D$ from the least square method is graphed against the Reynolds number. The results from the maximum
Fig. 5-5. CD & CI Relationships of Different Methods (LWT)
Fig. 5-6. CI vs. K-C: LSQ & LWT Kinematics

Fig. 5-7. CI vs. Re: MXVL & LWT Kinematics
value method are correlated with the KC number in Figure 5-9.

The inertia coefficient from measured kinematics show a monotonic trend increasing gradually with increasing parameter values and leveling out at around 2.0 (see Figs. 5-10 and 5-11).

A complete set of graphical results and summary of force coefficients is presented in Appendix A.

5.4 Center of Force

The center of force at the maximum moment for each run was determined and plotted in Figure 5-12. The trend is a gradual increase as wave conditions change from shallow to intermediate water depths and a sharp increase in deep water. The maximum moment occurs in either directions, towards the beach or towards the wave board. The determination of the center of force for waves in deep water conditions is difficult, because the magnitude of the force measured by the dynamometers are too small to quantify a reliable force center. For this reason, the results with h/L₀ value equal to 1.0 can be neglected. Accordingly, the center of force ranges from four percent below the centroid increasing to four percent above the centroid with increasing h/L₀. The center of force trend remained below the center line for wave conditions having h/L₀ values below about 0.4 (see Fig. 5-12). One possible explanation to this observation is that the center of
Fig. 5-8. CD vs. Re: LSQ & Measured Kinematics

Fig. 5-9. CD vs. K-C: MXVL & Measured Kinematics
Fig. 5-10. CI vs. K-C: FORI & Measured Kinematics

Fig. 5-11. CI vs. Re: MXVL & Measured Kinematics
Vertical Pipe  \[ h = 9.0 \text{ ft} \]

**Fig. 5-12. Center of Force Location vs. \( h / L_0 \)**

- \( \times \) — (+) Max
- \( \circ \) — (-) Max

**Model Center Line**

- Displacement / Length
- \( h / L_0 \)
force predicted during the force calibration was about three percent below the actual load point when the load was applied at the centroid. If the present results are corrected by this three percent, the range would be from one percent below to seven percent above the center line.

5.5 Maximum Force Coefficient

The maximum force coefficient correlates quite well with both parameters (see Fig. 5-13 and 5-14). The range of \( C_F \) varies from 2.0 to 100.0 increasing exponentially with the decreasing parameter values. The trend is more tightly grouped with the KC number. Both the predicted and measured kinematics produce acceptable trends. The greatest scatter is seen with the Reynolds numbers smaller than \( 0.5 \times 10^5 \) and with the KC parameter smaller than 0.5 when the measured kinematics are used. The results are virtually independent of the water depth.

5.6 Phase Lag

Theoretically, the horizontal velocity is in phase with the wave surface and the drag force is in phase with the velocity. The acceleration and the inertia force are 270 degrees out of phase with the wave profile. The phase lag results are shown in Figure 5-15 where the lag in degrees relative to the wave crest are graphed for the maximum measured velocity and various forces.

The velocity phase lag is near zero for shallow
Fig. 5-13. CF vs. Re: Measured Kinematics

Fig. 5-14. CF vs. K-C: LWT Kinematics
Fig. 5-15. Time Series Phase Angle vs. h / L₀
water wave conditions, however, the lag shifts 180 degrees or more under intermediate water conditions indicating that the maximum velocity occurred under the trough (towards the wave board). The acceleration phase varies widely except near $h/L_0$ values of 0.2 to 0.5, where the phase angle is about 270 degrees. The occurrence of the total maximum force is consistent. In shallow water wave conditions, the phase angle is about 315 degrees, while the angle is 105 degrees in intermediate and deep water wave conditions. A summary table of phase angles is included in Appendix A.

5.7 Comparison with Long Vertical Cylinder

Nath et al. (1985) conducted a large scale experiment on a long, smooth vertical cylinder (12.75-inch diameter) in the same wave channel at the O.H. Hinsdale Wave Research Laboratory. The drag coefficients of the long cylinder decreased from 0.5 to 0.4 in the range of the KC numbers from 5.0 to 12.0 when linear wave theory kinematics are used. For the corresponding range, the drag coefficients of the present study changed from 1.0 to 0.7 at the water depth of 11.5 feet (see Appendix Fig.I-3). The coefficients from the measured kinematics of the vertical pipe is about 1.2 at the KC parameter of 10.0 (see Appendix Fig.I-4), while it is 0.5 for the long cylinder. The drag coefficient of the short pipe is almost twice that of the long cylinder.
For the inertia coefficient, the results of the long cylinder experiment varies from 2.0 to 1.7 in the KC parameter range of 1.0 to 12.0 when the predicted kinematics are used. In that same range, the present study results changes from 2.0 to 1.3 decreasing with the increasing KC number (see Fig. 5-6). The results from the measured kinematics of the long cylinder varies form 2.2 to 2.0. Almost an identical result is produced from the short pipe experiment (see Appendix Fig.I-8).

Kim et al. (1981) carried out a large scale experiment at the same research facility with tires to be used as artificial reef units. The results of a model with four vertically stacked tires with a diameter of 1.9 feet has the drag coefficients ranging from 0.5 to 6.0 forming a parabola, and the inertia coefficients from 1.3 to 1.7 in the KC parameter range from 0.3 to 7.0.

The trend of drag coefficient of the vertical pipe is a declining line with its minimum value of 1.0 at the KC parameter of 10.0 (see Appendix Fig.I-20) versus 0.5 at the KC parameter of 5.0 for the tire model. The trend of inertia coefficient of the vertical pipe (see Appendix Fig.I-24) is in good agreement with the results of the vertical tire model. The only difference is the magnitude, of which the present study has shown a greater range from 0.5 to 2.1 versus 1.0 to 1.8.
6. RESULTS PART II: HORIZONTAL PIPE

6.1 Introduction

In this chapter, the results from the horizontal pipe model are presented in the following format.

(1) Discussion of the physical measurements of the experiment.
(2) Drag and inertia force coefficients.
(3) Center of force location.
(4) Lift force coefficient.
(5) Maximum force coefficient.
(6) Phase angle.
(7) Comparison with other seafloor cylinder results.

6.2 Measurements

The measurements in the horizontal pipe experiment at the water depth of 9.0 feet showed the greatest variability in this study (Table 6-1). Seven out of the 18 runs have variance coefficients greater than 0.11, and are therefore excluded in plots. However, the measurements at the 11.5 feet depth are much more consistent. The current measurement under small amplitude waves again are the least reliable. This is due to the relatively insignificant wave kinematics generated at the seafloor under small waves. An examination of Run.042 data, a low amplitude wave, reveals that two peaks with a similar
Table 6-1. Variance Coefficients of Measurements: Part II Horizontal Pipe (h = 9.0ft)

<table>
<thead>
<tr>
<th>Run No.</th>
<th>Dean's Stream Funkt. No.</th>
<th>T (sec)</th>
<th>H (ft)</th>
<th>No. of Waves Analyzed</th>
<th>Beginning Data Point</th>
<th>Wave Height</th>
<th>Variance Coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Current Force</td>
<td></td>
</tr>
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<td>4-A</td>
<td>9.375</td>
<td>1.70</td>
<td>3</td>
<td>1128</td>
<td>0.005</td>
<td>0.010</td>
</tr>
<tr>
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<td>5-A</td>
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<td>1.77</td>
<td>6</td>
<td>549</td>
<td>0.005</td>
<td>0.013</td>
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<tr>
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<td>5.929</td>
<td>2.25</td>
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<td>035</td>
<td>6-B</td>
<td>4.193</td>
<td>3.16</td>
<td>6</td>
<td>564</td>
<td>0.021</td>
<td>0.011</td>
</tr>
<tr>
<td>036</td>
<td>7-A</td>
<td>2.965</td>
<td>1.42</td>
<td>3</td>
<td>709</td>
<td>0.013</td>
<td>0.049</td>
</tr>
<tr>
<td>037</td>
<td>7-B</td>
<td>2.965</td>
<td>2.89</td>
<td>3</td>
<td>538</td>
<td>0.033</td>
<td>0.022</td>
</tr>
<tr>
<td>038</td>
<td>7-C</td>
<td>2.965</td>
<td>4.27</td>
<td>6</td>
<td>625</td>
<td>0.006</td>
<td>0.035</td>
</tr>
<tr>
<td>(039)</td>
<td>8-A</td>
<td>1.875</td>
<td>0.65</td>
<td>3</td>
<td>657</td>
<td>0.017</td>
<td>0.235</td>
</tr>
<tr>
<td>(040)</td>
<td>8-B</td>
<td>1.875</td>
<td>1.43</td>
<td>3</td>
<td>1079</td>
<td>0.017</td>
<td>0.009</td>
</tr>
<tr>
<td>041</td>
<td>8-C</td>
<td>1.875</td>
<td>2.00</td>
<td>3</td>
<td>786</td>
<td>0.004</td>
<td>0.011</td>
</tr>
<tr>
<td>(042)</td>
<td>9-A</td>
<td>1.326</td>
<td>0.34</td>
<td>3</td>
<td>1244</td>
<td>0.017</td>
<td>0.016</td>
</tr>
<tr>
<td>(043)</td>
<td>9-B</td>
<td>1.326</td>
<td>0.75</td>
<td>3</td>
<td>1494</td>
<td>0.026</td>
<td>0.019</td>
</tr>
<tr>
<td>(044)</td>
<td>9-C</td>
<td>1.326</td>
<td>0.96</td>
<td>3</td>
<td>984</td>
<td>0.029</td>
<td>0.053</td>
</tr>
<tr>
<td>045</td>
<td>6-B</td>
<td>4.193</td>
<td>3.11</td>
<td>3</td>
<td>772</td>
<td>0.029</td>
<td>0.003</td>
</tr>
<tr>
<td>046</td>
<td>7-C</td>
<td>2.965</td>
<td>4.24</td>
<td>6</td>
<td>716</td>
<td>0.004</td>
<td>0.031</td>
</tr>
<tr>
<td>(047)</td>
<td>9-B</td>
<td>1.326</td>
<td>0.71</td>
<td>4</td>
<td>857</td>
<td>0.014</td>
<td>0.050</td>
</tr>
<tr>
<td>(048)</td>
<td>9-C</td>
<td>1.326</td>
<td>1.10</td>
<td>3</td>
<td>837</td>
<td>0.019</td>
<td>0.034</td>
</tr>
</tbody>
</table>

(  ) = runs excluded in plots  < > = unaccepted values
magnitude are present at one-half the cycle of the current measurement. This data has been excluded in the analysis as the variance coefficient of current cycle was over 0.11.

The extreme values of the measurements are summarized below.

<table>
<thead>
<tr>
<th></th>
<th>( h=11.5 ft )</th>
<th>( h=9.0 ft )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wave height (ft)</td>
<td>Max. 4.6</td>
<td>Min. 0.5</td>
</tr>
<tr>
<td></td>
<td>Max. 4.3</td>
<td>Min. 0.3</td>
</tr>
<tr>
<td>Hor. current (ft/sec)</td>
<td>-2.2</td>
<td>0.2</td>
</tr>
<tr>
<td></td>
<td>-2.2</td>
<td>0.5</td>
</tr>
<tr>
<td>Hor. force (lb)</td>
<td>+106.0</td>
<td>1.8</td>
</tr>
<tr>
<td></td>
<td>+101.1</td>
<td>-25.4</td>
</tr>
<tr>
<td>Ver. force (lb)</td>
<td>-72.4</td>
<td>1.0</td>
</tr>
<tr>
<td></td>
<td>-81.4</td>
<td>6.1</td>
</tr>
</tbody>
</table>

The maximum horizontal force is in the direction of wave propagation, while the lift force is in the downward direction.

Figure 5-1 in the previous chapter presents the relative maximum forces for the different models. For the same pipe model, the maximum force in the horizontal orientation is about 20 percent greater than the vertical orientation. The horizontal pipe experiences the greatest wave force at intermediate depth conditions in the range from 0.1 to 0.2 on h/L₀ scale. Figure 6-1 shows the ratio of the maximum lift force to the maximum horizontal force. The ratio varies from 0.2 to 0.8 for the horizontal pipe, and yet throughout the vast range of shallow and intermediate water depths it was about 0.6. The lift force at
Fig. 6-1. Lift Force / Horizontal Force
different wave conditions are plotted in Figure 6-2. Again, the maximum forces are recorded in the $h/L_0$ range from 0.1 to 0.2. It is apparent that the force on the horizontal pipe model in deep water conditions is relatively insignificant.

### 6.3 Drag & Inertia Force Coefficients

**Results from Predicted Kinematics**

The range of the Reynolds number is from 0.1 to $3.0 \times 10^5$ and that of the Keulegan-Carpenter number is from 0.2 to 12.0. The drag force coefficient ranges from 17.0 to 1.0. The drag coefficient decreases with increasing Reynolds number in the range of 0.1 and $1.0 \times 10^5$, and levels out at about $C_D = 2.0$ (see Fig. 6-3). On the KC scale, the results show a similar trend with somewhat more scatter (see Fig. 6-4). Figure 6-5 shows the relationship among the force coefficients determined by different methods. The results of the Fourier method are almost identical to those determined by the least square method. The maximum value results fluctuate most.

The inertia coefficient changes very little throughout the range with an almost constant value of 2.0 relative to either the Reynolds number or the KC parameter (see Fig. 6-6 and 6-7). The inertia coefficients determined by the maximum value method are slightly higher than those from the other two methods.
Fig. 6-2. Max. Lift Force vs. h / L₀

- Δ--Horizontal Pipe
- X--Three Layers

h = 11.5 ft
Fig. 6-3. CD vs. Re: LSQ & LWT Kinematics

Fig. 6-4. CD vs. K-C: MXVL & LWT Kinematics
Fig. 6-5. CD & CI Relationships of Different Methods (LWT)
Fig. 6-6. CI vs. K-C: FORI & LWT Kinematics

Fig. 6-7. CI vs. K-C: MXVL & LWT Kinematics
Results from Measured Kinematics

The force coefficients results from measured kinematics span a narrower range in the governing parameters. The drag coefficient forms a clear trend in the range of 0.8 - 2.4 on the Reynolds number scale (see Fig. 6-8). A second trend, which runs parallel to the main trend at a smaller value of $C_D$, is observed in the figure. Similar graphical results are found relative to the KC scale (see Fig. 6-9). At present, no explanation for this behavior is available. However, because this result only appears with the measured kinematics, it is suspected that an error in the recorded gain of the velocity signal conditioning may have occurred. The secondary trend does not appear in the results from the 9.0 foot experiment because the corresponding runs at the 9.0 foot depth are eliminated in plots due to a large coefficient of variance in measurements. The results from the maximum value method show a dome shaped curve on the KC scale with $C_D$ peaking at about 5.0 at a KC value of 5.0. However, graphical results plotted on the Reynolds number scale show no similar relationship. The relative ratios of the coefficients determined by different methods indicate little variation in the values (see Fig. 6-10). Exceptions occur at small KC numbers.

The inertia coefficient is nearly constant in the Reynolds number of 0.8 - 2.7 and in the KC number range of
**Horizontal Pipe**

Fig. 6-8. CD vs. Re: LSQ & Measured Kinematics

Fig. 6-9. CD vs. K-C: LSQ & Measured Kinematics
Fig. 6-10. CD & CI Relationships of Different Methods (Measured)
The coefficient value occurs between 2.0 and 3.0. The least square method provides the tightest grouping of the data (see Fig. 6-11 and 6-12). The secondary trend appearing in the drag coefficient discussion is seen again in the inertia force coefficient results. Note that this secondary trend yields a reduction in the inertia coefficient by a factor of two while the reduction in the drag coefficient is approximately a factor of four. An error of two in the velocity gain setting could account for this, because the velocity squared relationship in the drag equation would reduce the drag coefficient by four while the linear acceleration relationship in the inertia equation would only change the inertia coefficient by a factor of two.

6.4 Center of Force

The center of force at the maximum over turning moment of each run is examined. As shown in Figure 6-13, the center of force gradually moves upward as the relative water depth change from shallow to deep water. Though the center of force moves considerably upward in deep water conditions, the following should be noted. The prediction of the center of force in deep water is less reliable due to the small magnitude of the recorded force. Nevertheless, all center of force calculations are within five percent of the mid-height of the pipe.
Fig. 6-11. CI vs. Re : LSQ & Measured Kinematics

Fig. 6-12. CI vs. K-C : LSQ & Measured Kinematics
Fig. 6-13. Center of Force Location vs. $h / L_0$
6.5 Lift Force

The lift force coefficient determined from the predicted kinematics correlates well with both the Reynolds number and the Keulegan-Carpenter parameter in the range from 0.1 to \(3.0 \times 10^5\) and from 0.1 to 12, respectively. The relationship is more linear relative to with the KC number than the Reynolds number, especially in the high Reynolds number region. The \(C_L\) values increase exponentially from 1.9 to 50.0 as the parameters decrease (see Fig. 6-14). The results from 9.0 feet or 11.5 feet group on a single line indicating that the depth effect seems to be accounted for by the kinematics.

The results from the measured kinematics show a well defined trend in the range from 2.0 to 11.0 for the KC scale. The lift force coefficient decreases from 5.0 to 2.0 monotonically as the KC parameter increases (see Fig. 6-15). Here again, a secondary trend, which also appears in the drag and inertia force coefficient data, as well as third trend are observed for lift coefficients with KC numbers smaller than 3.0. A factor of four for the second trend and nine for the third trend suggest gain errors of two and three in the velocity records.

6.6 Maximum Force Coefficient

The maximum force coefficient determined from the predicted kinematics correlates well with the Reynolds
Fig. 6-14. CL vs. K-C: LWT Kinematics

Fig. 6-15. CL vs. K-C: Measured Kinematics
number and the Keulegan-Carpenter number in the range from 0.1 to $3.0 \times 10^5$ and from 0.1 to 12.0, respectively. $C_F$ decreases from 100 to 3.0 exponentially as the parameters increases (see Fig. 6-16).

The results from the measured kinematics are somewhat scattered against the Reynolds number, but correlate well with the KC number in the range from 2.0 to 12.0 (see Fig. 6-17). The maximum force coefficient in that region varies from 3.5 to 10.0, decreasing with increasing KC parameter. The results from the measured kinematics are slightly higher than those from the predicted kinematics. Secondary and third trends for KC numbers smaller than 2.0 are again in evidence resulting in changes in force coefficient values by factors of four and 25. Again, gain errors in the recorded velocities are suspected. The water depth has no effect on the trend of the maximum force coefficient.

6.7 Phase Angle

Phase angles of the measured velocity, acceleration, lift force, and total force relative to the wave crest are plotted in Figure 6-18. The velocity and drag force are theoretically in phase with the wave surface profile. The maximum velocity occurs near the wave crest under shallow water conditions. However, waves with $h/L_0$ values greater than 0.2 have maximum velocity and drag force values under the trough yielding phase angles of near 230 degrees. The acceleration phase, which corresponds to the inertia force
Fig. 6-16. CF vs. Re: LWT Kinematics

Fig. 6-17. CF vs. K-C: Measured Kinematics
Fig. 6-18. Time Series Phase Angle vs. $h / L_0$

**Horizontal Pipe**

$h = 11.5$ ft

- $\Delta$ -- Lift Force
- $\times$ -- Velocity & Drag Force
- $+$ -- Inertia Force
- $\bigcirc$ -- Total Force

**Phase Angle (degrees)**

<table>
<thead>
<tr>
<th>Phase Angle (degrees)</th>
</tr>
</thead>
<tbody>
<tr>
<td>360</td>
</tr>
<tr>
<td>270</td>
</tr>
<tr>
<td>180</td>
</tr>
<tr>
<td>90</td>
</tr>
<tr>
<td>0</td>
</tr>
</tbody>
</table>

**Scale**

- $0.01$ to $1.00$

**Legend**

- $\times$ -- Velocity & Drag Force
- $+$ -- Inertia Force
- $\bigcirc$ -- Total Force
- $\Delta$ -- Lift Force

**Graph Title**

Fig. 6-18. Time Series Phase Angle vs. $h / L_0$
phase varies from 240 to 330 degrees depending on wave conditions.

With the exception of deep water conditions, the maximum total force phase is quite consistent, varying from 270 to 330 degrees. The occurrence of the maximum measured lift force occurs simultaneously with the maximum total in the $h/L_0$ range from 0.05 to 0.2. A phase angle summary is attached in Appendix A.

6.8 Comparison with Other Seafloor Cylinder

Grace et al. (1979) experimented a 16-inch outside diameter and 17.5-foot long steel pipe in the ocean offshore from Hawaii. Wave heights up to 17 feet and wave periods of 12 to 17 seconds were experienced at a water depth of 37 feet. In the Reynolds number range from 1.6 to $6.0 \times 10^5$, the mean drag coefficient varied from 0.7 to 0.9 and the inertia coefficient was 2.41.

The results of the present study determined by the maximum value method has the drag coefficient decreasing from 2.0 to 1.0 and the inertia coefficient of 2.5 in the Reynolds number range of 1.0 to 3.0 (see App. Figs.II-17 and II-18). The inertia coefficients are in agreement while the drag coefficients on the short pipe is greater than that of the long pipe. The maximum force coefficient of the long pipe decreased from 5.0 to 2.0 in the $KC$ parameter range from 2.0 to 14.0 when the pipe was placed within 15 degrees of the wave crest lines. The same trend
is observed from the present study, where \( C_F \) value
determined by the measured kinematics decreased from 10.0
to 4.0 in the KC parameter range from 2.0 to 12.0 (see
App. Fig.II-38).

Teng et al. (1986) tested a 8.6-inch diameter and
8.7-foot long smooth cylinder in horizontal orientation at
the same wave channel. The cylinder was placed at 7.8 feet
from the floor in a 11.5 foot water depth. The drag
coefficient of the horizontal cylinder decreased from 1.0
to 0.4 and the inertia coefficient varied from 1.8 to 2.2
for a range in the KC parameter from 4.0 to 20.0.

In the present study on the short, the drag coeffi-
cient determined by the Fourier method decreases from 3.0
to 1.2 and the inertia coefficient is about 2.0 (see App.
Figs.II-11 and II-13). Again, a good agreement exists
between the two inertia force coefficients, while the drag
coefficient of the short pipe on the seabed is much
greater than that of the long slender pipe in the middle
of water column. The maximum force coefficient of the long
cylinder varied from 6.0 to 1.5, while that of the short
pipe is from 6.0 to 3.0 (see App. Fig.II-37).

Kim et al. (1981) experimented with tire models, of
which a model with four tires of 1.3-foot diameter
fastened together to form a pipe shape and placed in the
same orientation as the present study is of interest. The
trend and the magnitude of \( C_F \) versus the KC parameter of
the two experiments are closely matched.
7. RESULTS PART III & IV : HORIZONTAL PLATES

7.1 Introduction

In this chapter, the results from Experiment III and Experiment IV on the horizontal plates are presented. The two experiments are similar in that the same plate is modeled in the same horizontal orientation. The difference is the number of layers in the stack of plates yielding a different elevation of the top plate. Also, the four layers in Part III were tested at a depth of 11.5 feet only, while the three layers in Part IV were examined at both 11.5 and 9.0 feet. The results of both experiments are presented and compared with greater emphasis on Part IV results. The following topics are discussed in the order listed.

(1) The statistical review of measurements
(2) Drag and inertia force coefficients.
(3) Lift force coefficient.
(4) Maximum force coefficient.
(5) Phase lag of velocity and force measurements.
(6) Comparison with other structural shape.

7.2 Measurements

The variance coefficients of measurements indicate that the measurements for the 11.5 foot depth experiment are more consistent than those of a depth of 9.0 feet.
Again, measurements under deep water conditions produce more variation than those under shallow and intermediate water depths. The current measurements under small waves (wave heights less than 1.0 foot) are the least reliable.

Recall that experimental results are excluded if the coefficient of variance exceeds 0.11. This occurs for four out of 19 runs (including the repeated runs) in Part III, while only one of 16 is excluded in Part IV at a depth of 11.5 feet. This difference in variance may be a function of the blocking effect that the four layer stack (Part III) has relative to the three layer stack. The frontal area for Part III represents 21.7 percent of the still water column area, while it was 15.9 for Part IV.

The approximate range of measured values in the Part III and Part IV experiments at the 11.5 foot depth are as follows.

<table>
<thead>
<tr>
<th></th>
<th>(Part III)</th>
<th></th>
<th>(Part IV)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Max.</td>
<td>Min.</td>
<td>Max.</td>
</tr>
<tr>
<td>Wave height (ft)</td>
<td>4.7</td>
<td>0.5</td>
<td>4.7</td>
</tr>
<tr>
<td>Hor. current(ft/sec)</td>
<td>2.7</td>
<td>0.2</td>
<td>2.7</td>
</tr>
<tr>
<td>Hor. force (lb)</td>
<td>-24.6</td>
<td>0.6</td>
<td>-23.7</td>
</tr>
<tr>
<td>Ver. Force (lb)</td>
<td>-33.2</td>
<td>2.7</td>
<td>-27.4</td>
</tr>
</tbody>
</table>

The maximum forces recorded with the four-layer stack are greater that the maximum forces with the three-layer stack. This occurs because the higher elevation of the four-layer stack exposes the top plate to larger velo-
cities and accelerations. The measurements also reveal that the maximum lift force is greater than the maximum horizontal force. The maximum horizontal force opposes the direction of wave propagation and the maximum lift force direction is downward. The absolute maximum horizontal and lift forces occur at an h/L_0 value of 0.2 (see Figs. 5-1 and 6-2 in the previous chapters).

7.3 Drag & Inertia Force Coefficients

Results from Predicted Coefficients

Drag force coefficients determined from the predicted kinematics correlate well with the Reynolds number and the keulegan-Carpenter parameter in a range from 0.2 to 5.0 x 10^5 and 0.1 to 7.0, respectively. C_D value vary from 2.0 to 50.0 exponentially increasing with decreasing values of the two parameters (see Figs. 7-1 and 7-2). In Figure 7-2, the drag coefficient attacks a relative minimum of 2.0 at a KC number of 5.0. The ranges of the parameters and the drag coefficients of the Part III experiments are about the same as that of Part IV demonstrating that the number of plates and the elevation of the plate have little effect on the force coefficients.

The inertia force coefficient is relatively independent of the two parameters. C_I increases gradually from 1.7 to 2.2 with increasing Reynolds number and KC parameters (see Figs. 7-3 and 7-4). A comparison of the
Fig. 7-1. CD vs. Re : LSQ & LWT Kinematics

Fig. 7-2. CD vs. K-C : FORI & LWT Kinematics
Three Layers

Fig. 7-3. CI vs. Re.: LSQ & LWT Kinematics

Three Layers

Fig. 7-4. CI vs. K-C: MXVL & LWT Kinematics
results from Part III and Part IV shows no measurable differences in trends or magnitudes.

**Results from Measured Kinematics**

The drag coefficients from the measured kinematics of Part IV are more tightly correlated against the Reynolds Number and the K-C parameter than that of Part III. The drag coefficient determined by the maximum value method result in the least scatter of all methods when compared to predicted kinematics (see Figs. 7-5 and 7-6). The results from the other methods are more scattered in the lower range of the parameters (the Reynolds number less than $2.5 \times 10^5$ and the KC parameter smaller than 2.0). Comparing the drag coefficients of the three different methods versus the KC parameter in Figure 7-7 reveals a very similar results for the least square method and Fourier method, however, the maximum value method produces relatively higher values than the other two.

The inertia coefficient provides monotonic trends with the Reynolds number and KC parameter. $C^I$ range is greater at lower parameter values, with a lower bound of 0.5 and, then increasing with increasing parameter values before leveling off at about 2.0 (see Figs. 7-8 and 7-9). In Figure 7-9, the formation of a secondary trend, which was discussed in Chapter 6, appears at lower parameter values. The inertia coefficients determined by the maximum value method appears higher than the other two at the
Fig. 7-5. CD vs. Re: MXVL & Measured Kinematics

Fig. 7-6. CD vs. K-C: MXVL & Measured Kinematics
Three Layers

Drag Force:

\[ \frac{CD_{(For1)}}{CD_{(LSQ)}} \]

\[ \frac{CD_{(Mxv1)}}{CD_{(LSQ)}} \]

Inertia Force:

\[ \frac{C1_{(For1)}}{C1_{(LSQ)}} \]

\[ \frac{C1_{(Mxv1)}}{C1_{(LSQ)}} \]

Fig. 7-7. CD & CI Relationships of Different Methods (LWT)
Fig. 7-8. CI vs. Re: FORI & Measured Kinematics

Fig. 7-9. CI vs. K-C: LSQ & Measured Kinematics
upper number of KC parameters.

Figure 5-2 presents the ratio of the drag force to the inertia force. The plate model provides the highest drag force to the inertia force ratio. The ratio ranges from 40 percent to almost 100 percent.

7.4 Lift Force Coefficient

The lift force coefficient determined from the predicted kinematics correlates well with both the Reynolds number and KC parameter. The effective range of the Reynolds number is $0.5 - 4.5 \times 10^5$ and that of the KC number is from 0.3 to 8.0. The relationship is more definitive for predicted kinematics graphed as a function of the KC parameter (see Fig. 7-10) as compared to Reynolds number (see Fig. 7-11). The lift coefficient ranges from 4.0 to near 200.0.

The lift force coefficient from the measured kinematics also show a clear trend with both parameters (see Figs. 7-12 and 7-13). The results from the 9.0 foot water depth yield slightly higher values than those from the 11.5 foot depth. The trends of the lift force coefficient on the governing parameters of Part III and Part IV are comparable.

7.5 Maximum Force Coefficient

The maximum force coefficient decreases exponentially with increasing Reynolds number and KC parameters in a
Fig. 7-10. CL vs. K-C : LWT Kinematics

Fig. 7-11. CL vs. Re : LWT Kinematics
Fig. 7-12. CL vs. Re: Measured Kinematics

Fig. 7-13. CL vs. K-C: Measured Kinematics
pattern similar to that of the lift force coefficient (see Figs. 7-14 and 7-15). The maximum force coefficient ranges from 5.0 to over 100.0. The coefficient correlates well with either the predicted or the measured kinematics, while showing a tighter grouping with the KC parameter. The trends are a little more scattered and more gently sloped for the measured kinematics as compared to the predicted ones. A secondary trend appears again, yielding lower $C_F$ values. The water depth difference is not noticeable with the predicted kinematics, however, the 9.0 foot depth results are of lesser slope than the 11.5 foot depth results when compared to measured kinematics.

7.6 Phase Lag

Figure 7-16 shows the phase lags of the maximum velocity and the forces relative to the wave crest. The maximum velocity occurs near zero degrees as wave theories predict, but it also appears at phase angles of 210 degrees or more when the $h/L_0$ value is greater than 0.2. This is evidence that the absolute maximum velocity occurs under the wave trough. The acceleration phase or the inertia force phase fluctuates the most. The inertia force phase ranges from about 70 to 230 degrees. The total force phase is either near 320 or 110 degrees and is relatively constant at those values. The maximum lift force phase is either zero or 180 degrees.
Three Layers

Fig. 7-14. CF vs. K-C : LWT Kinematics

Fig. 7-15. CF vs. K-C : Measured Kinematics
Fig. 7-16. Time Series Phase Angle vs. $h / L_0$
7.7 Comparison with Other Structural Shapes

Since no experiments similar to the present plate model experiment are known to the author, the results of the horizontal pipe model of the present study are utilized to compare the trends of the two. A summary of the relevant values are as follows.

<table>
<thead>
<tr>
<th></th>
<th>Hor. Pipe</th>
<th>Plate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reynolds No. ( \times 10^5 )</td>
<td>0.1 - 3.0</td>
<td>0.2 - 5.0</td>
</tr>
<tr>
<td>KC parameter</td>
<td>0.2 - 12.0</td>
<td>0.1 - 8.0</td>
</tr>
<tr>
<td>Drag coefficient</td>
<td>1.0 - 17.0</td>
<td>2.0 - 50.0</td>
</tr>
<tr>
<td>Inertia coefficient</td>
<td>2.0 - 2.5</td>
<td>1.5 - 2.0</td>
</tr>
<tr>
<td>Lift force coeffi.</td>
<td>2.5 - 4.5</td>
<td>3.0 - 30.0</td>
</tr>
<tr>
<td>Max. force coeffi.</td>
<td>4.0 - 11.0</td>
<td>4.0 - 40.0</td>
</tr>
</tbody>
</table>

The Reynolds number range is greater for the plate model while the KC parameter range is wider for the pipe model. The trend of all the force coefficients from both experiments are similar. The drag force, lift force and maximum force coefficients decrease exponentially with increasing Reynolds number and KC parameter values, while the inertia coefficient increases with a mild slope. Overall, the force coefficients of the plate model have wider ranges and greater magnitude than that of the horizontal pipe.
8. CONCLUSIONS

8.1 Summary

This thesis is an experiment oriented project, where the technical skills of constructing the test models and prudent execution of the experiments to collect quality data are as important as the methods used in data analysis and the interpretation of the results. Experimental results are heavily dependent on input data and experimental conditions. Much information on the experimental procedures and the data analysis is presented. In addition, all of the numerical results and the computer program used in data processing are included in the appendices to facilitate readers who are involved in a project related to this research and who require background information.

The results of this study show a rational behavior for all force coefficients with respect to both the Reynolds number and the Keulegan-Carpenter parameter making confident design applications a reality.

The following conclusions are drawn based on the experimental results.

(1) A comparison of the results of the present study on the short pipe experiments to previous experiments on long cylinders reveals the same trends. Except for the inertia coefficient, the force coefficients of the short
pipe are greater than that of the long cylinders.

(2) The results from the three layers and the four layers experiments on the plate model indicate that neither the elevation of the test plate from the bottom nor the number of plates affects the force coefficients.

(3) The results from water depths of 9.0 feet and 11.5 feet form a single line indicating that the depth effect seems to be accounted for by the kinematics.

(4) Data smoothing and wave selection are essential for data processing especially for small amplitude waves. Wave height and force measurements are quite reliable throughout the test wave conditions, however, current measurements are difficult to resolve in deep water conditions.

(5) The overall results, in general, show clear trends in the intermediate water wave conditions, while less consistent results are observed in shallow and deep water conditions. The presence of a return flow in the wave channel and its effect on the results are in evidence.

(6) The drag and inertia coefficients correlate quite well with both of the governing parameters, the Reynolds number and the Keulegan-Carpenter parameter over the range of 0.1 to 3.0 x 10^5 and 0.1 to 12.0, respectively. The drag force coefficient decreases from 50 to
0.1 with increasing parameter values. The inertia coefficient moderately increases from 1.5 to 2.8 with increasing parameter values. Among the three different methods used in determining the force coefficients, the results from the least square method and the Fourier method are almost identical, while the values from the maximum value method are greater than the other two, especially for the drag coefficient.

(7) The drag force to inertia force ratio is the greatest for the plate model which ranges from 40 to 90 percent. The ratio for the pipe model is from 10 to 70 percent. The maximum horizontal force occurs in the intermediate water wave conditions in the $h/L_0$ value range of 0.1 to 0.2.

(8) The center of force at the maximum overturning moment on the pipe experiments gradually moves upward as the relative water depth changes from shallow to deep water.

(9) The lift force is significant on the horizontal pipe and plate models reaching from 20 to 140 percent of the respective maximum horizontal forces. The absolute maximum vertical forces are in the downward direction.

(10) The maximum force coefficient follows the trend of the lift force coefficient ranging from 4.0 to 40.0. Except for the horizontal pipe experiment, the absolute
maximum horizontal force occurs in the direction opposite to that of wave propagation.

(11) The phase lags of the velocity and the total force (horizontal force) with respect to the wave crest are consistent while that of the acceleration and the lift force (vertical force) fluctuate.

One can determine a design wave force on a particular reef unit by using the results in this research and the force equations expressed in Chapter 2. The force coefficients, which correspond to the governing parameter values, Reynolds number and Keulegan-Carpenter number, should be used with either predicted or measured kinematics. The parameter values of the reef unit under a wave condition can be determined by the parameter definitions in Chapter 2.

Since the maximum predictable force is the interest of conventional static designs, the first step may be the determination of the maximum horizontal and vertical forces on the unit using the maximum force and the lift force coefficients. A more detailed force analysis can be achieved by determining the drag and inertia forces by one of the three methods. The coefficients from the maximum value methods can predict the most likely maximum drag and inertia force as well as the total force on the unit. However, the total force determined by either the least square method or the Fourier method should be compared
with that of the maximum value method to predict the absolute maximum force.

8.2 Recommendations for Further Work

Artificial reef units are likely to experience the maximum wave force under breaking waves. Further experiments determining the force coefficients under breaking wave conditions will provide the most severe loading conditions on the units.

The experiments with the plate model can be extended by changing the void ratio (the space gap between the layers). Also, experiments with a smaller cross-sectional area of the plate stack, where the layer length could be a half of the wave channel width, could reveal if blocking and diffraction effects are important relative to the behavior of the plate.

Experiments with models of roughened surfaces, which simulate attached marine plants and animals on the reef surfaces, are also of interest.

Finally, concrete units will resist sliding via friction on the seabed. The frictional resistance of concrete pipe and plates on various seabed materials should be determined.
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Dibble, T.L. (1980). Frequency Response Characterization of Current Meters, A Project of MS Degree, Department of Civil Engineering, Oregon State University, Corvallis, Oregon.


Hudspeth, R.T. (1986). *Forces on Marine Structures*, Class Notes, Department of Civil Engineering, Oregon State University, Corvallis, Oregon.


Teng C., and J.H. Nath (1986). "Smooth and Roughened Horizontal Cylinders in Periodic Waves and Current," Report for the National Science Foundation and the Oregon State University Sea Grant College Program, Department of Civil Engineering, Oregon State University, Corvallis, Oregon.
APPENDIX A.
SUPPLEMENTAL PLOTS & DATA

Figure

Part I: Vertical Pipe

I- 1 CD vs. Re : LSQ & LWT Kinematics
I- 2 CD vs. Re : LSQ & Measured Kinematics
I- 3 CD vs. K-C : LSQ & LWT Kinematics
I- 4 CD vs. K-C : LSQ & Measured Kinematics
I- 5 CI vs. Re : LSQ & LWT Kinematics
I- 6 CI vs. Re : LSQ & Measured Kinematics
I- 7 CI vs. K-C : LSQ & LWT Kinematics
I- 8 CI vs. K-C : LSQ & Measured Kinematics
I- 9 CD vs. Re : FORI & LWT Kinematics
I-10 CD vs. Re : FORI & Measured Kinematics
I-11 CD vs. K-C : FORI & LWT Kinematics
I-12 CD vs. K-C : FORI & Measured Kinematics
I-13 CI vs. Re : FORI & LWT Kinematics
I-14 CI vs. Re : FORI & Measured Kinematics
I-15 CI vs. K-C : FORI & LWT Kinematics
I-16 CI vs. K-C : FORI & Measured Kinematics
I-17 CD vs. Re : MXVL & LWT Kinematics
I-18 CD vs. Re : MXVL & Measured Kinematics
I-19 CD vs. K-C : MXVL & LWT Kinematics
I-20 CD vs. K-C : MXVL & Measured Kinematics
I-21 CI vs. Re : MXVL & LWT Kinematics
I-22 CI vs. Re : MXVL & Measured Kinematics
I-23 CI vs. K-C : MXVL & LWT Kinematics
I-24 CI vs. K-C : MXVL & Measured Kinematics
I-25 CD & CI Relationship of Different Methods : LWT (h=11.5 ft)
I-26 CD & CI Relationship of Different Methods : LWT (h= 9.0 ft)
I-27 CD & CI Relationship of Different Methods : Meas. (h=11.5 ft)
I-28 CD & CI Relationship of Different Methods : Meas. (h= 9.0 ft)
I-29 Center of Force Location vs. h/Lo : h=11.5 ft
I-30 Center of Force Location vs. h/Lo : h= 9.0 ft
I-31 CF vs. Re : IWT Kinematics
I-32 CF vs. Re : Measured Kinematics
I-33 CF vs. K-C : IWT Kinematics
I-34 CF vs. K-C : Measured Kinematics
I-35 Time Series Phase Angle vs. h/Lo : h=11.5 ft
I-36 Time Series Phase Angle vs. h/Lo : h= 9.0 ft

Part II : Horizontal Pipe

II- 1 CD vs. Re : LSQ & IWT Kinematics
II- 2 CD vs. Re : LSQ & Measured Kinematics
II- 3 CD vs. K-C : LSQ & IWT Kinematics
II- 4 CD vs. K-C : LSQ & Measured Kinematics
II- 5 CI vs. Re : LSQ & IWT Kinematics
II- 6 CI vs. Re : LSQ & Measured Kinematics
II- 7 CI vs. K-C : LSQ & IWT Kinematics
II- 8 CI vs. K-C : LSQ & Measured Kinematics
II- 9 CD vs. Re : FORI & IWT Kinematics
II-10 CD vs. Re : FORI & Measured Kinematics
II-11 CD vs. K-C : FORI & IWT Kinematics
II-12 CD vs. K-C : FORI & Measured Kinematics
II-13 CI vs. Re : FORI & IWT Kinematics
II-14 CI vs. Re : FORI & Measured Kinematics
II-15 CI vs. K-C : FORI & IWT Kinematics
II-16 CI vs. K-C : FORI & Measured Kinematics
II-17 CD vs. Re : MXVL & IWT Kinematics
II-18 CD vs. Re : MXVL & Measured Kinematics
II-19 CD vs. K-C : MXVL & IWT Kinematics
II-20 CD vs. K-C : MXVL & Measured Kinematics
II-21 CI vs. Re : MXVL & IWT Kinematics
II-22 CI vs. Re : MXVL & Measured Kinematics
II-23 CI vs. K-C : MXVL & IWT Kinematics
II-24 CI vs. K-C : MXVL & Measured Kinematics
II-25 CD & CI Relationship of Different Methods : LWT (h=11.5 ft)
II-26 CD & CI Relationship of Different Methods : LWT (h= 9.0 ft)
II-27 CD & CI Relationship of Different Methods : Meas. (h=11.5 ft)
II-28 CD & CI Relationship of Different Methods : Meas. (h = 9.0 ft)
II-29 Center of Force Location vs. h/Lo : h=11.5 ft
II-30 Center of Force Location vs. h/Lo : h= 9.0 ft
II-31 CL vs. Re : LWT Kinematics
II-32 CL vs. Re : Measured Kinematics
II-33 CL vs. K-C : LWT Kinematics
II-34 CL vs. K-C : Measured Kinematics
II-35 CF vs. Re : LWT Kinematics
II-36 CF vs. Re : Measured Kinematics
II-37 CF vs. K-C : LWT Kinematics
II-38 CF vs. K-C : Measured Kinematics
II-39 Time Series Phase Angle vs. h/Lo : h=11.5 ft
II-40 Time Series Phase Angle vs. h/Lo : h= 9.0 ft

Part III : Four Layers (h=11.5ft)

III- 1 CD vs. Re : LSQ & LWT Kinematics
III- 2 CD vs. Re : LSQ & Measured Kinematics
III- 3 CD vs. K-C : LSQ & LWT Kinematics
III- 4 CD vs. K-C : LSQ & Measured Kinematics
III- 5 CI vs. Re : LSQ & LWT Kinematics
III- 6 CI vs. Re : LSQ & Measured Kinematics
III- 7 CI vs. K-C : LSQ & LWT Kinematics
III- 8 CI vs. K-C : LSQ & Measured Kinematics
III- 9 CD vs. Re : FORI & LWT Kinematics
III-10 CD vs. Re : FORI & Measured Kinematics
III-11 CD vs. K-C : FORI & LWT Kinematics
III-12 CD vs. K-C : FORI & Measured Kinematics
III-13 CI vs. Re : FORI & LWT Kinematics
III-14 CI vs. Re : FORI & Measured Kinematics
III-15 CI vs. K-C : FORI & LWT Kinematics
III-16 CI vs. K-C : FORI & Measured Kinematics
Part IV: Three Layers

IV-1 CD vs. Re : LSQ & LWT Kinematics
IV-2 CD vs. Re : LSQ & Measured Kinematics
IV-3 CD vs. K-C : LSQ & LWT Kinematics
IV-4 CD vs. K-C : LSQ & Measured Kinematics
IV-5 CI vs. Re : LSQ & LWT Kinematics
IV-6 CI vs. Re : LSQ & Measured Kinematics
IV-7 CI vs. K-C : LSQ & LWT Kinematics
IV-8 CI vs. K-C : LSQ & Measured Kinematics
IV-9 CD vs. Re : FORI & LWT Kinematics
IV-10 CD vs. Re : FORI & Measured Kinematics
IV-11 CD vs. K-C : FORI & LWT Kinematics
IV-12 CD vs. K-C : FORI & Measured Kinematics
IV-13 CI vs. Re : FORI & LWT Kinematics

Part IV: Three Layers

IV-1 CD vs. Re : MXVL & LWT Kinematics
IV-2 CD vs. Re : MXVL & Measured Kinematics
IV-3 CD vs. K-C : MXVL & LWT Kinematics
IV-4 CD vs. K-C : MXVL & Measured Kinematics
IV-5 CI vs. Re : MXVL & LWT Kinematics
IV-6 CI vs. Re : MXVL & Measured Kinematics
IV-7 CI vs. K-C : MXVL & LWT Kinematics
IV-8 CI vs. K-C : MXVL & Measured Kinematics

III-25 CD & CI Relationship of Different Methods : LWT
III-26 CD & CI Relationship of Different Methods : Measured
III-27 CL vs. Re : LWT Kinematics
III-28 CL vs. Re : Measured Kinematics
III-29 CL vs. K-C : LWT Kinematics
III-30 CL vs. K-C : Measured Kinematics
III-31 CF vs. Re : LWT Kinematics
III-32 CF vs. Re : Measured Kinematics
III-33 CF vs. K-C : LWT Kinematics
III-34 CF vs. K-C : Measured Kinematics
III-35 Time Series Phase Angle vs. h/Lo : h=11.5 ft
IV-14 CI vs. Re : FORI & Measured Kinematics
IV-15 CI vs. K-C : FORI & LWT Kinematics
IV-16 CI vs. K-C : FORI & Measured Kinematics
IV-17 CD vs. Re : MXVL & LWT Kinematics
IV-18 CD vs. Re : MXVL & Measured Kinematics
IV-19 CD vs. K-C : MXVL & LWT Kinematics
IV-20 CD vs. K-C : MXVL & Measured Kinematics
IV-21 CI vs. Re : MXVL & LWT Kinematics
IV-22 CI vs. Re : MXVL & Measured Kinematics
IV-23 CI vs. K-C : MXVL & LWT Kinematics
IV-24 CI vs. K-C : MXVL & Measured Kinematics
IV-25 CD & CI Relationship of Different Methods : LWT (h=11.5 ft)
IV-26 CD & CI Relationship of Different Methods : LWT (h= 9.0 ft)
IV-27 CD & CI Relationship of Different Methods : Meas. (h=11.5 ft)
IV-28 CD & CI Relationship of Different Methods : Meas. (h= 9.0 ft)
IV-29 CL vs. Re : LWT Kinematics
IV-30 CL vs. Re : Measured Kinematics
IV-31 CL vs. K-C : LWT Kinematics
IV-32 CL vs. K-C : Measured Kinematics
IV-33 CF vs. Re : LWT Kinematics
IV-34 CF vs. Re : Measured Kinematics
IV-35 CF vs. K-C : LWT Kinematics
IV-36 CF vs. K-C : Measured Kinematics
IV-37 Time Series Phase Angle vs. h/Lo : h=11.5 ft
IV-38 Time Series Phase Angle vs. h/Lo : h= 9.0 ft

**Force Comparison of Different Models**

V- 1 Drag Force / Inertia Force
V- 2 Lift Force / Horizontal Force
V- 3 Max. Horizontal Force vs. h/Lo
V- 4 Max. Lift Force vs. h/Lo
### Table

#### Part I: Vertical Pipe

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<td>Time Series Phase Angle</td>
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#### Part III: Four Layers (h=11.5 ft)

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<td>Force Coeff. from Predicted Kinematics</td>
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<tr>
<td>III-4</td>
<td>Force Coeff. from Measured Kinematics</td>
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<tr>
<td>III-5</td>
<td>Time Series Phase Angle</td>
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Part IV: Four Layers

IV-1 Variance Coeff. of Measurements: h = 11.5 ft
IV-2 Variance Coeff. of Measurements: h = 9.0 ft
IV-3 Kinematics Results: h = 11.5 ft
IV-4 Kinematics Results: h = 9.0 ft
IV-5 Force Coeff. from Predicted Kinematics: h = 11.5 ft
IV-6 Force Coeff. from Predicted Kinematics: h = 9.0 ft
IV-7 Force Coeff. from Measured Kinematics: h = 11.5 ft
IV-8 Force Coeff. from Measured Kinematics: h = 9.0 ft
IV-9 Time Series Phase Angle: h = 11.5 ft
IV-10 Time Series Phase Angle: h = 9.0 ft
**Fig. I-1** CD vs. Re : LSQ & LWT Kinematics

**Fig. I-2** CD vs. Re : LSQ & Measured Kinematics
Fig. I-3 CD vs. K-C: LSQ & LWT Kinematics

Fig. I-4 CD vs. K-C: LSQ & Measured Kinematics
Fig. 1-5 CI vs. Re : LSQ & LWT Kinematics

Fig. 1-6 CI vs. Re : LSQ & Measured Kinematics
Fig. I-7  CI vs. K-C: LSQ & LWT Kinematics

Fig. I-8  CI vs. K-C: LSQ & Measured Kinematics
Fig. I-9  CD vs. Re : FORI & LWT Kinematics

Fig. I-10  CD vs. Re : FORI & Measured Kinematics
Fig. I-11 CD vs. K-C: FORI & LWT Kinematics

Fig. I-12 CD vs. K-C: FORI & Measured Kinematics
**Vertical Pipe**

![Graph of CI vs. Re for vertical pipe with data points for 9.0 ft and 11.5 ft.](image)

**Fig. I-13** CI vs. Re: FORI & LWT Kinematics

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**Vertical Pipe**

![Graph of CI vs. Re for vertical pipe with data points for 9.0 ft and 11.5 ft.](image)

**Fig. I-14** CI vs. Re: FORI & Measured Kinematics
Fig. I-15 CI vs. K-C: FORI & LWT Kinematics

Fig. I-16 CI vs. K-C: FORI & Measured Kinematics
Fig. 1-17 CD vs. Re: MXVL & LMT Kinematics

Fig. 1-18 CD vs. Re: MXVL & Measured Kinematics

Vertical Pipe

Δ = 9.0 ft
Θ = 11.5 ft
Fig. I-19  CD vs. K-C: MXVL & LWT Kinematics

Fig. I-20  CD vs. K-C: MXVL & Measured Kinematics
Fig. I-21  CI vs. Re : MXVL & LWT Kinematics

Vertical Pipe

Fig. I-22  CI vs. Re : MXVL & Measured Kinematics
Vertical Pipe

Fig. I-23 CI vs. K-C: MXVL & LWT Kinematics

Fig. I-24 CI vs. K-C: MXVL & Measured Kinematics
Fig. I-25 CD & CI Relationships of Different Methods (LWT)

Fig. I-26 CD & CI Relationships of Different Methods (LWT)
Vertical Pipe  

Drag Force

Inertia Force

Fig. I-27  CD & CI Relationships of Different Methods (Measured)

Vertical Pipe  

Drag Force

Inertia Force

Fig. I-28  CD & CI Relationships of Different Methods (Measured)
Fig. I-29  Center of Force Location vs. $h / L_o$

Fig. I-30  Center of Force Location vs. $h / L_o$
Fig. I-31  CF vs. Re : LWT Kinematics

Fig. I-32  CF vs. Re : Measured Kinematics
Fig. I-33 CF vs. K-C: LWT Kinematics

Fig. I-34 CF vs. K-C: Measured Kinematics
Fig. I-35  Time Series Phase Angle vs. h/Lo

Vertical Pipe  h = 11.5 ft

X--Velocity & Drag Force
---Inertia Force
O--Total Force

Fig. I-36  Time Series Phase Angle vs. h/Lo

Vertical Pipe  h = 9.0 ft

X--Velocity & Drag Force
---Inertia Force
O--Total Force

0.01  0.05  0.10  0.50  1.00

h/Lo
Fig. II-1  CD vs. Re : LSQ & LWT Kinematics

Fig. II-2  CD vs. Re : LSQ & Measured Kinematics
Fig. II-3 CD vs. K-C: LSQ & LWT Kinematics

Fig. II-4 CD vs. K-C: LSQ & Measured Kinematics
Fig. II-5 CI vs. Re: LSQ & LWT Kinematics

Fig. II-6 CI vs. Re: LSQ & Measured Kinematics
Fig. II-7 CI vs. K-C: LSQ & LWT Kinematics

Fig. II-8 CI vs. K-C: LSQ & Measured Kinematics
Fig. II-9  CD vs. Re : FORI & LWT Kinematics

Fig. II-10  CD vs. Re : FORI & Measured Kinematics
Fig.II-11 CD vs. K-C : FORI & LWT Kinematics

Fig.II-12 CD vs. K-C : FORI & Measured Kinematics
Horizontal Pipe

Fig. II-13 CI vs. Re: FORI & LWT Kinematics

Fig. II-14 CI vs. Re: FORI & Measured Kinematics
Fig. II-15 CI vs. K-C: FORI & LWT Kinematics

Horizontal Pipe

Fig. II-16 CI vs. K-C: FORI & Measured Kinematics
Fig. II-17 CD vs. Re: MXVL & LWT Kinematics

Fig. II-18 CD vs. Re: MXVL & Measured Kinematics
**Fig.II-19** CD vs. K-C : MXVL & LWT Kinematics

**Fig.II-20** CD vs. K-C : MXVL & Measured Kinematics
Fig.II-21 CI vs. Re : MXVL & LWT Kinematics

Fig.II-22 CI vs. Re : MXVL & Measured Kinematics
Fig.II-23 CI vs. K-C : MXVL & LWT Kinematics

Fig.II-24 CI vs. K-C : MXVL & Measured Kinematics
Fig. II-25 CD & CI Relationships of Different Methods (LWT)

Fig. II-26 CD & CI Relationships of Different Methods (LWT)
Fig. II-27 CD & CI Relationships of Different Methods (Measured)

Fig. II-28 CD & CI Relationships of Different Methods (Measured)
Fig. II-29  Center of Force Location vs. \( h / L \)

Fig. II-30  Center of Force Location vs. \( h / L \)
Fig.II-31  CL vs. Re : LWT Kinematics

Fig.II-32  CL vs. Re : Measured Kinematics
Fig. II-33  CL vs. K-C : LWT Kinematics

Fig. II-34  CL vs. K-C : Measured Kinematics
Fig.II-35  CF vs. Re : LWT Kinematics

Fig.II-36  CF vs. Re : Measured Kinematics
Horizontal Pipe

Fig.II-37 CF vs. K-C : LWT Kinematics

Fig.II-38 CF vs. K-C : Measured Kinematics
Fig. II-39  Time Series Phase Angle vs. h/Lo 

Fig. II-40  Time Series Phase Angle vs. h/Lo
Fig. III-1  CD vs. Re : LSQ & LWT Kinematics

Fig. III-2  CD vs. Re : LSQ & Measured Kinematics
Fig. III-3  CD vs. K-C : LSQ & LWT Kinematics

Fig. III-4  CD vs. K-C : LSQ & Measured Kinematics
Fig. III-5  CI vs. Re : LSQ & LWT Kinematics

Fig. III-6  CI vs. Re : LSQ & Measured Kinematics
Fig. III-7 CI vs. K-C: LSQ & LWT Kinematics

Fig. III-8 CI vs. K-C: LSQ & Measured Kinematics
Fig. III-9  CD vs. Re : FORI & LWT Kinematics

Fig. III-10  CD vs. Re : FORI & Measured Kinematics
Fig. III-11 CD vs. K-C: FORI & LWT Kinematics

Fig. III-12 CD vs. K-C: FORI & Measured Kinematics
Fig. III-13 CI vs. Re : FORI & LWT Kinematics

Fig. III-14 CI vs. Re : FORI & Measured Kinematics
Fig. III-15 CI vs. K-C: FORI & LWT Kinematics

Fig. III-16 CI vs. K-C: FORI & Measured Kinematics
Fig. III-17 CD vs. Re : MXVL & LWT Kinematics

Fig. III-18 CD vs. Re : MXVL & Measured Kinematics
Fig. III-19 CD vs. K-C : MXVL & LWT Kinematics

Fig. III-20 CD vs. K-C : MXVL & Measured Kinematics
Fig. III-21 CI vs. Re : MXVL & LWT Kinematics

Fig. III-22 CI vs. Re : MXVL & Measured Kinematics
Fig. III-23 CI vs. K-C: MXVL & LWT Kinematics

Fig. III-24 CI vs. K-C: MXVL & Measured Kinematics
Drag Force

Inertia Force

Fig. III-25 CD & CI Relationships of Different Methods (LWT)

Fig. III-26 CD & CI Relationships of Different Methods (Measured)
Fig. III-27  CL vs. Re : LWT Kinematics

Fig. III-28  CL vs. Re : Measured Kinematics
Fig. III-29  CL vs. K-C : LWT Kinematics

Fig. III-30  CL vs. K-C : Measured Kinematics
Fig. III-31  CF vs. Re : LWT Kinematics

Fig. III-32  CF vs. Re : Measured Kinematics
Fig. III-33  CF vs. K-C : LWT Kinematics

Fig. III-34  CF vs. K-C : Measured Kinematics
Four Layers

h = 11.5 ft

Phase Angle (degree)

0
0.01
0.05
0.10
0.50
1.00

Fig. III-35 Time Series Phase Angle vs. h/Lo

h/Lo

---Velocity & Drag Force
+---Inertia Force
O---Total Force
A---Lift Force
Fig. IV-1 \( CD \) vs. \( Re \) : LSQ & LWT Kinematics

Fig. IV-2 \( CD \) vs. \( Re \) : LSQ & Measured Kinematics
Three Layers

CD vs. K-C: LSQ & LWT Kinematics

Fig. IV-3

CD vs. K-C: LSQ & Measured Kinematics

Fig. IV-4
Fig. IV-5  CI vs. Re : LSQ & LWT Kinematics

Fig. IV-6  CI vs. Re : LSQ & Measured Kinematics
Fig. IV-7  CI vs. K-C: LSQ & LWT Kinematics

Fig. IV-8  CI vs. K-C: LSQ & Measured Kinematics
Fig. IV-9  CD vs. Re : FORI & LWT Kinematics

Fig. IV-10  CD vs. Re : FORI & Measured Kinematics
Fig. IV-11 CD vs. K-C: FORI & LWT Kinematics

Fig. IV-12 CD vs. K-C: FORI & Measured Kinematics
Fig. IV-13 CI vs. Re: FORI & LWT Kinematics

Fig. IV-14 CI vs. Re: FORI & Measured Kinematics
Fig. IV-15 CI vs. K-C: FORI & LWT Kinematics

Fig. IV-16 CI vs. K-C: FORI & Measured Kinematics
Three Layers

Fig. IV-17  CD vs. Re : MXVL & LWT Kinematics

Fig. IV-18  CD vs. Re : MXVL & Measured Kinematics
Three Layers

Fig. IV-19 CD vs. K-C: MXVL & LWT Kinematics

![Graph showing CD vs. K-C for MXVL & LWT Kinematics with three layers, indicating data points for 9.0 ft and 11.5 ft.

Fig. IV-20 CD vs. K-C: MXVL & Measured Kinematics

![Graph showing CD vs. K-C for MXVL & Measured Kinematics with three layers, indicating data points for 9.0 ft and 11.5 ft.]
Three Layers

Fig. IV-21  CI vs. Re : MXVL & LWT Kinematics

Three Layers

Fig. IV-22  CI vs. Re : MXVL & Measured Kinematics
Three Layers

Fig. IV-23 CI vs. K-C : MXVL & LWT Kinematics

Fig. IV-24 CI vs. K-C : MXVL & Measured Kinematics
Three Layers

\( h = 11.5 \text{ ft} \)

Drag Force

\[ \star \rightarrow \text{CD (Fori)} / \text{CD (LSQ)} \quad + \rightarrow \text{CD (Mxvi)} / \text{CD (LSQ)} \]

Inertia Force

\[ \bigcirc \rightarrow \text{CI (Fori)} / \text{CI (LSQ)} \quad \times \rightarrow \text{CI (Mxvi)} / \text{CI (LSQ)} \]

Fig. IV-25 CD & CI Relationships of Different Methods (LWT)

Three Layers

\( h = 9.0 \text{ ft} \)

Drag Force

\[ \star \rightarrow \text{CD (Fori)} / \text{CD (LSQ)} \quad + \rightarrow \text{CD (Mxvi)} / \text{CD (LSQ)} \]

Inertia Force

\[ \bigcirc \rightarrow \text{CI (Fori)} / \text{CI (LSQ)} \quad \times \rightarrow \text{CI (Mxvi)} / \text{CI (LSQ)} \]

Fig. IV-26 CD & CI Relationships of Different Methods (LWT)
Three Layers

Drag Force

\[ \text{h} = 11.5 \text{ ft} \]

Inertia Force

\[ \text{h} = 9.0 \text{ ft} \]

Fig. IV-27 CD & CI Relationships of Different Methods (Measured)

Fig. IV-28 CD & CI Relationships of Different Methods (Measured)
Fig. IV-29  CL vs. Re : LWT Kinematics

Fig. IV-30  CL vs. K-C : Measured Kinematics
Three Layers

Fig. IV-31  CL vs. K-C : LWT Kinematics

Fig. IV-32  CL vs. Re : Measured Kinematics
Fig. IV-33  CF vs. Re : LWT Kinematics

Fig. IV-34  CF vs. Re : Measured Kinematics
Fig. IV-36  CF vs. K-C: Measured Kinematics

Fig. IV-35  CF vs. K-C: LWT Kinematics
Fig. IV-37  Time Series Phase Angle vs. h/Lo

Fig. IV-38  Time Series Phase Angle vs. h/Lo
Fig. V-1  Drag Force / Inertia Force

Fig. V-2  Lift Force / Horizontal Force
Fig. V-3  Max. Horizontal Force vs. \( \frac{h}{L} \)

Fig. V-4  Max. Lift Force vs. \( \frac{h}{L} \)
Table I-1. Variance Coefficients of Measurements: Part I Vertical Pipe (h=11.5ft)

<table>
<thead>
<tr>
<th>Run No.</th>
<th>Dean's Stream No.</th>
<th>T (sec)</th>
<th>H (ft)</th>
<th>No. of Waves Analyzed</th>
<th>Beginning Data Point</th>
<th>(Variance Coefficient)</th>
<th>Wave Height Functions</th>
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( ) = runs excluded in plots
< > = unaccepted values
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<th>Run No.</th>
<th>Dean's Stream No.</th>
<th>T (sec)</th>
<th>H (ft)</th>
<th>No. Waves Analyzed</th>
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<th>Current Force</th>
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( ) = runs excluded in plots  < > = unaccepted values
Table I-3. Kinematics Results: Part I Vertical Pipe (h=11.5ft)

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<th>Run No.</th>
<th>Dean's Stream No.</th>
<th>T (sec)</th>
<th>H (ft)</th>
<th>h Lo</th>
<th>Predicted Velocity (ft/sec)</th>
<th>Measured Velocity (ft/sec)</th>
<th>Acceleration (ft/sec²)</th>
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<td></td>
<td></td>
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<td>Avg.</td>
<td>Maximum (-)</td>
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( ) = runs excluded in plots

\(\text{Maximum} (\pm) = \text{maximum velocity towards beach}\)

\(\text{Maximum} (-) = \text{maximum velocity towards wave board}\)
<table>
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<tr>
<th>Run No.</th>
<th>Dean's Stream No.</th>
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<th>H (ft)</th>
<th>h Lo</th>
<th>Predicted Velocity (ft/sec)</th>
<th>Measured Velocity (ft/sec)</th>
<th>Acceleration (ft/sec²)</th>
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( ) = runs excluded in plots

(**+) = maximum velocity towards beach

(-) = maximum velocity towards wave board
Table I-5. Force Coefficients from Predicted Kinematics: Part I Vertical Pipe (h=11.5ft)

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<th>Force Vert Max. (10E+5)</th>
<th>Re</th>
<th>KC</th>
<th>Least Square Fourier</th>
<th>Maximum CF</th>
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**+** = force upward or towards beach
**-** = force downward or towards wave board
*** = coefficients greater than 999.99
( ) = runs excluded in plots
### Table I-6. Force Coefficients from Predicted Kinematics: Part I  Vertical Pipe (h= 9.0ft)

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<th>Run No.</th>
<th>Um(+) (ft/sec)</th>
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<th>Vert Max. (10^(-5))</th>
<th>Re</th>
<th>KC</th>
<th>Least Square</th>
<th>Fourier</th>
<th>Maximum</th>
<th>CL</th>
<th>CF</th>
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</table>

**(+)** = force upward or towards beach  
**(-)** = force downward or towards wave board  
**xxx** coefficients greater than 999.99  
( ) = runs excluded in plots
Table I-7. Force Coefficients from Measured Kinematics: Part I Vertical Pipe (h=11.5ft)

<table>
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<tr>
<th>Run No.</th>
<th>$U_m(+)$ (ft/sec)</th>
<th>Force (lb)</th>
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** (+) upward & towards beach force**

** (-) downward & towards wave board force**

** ***coefficients greater than 999.99**
Table I-B. Force Coefficients from Measured Kinematics: Part I  Vertical Pipe  (h= 9.0ft)

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<th>Re</th>
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**Notes:**

- (+) upward & towards beach force
- (-) downward & towards wave board force
- coefficients greater than 999.99

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<th>H (ft)</th>
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<th>Wave Crest</th>
<th>Max. Velocity</th>
<th>Max. Accel.</th>
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Table I-9. Time Series Phase Angle: Part I Vertical Pipe (h=11.5ft)

unit: degree
Table I-10. Time Series Phase Angle: Part I Vertical Pipe (h = 9.0ft)  

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<th>Max. Velocity &amp; Drag Force</th>
<th>Max. Accel. &amp; Inertia Force</th>
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( ) = runs excluded in plots
Table II-1. Variance Coefficients of Measurements: Part II Horizontal Pipe (h= 9.0ft)

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( ) = runs excluded in plots
< > = unaccepted values
Table II-2. Variance Coefficients of Measurements: Part II Horizontal Pipe (h=11.5 ft)

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( ) = runs excluded in plots
< > = unaccepted values
Table II-3. Kinematics Results: Part II Horizontal Pipe (h = 9.0ft)

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( ) = runs excluded in plots

(+) = maximum velocity towards beach
(-) = maximum velocity towards wave board
Table II-4. Kinematics Results: Part II Horizontal Pipe (h=11.5ft)

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<th>h (ft)</th>
<th>Predicted Velocity (ft/sec)</th>
<th>Measured Velocity (ft/sec)</th>
<th>Acceleration (ft/sec²)</th>
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( ) = runs excluded in plots

**Note:** (+) = maximum velocity towards beach

(-) = maximum velocity towards wave board
Table II-5. Force Coefficients from Predicted Kinematics: Part II Horizontal Pipe (h=9.0ft)

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<th>Hori Max. (10E+5)</th>
<th>Vert Max. (10E+5)</th>
<th>Re</th>
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<th>Least Square Fourier Maximum</th>
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**(+)** = force upward or towards beach  
**(-)** = force downward or towards wave board  
*** = coefficients greater than 9999.99

(*) = runs excluded in plots
Table II-6. Force Coefficients from Predicted Kinematics: Part II Horizontal Pipe (h=11.5ft)

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**Notes:**

- **(+):** force upward or towards the beach
- **(-):** force downward or towards the wave board
- **(°):** runs excluded in plots
- **( ):** coefficients greater than 999.99
Table II-7. Force Coefficients from Measured Kinematics: Part I Horizontal Pipe (h= 9.0ft)

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**Note:**
- (+) upward & towards beach force
- (-) downward & towards wave board force
- Coefficients greater than 999.99
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**(*) upward & towards beach force**

**(-) downward & towards wave board force**

**(***) coefficients greater than 999.99
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( ) = runs excluded in plots
< > = unaccepted values
Table III-2. Kinematics Results: Part III Four Layers (h=11.5ft)

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<th>H (ft)</th>
<th>h Lo</th>
<th>Predicted Velocity (ft/sec)</th>
<th>Measured Velocity (+) (ft/sec)</th>
<th>Measured Velocity (-) (ft/sec)</th>
<th>Predicted Acceleration (ft/sec²)</th>
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( ) = runs excluded in plots

(+): maximum velocity towards beach
(-): maximum velocity towards wave board
Table III-3. Force Coefficients from Predicted Kinematics: Part III Four Layers (h=11.5ft)

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<th>Re</th>
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<th>CL</th>
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**(+)** = maximum velocity towards beach
(-) = maximum velocity towards wave board

** coefficients greater than 999.99
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**Note:**

- (+) upward & towards beach force
- (-) downward & towards wave board force
- ( ) = runs excluded in plots
Table III-5. Time Series Phase Angle: Part III Four Layers (h=11.5ft)

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( ) = runs excluded in plots
Table IV-1. Variance Coefficients of Measurements: Part IV Three Layers (h=11.5ft)

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( ) = runs excluded in plots
< > = unaccepted values
### Table IV-2. Variance Coefficients of Measurements: Part IV Three Layers (h=9.0ft)

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( ) = runs excluded in plots  
< > = unaccepted values
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<th>Acceleration (ft/sec²)</th>
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( ) = runs excluded in plots

**+** = maximum velocity towards beach

**(−)** = maximum velocity towards wave board
Table IV-4. Kinematics Results: Part IV Three Layers (h = 9.0ft)

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<th>Predicted Velocity (ft/sec)</th>
<th>Measured Velocity (ft/sec)</th>
<th>Average (Max.)</th>
<th>Maximum (Max.)</th>
<th>(-) Max.</th>
<th>Acceleration (ft/sec²)</th>
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( ) = runs excluded in plots

(+) = maximum velocity towards beach
(-) = maximum velocity towards wave board
Table IV-5. Force Coefficients from Predicted Kinematics: Part IV Three Layers (h=11.5ft)

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**Note:**

- **(**) = force upward or towards beach
- **(-)** = force downward or towards waveboard
- **XXX** coefficients greater than 999.99
- **(*)** = runs excluded in plots
### Table IV-6. Force Coefficients from Predicted Kinematics: Part IV Three Layers (h = 9.0ft)

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**(+)** = force upward or towards beach  
**(-)** = force downward or towards wave board  
**= runs excluded in plots

**Coeficients greater than 999.99**
Table IV-7. Force Coefficients from Measured Kinematics: Part IV Four Layers (h=11.5ft)

<table>
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<th>Re</th>
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**Note:**
- (+) = force upward or towards beach
- (-) = force downward or towards wave board
- (I) = runs excluded in plots

**Coefficients:**
- **MM** = coefficients greater than 999.99
- **MMM** = force coefficients greater than 999.99
### Table IV-B. Force Coefficients from Measured Kinematics: Part I Three Layers (h= 9.0ft)

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<th>$F_{\text{Vert}}$ Max. (lb)</th>
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- $\text{(+)} = \text{force upward or towards beach}$
- $\text{(-)} = \text{force downward or towards wave board}$
- $\text{coefficients greater than 999.99}$
- $(\ ) = \text{runs excluded in plots}$
### Table IV-9. Time Series Phase Angle: Part IV Three Layers (h=11.5ft)

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<td>0.998</td>
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( ) = runs excluded in plots
Table IV-10. Time Series Phase Angle: Part IV Three Layers (h= 9.0ft)

<table>
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<td>1.80</td>
<td>0.050</td>
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<td>0.500</td>
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<td>8-B</td>
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<td>1.42</td>
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<td>0</td>
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<td>233</td>
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<td>8-C</td>
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<tr>
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<td>0.80</td>
<td>1.000</td>
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</table>

( ) = runs excluded in plots
APPENDIX B.

COMPUTER PROGRAM : PRGM 8

Microsoft FORTRAN77 V3.31 August 1985

Line# 1 7
1 *STORAGE:2
2 *PAGESIZE:59
3 *LARGE
4 *DEBUG
5 C***********************************************************************

6 PROGRAM PRGM 8

7 C***********************************************************************

8 9 C***********************************************************************

10 C 04-Jun-87 Used NCOD (Code Number) to create
11 C PLTDT (Plot Data File)
12 C WSEL (Wave Selection Data)
13 C TABL (Data Summary Table)
14 C 15-Apr-87 Removed subroutines
15 C BADPTS, INTERP, PLOTIT, XLINE, & GETX
16 C which are obsolete when software FIXDTA is used for
17 C smoothing field data
18 C Added Subroutines: CENFOR, & VLPH
19 C Modified measured current for
20 C center of force elevation
21 C current meter time constant & amplitude attenuation
22 C 30-Nov-86 Modified to execute multiple run data continuously
23 C with input data file PARARUN
24 C 30-Oct-86 Added Fourier Method
25 C Added Maximum Force Coefficient
26 C 03-Oct-86 Added acceleration from measured current
27 C 02-Sep-86 Problem with negative values of CI corrected
28 C 18-Aug-86 Added Subroutine MAXVAL
29 C 06-Aug-86 Added GETX.FOR (needs INCHAR.OBJ to link)
30 C Major rearrangement of Subroutines
31 C 23-Jul-86 A new program is a modified version of
32 C Program SGCYLV by D. Standley 21-Feb-86 &
33 C Program LABTEST by Teng Oct-85
34 C Calculates CD & CI
35 C Method: Least Square Method
36 C Uses measured forces of SEAGRANT CYLINDER data &
37 C wave kinematics predicted by Linear Wave Theory
38 C 21-Feb-86 13:50
39 C 28-Aug-85 16:39
40 C Channel Identification of SEAGRANT CYLINDER for Ong Shin
41 C
42 C Channel Identification
43 C
44 C
45 C
46 C
47 C
48 C
49 C
50 C
51 C
52 C
53 C
54 C
55 C

Read in SEAGRANT CYLINDER data and convert it to physical units.
Bad points are removed from the sonic profiler channel.

There are 9 channels of data
There are 256 pre-run zero values per channel.
The data were sampled at 256 points per wave period.
There were 10 periods of data taken (2560 points)
The water surface elevation is IETA = ch# 9
MM #115 was calibrated by J. Ramsden Sep. 10, 1985

Ong-In Shin

CHARACTER NAMEF*9, NAMEZ*9, NAMED*9, IDUM*1, PLTDT*10, DEAN*3

COMMON/MANP/ PI, TWOP1, GRAV, RHQ, VIS, WP, DEP, FREQ, HOWO
COMMON/MANR/ READG(2560, 9)
COMMON/MAMO/ RGTH, DIA, AREA, VOL, DEL
COMMON/MANG/ NCOD, NRUN, NPTS, NPTZ, NPTC, NWAVS, ISTART
COMMON/WVCA/ WL, WH, WK, WKO, WKO2, WKDNEW
COMMON/WVCC/ ISM(9), ISN(9), NPC(9), IP(9)
COMMON/FORE/ FHMV, FHNV, FHMA, AFMH, AFNV, FVMV, FVNV, AFMV, AFNV
COMMON/VEAR/ UMMX, HAMX, WAAMX, TAUH, TAUH, UMPO, UMANE, UMAV
COMMON/LWTO/ UMAX, UDOTM
COMMON/MXCF/ FMH, FTVH
COMMON/FRPH/ FTPH, FLPH, FDPH, FIPH, FDIL, FDIM, FVFH
COMMON/LSGU/ CDL1, CIL1, CDL2, CIL2
DIMENSION VOLTS(2560), CALIB(9)

Description of constants & parameters
IETA : Channel No. for Surface Profile
NCHAN : Total Number of Channels
NPTS : Total Points per Each Run Data (2560 Points)
NPTZ : Total Points per Pre-run Zero,
Also Total Points per Each Wave Data (256 points)
GRAV : Gravity (ft/sec**2)
RHO : Density (slugs/ft**3)
VIS : Viscosity (ft**2/sec)
DIA : Model Diameter (ft)
RGTH : Model Length (ft)
AREA : Model Face Area
VOL : Model Volume (ft**3)
DEL : Surface Roughness
DEP : Water Depth (ft)
WP : Wave Period (sec)
FCBASR & FCBASZ : Frequency Cut Bases used in other Programs
File Logical Units
LUND = 1
LUNZ = 2
Line# 1  7
111  LUNO = 3
112  LUNIN= 4
113  LTDT = 5
114  LWSEL= 6
115  LTABL= 7
116
117  WRITE(*,100)' Enter Run Number to Start :'
118  READ (*,102)NSTRT
119  WRITE(*,100)' Enter Run Number to End :'
120  READ (*, 102)NEND
121  WRITE(*,100)' Enter Run Code (1=Out Data, 2=Plot Data, 3=Wave Select, 4=Table Data, 5=Plot & Table Data) :'
122  READ (*,102)NCOD
123
124    OPEN (LUNIN, FILE=' PARRUN', STATUS=' OLD')
125    IF (NCOD .EQ. 2) THEN
126      OPEN (LTDT, FILE=' PLTDT', STATUS=' NEW')
127    ELSE IF (NCOD .EQ. 3) THEN
128      OPEN (LWSEL, FILE=' WSEL', STATUS=' NEW')
129    ELSE IF (NCOD .EQ. 4) THEN
130      OPEN (LTABL, FILE=' TPBL', STATUS=' NEW')
131    ELSE IF (NCOD .EQ. 5) THEN
132      OPEN (LTDT, FILE=' PLTDT', STATUS=' NEW')
133      OPEN (LTABL, FILE=' TPBL', STATUS=' NEW')
134    ENDIF
135
136    222 READ (4,102)NRUN
137    IF (NRUN .EQ. 115) THEN
138      CLOSE (4)
139      WRITE(5,102)NRUN
140      CLOSE (5)
141      STOP
142    ELSE IF (NRUN .LT. NSTART) THEN
143      DO 12 1=1,9
144        READ (4,101)IDUM
145        END IF
146
147  12 READ (4,101)IDUM
148    GO TO 222
149    END IF
150
151  333 READ(4,201)NAMEF, DEAN
152    INQUIRE (FILE=NAMEF, EXIST=EXISTS)
153    IF (.NOT. EXISTS) THEN
154      DO 15 J=1,8
155        READ (4,101) IDUM
156      GO TO 222
157      END IF
158
159      OPEN(LUND, FILE=NAMEF, STATUS=' OLD', ACCESS=' DIRECT',
160      FORM=' UNFORMATTED', RECL=512)
161  1
162      READ (4,101)NAMEZ
163      OPEN(LUNZ, FILE=NAMEZ, STATUS=' OLD', ACCESS=' DIRECT',
164      FORM=' UNFORMATTED', RECL=512)
165      READ (4,101)NAMEE
OPEN(LUNO, FILE=NAMEO, STATUS='NEW')
READ(4,*) DEP
READ(4,*) WP
READ(4,*) FCBSR, FCBSZ
READ(4,*) NWAVS
READ(4,*) ISTART
KOUNT = 1
WRITE (*,111) NAMEO
WRITE (3,111) NAMEF
WRITE (3,121) NAMEF, DEAN
IF (NCOD .EQ. 3) THEN
  WRITE (6,111) NAMEO
  WRITE (6,*), 'Wave Selection Data'
END IF
IOM4-
IETAT = 9
NCHAN= 9
NPTS = 2560
NPTZ = 256
PI = 4.*ATANT(1.)
TWOPI= 2.*PI
GRAV = 32.174
RHO = 1.939
VIS = 1.25E-5
DEL = 1.
FREQ = (2.*PI) / WP
HOWO = (TWOPI*DEP)/(GRAV*WP**2)
C -------------------------------------------------------
Model dimensions
IF (NRUN .LT. 65) THEN
  DIA = 15.3125 / 12.0
  RGTH = 46.3125 / 12.0
  AREA = 5.0269
  VOL = 4.9537
ELSE
  DIA = 25.0 / 12.0
  RGTH = 30.125 / 12.0
  AREA = 0.8891
  VOL = 1.8528
ENDIF
C ----------------------------------------------------------
Calibration constants
IF (NRUN .LT. 31) THEN
  WRITE (3,*), 'PART I : Vertical Pipe / Diameter (D) = 1.276 ft'
  CALIB(1) = -20.19
  CALIB(2) = 19.97
  CALIB(3) = -18.61
  CALIB(4) = -18.42
  CALIB(5) = -15.44
ELSE IF (NRUN .LT. 65) THEN
WRITE (3,*)
PART II: Horizontal Pipe / Diameter (D) = 16 ft'
CALIB(1) = -20.63
CALIB(2) = 20.48
CALIB(3) = -20.32
CALIB(4) = -20.26
CALIB(5) = -20.26
CALIB(6) = -20.39
ELSE IF (NRUN .LT. 84) THEN
WRITE (3,*)
PART III: Four Plate Layers / Diameter (D) = 12.083 ft'
CALIB(1) = -20.45
CALIB(2) = 20.32
CALIB(3) = -19.49
CALIB(4) = -19.28
CALIB(5) = -19.62
CALIB(6) = -19.52
ELSE
WRITE (3,*)
PART IV: Three Plate Layers / Diameter (D) = 7.67
CALIB(1) = -20.89
CALIB(2) = 20.48
CALIB(3) = -19.86
CALIB(4) = -19.93
CALIB(5) = -20.08
CALIB(6) = -19.97
ENDIF

C-----------------------------------------------
C Read the zeroes first and average them.
C Then read the force data and subtract the ZERO.
C Convert the force to lbs from volts.
C For the current meters channels 7,8 convert to Ft/sec
C For water surface channel 9 convert to Feet
DO 20 ICHAN=1,9
IBAD = 0
IF(ICHAN .EQ. IETA) IBAD = 1
CALL READIN (LUNZ, NCHAN, ICHAN, VOLTS, NPTZ, IBAD)
SUM = 0.
DO 22 I=1,NPTZ
SUM = SUM + VOLTS(I)
ZERO = SUM / REAL(NPTZ)
IBAD = 0
IF(ICHAN .EQ. IETA) IBAD = 1
CALL READIN (LUND, NCHAN, ICHAN, VOLTS, NPTS, IBAD)
DO 24 I=1,NPTS
24 READG(I,ICHAN) = (VOLTS(I) - ZERO) * CALIB(ICHAN)
CONTINUE

C --------------------------------------------------------
Cal]. Sub. WAVCHA for wave characteristics line=467
CALL WAVCHA (w, WLD, DWLD, DGT2, CWP, CWH)

C ----------------------------------------------------------
Call Subr. CENFOR for center of force 709
CALL CENFOR (RTDM, RTDN, RTAD)

C ----------------------------------------------------------
Call Subr. MESCAL for measured & calculated values 830
CALL VELACL (PKC2, REN2, CHVP, CHVA)

C ----------------------------------------------------------
Call Subr. VLPH for velocity phase lag 1143
CALL VLPH (DHVM)

C ----------------------------------------------------------
Call Subr. FORCES for various measured forces 1201
CALL FORCES (CFHP, CFHA)
IF (NCOD .EQ. 3) GO TO 444

C ----------------------------------------------------------
Call Subr. Linear Wave Theory for water kinematics 1428
CALL LWT (PKCI, REN1)

C ----------------------------------------------------------
Call Subr. Least Square Method for CD, CI 1567
CALL LSQ

C ----------------------------------------------------------
Call Subr. Fourier Averaged Method for CD, CI 1705
CALL FOUAVG (CDF1, CIF1, CDF2, CIF2)

C ----------------------------------------------------------
Call Subr. Maximum Value Method for CD, CI 1798
CALL MAXVAL (CDM1, CIM1, CDM2, CIM2)

C ----------------------------------------------------------
Call Subr. Maximum Force Coefficient for CF1, CF2 1914
CALL MXFCEF (CF1, CF2, CL1, CL2)

C ----------------------------------------------------------
Call Subr. FRPP for Force Phases & Proprtions 1967
CALL FRPP

IF ( (NCOD .EQ. 2).OR. (NCOD .EQ. 5) ) THEN
DFL1 = CDF1 / CDL1
DML1 = CDM1 / CDL1
EFL1 = CIF1 / CIL1
EML1 = CIM1 / CIL1
DFL2 = CDF2 / CDL2
DML2 = CDM2 / CDL2
EFL2 = CIF2 / CIL2
EML2 = CIM2 / CIL2
WRITE (5,102) NRUN
WRITE (5,641) WLD, DWLD, DGT2, RTDM, RTDN, RTAD
WRITE (5,611) PKC2, REN2, PKC1, REN1
WRITE (5,621) CDL1, CIL1, CDL2, CIL2
WRITE (5,621) CDF1, CIF1, CDF2, CIF2
WRITE (5,621) CDM1, CIM1, CDM2, CIM2
C----------------------------------------------------------
C Determines max coefficients of variance for all possible sets
C of 3 or more consecutive waves.
C There are 10 sets per run.

IF (NCOD .EQ. 3) THEN
  WRITE (6,151) NWAVS,ISTART
  WRITE (6,641) CWP,CWH,CHVP,CHVA,CFHP,CFHA
  CVMX = CWP
  IF (CWH .ST. CVMX) CVMX = CWH
  IF (CHVP .GT. CVMX) CVMX = CHVP
  IF (CHVA .ST. CVMX) CVMX = CHVA
  IF (CFHP .GT. CVMX) CVMX = CFHP
  IF (CFHA .GT. CVMX) CVMX = CFHA
  WRITE (6,161) CVMX
  NWAVS = NWAVS - 1
  IF (NWAVS .EQ. 2) THEN
    IF ((NWAVS .EQ. 2).AND.(KOUNT .EQ. 4)) GO TO 666
    KOUNT = KOUNT + 1
    NWAVS = 6 - KOUNT + 1
    ISTART = ISM(2)
  END IF
GO TO 555
END IF

IF ((NCOD .EQ. 4).OR.(NCOD .EQ. 5)) THEN
  WRITE (6,121) NRMEF,DEAN
  WRITE (6,313) WP,WH,NWAVS,ISM(1),CWP,CWH,CHVP,CHVA,CFHP,CFHA
  WRITE (6,323) WP,WH,DWLD,UMAX,UMAV,UMPQ,UMNE,UDOTM,HAAM
  WRITE (6,343) UMAX,FMH,FMV,REN1,PKC1,CDL1,CIL1,CDF1,CIF1,
               CDM1,CM1,CL1,CF1
  WRITE (6,343) UMMX,FMH,FMV,REN2,PKC2,CDL2,CIL2,CDF2,CIF2,
               CDM2,CM2,CL2,CF2
  WRITE (6,361) DWLD,DHVM,FDPH,FIPH,FTPHE,FLPH,FDIM,FVFH
END IF

CLOSE (LUND)
CLOSE (LUNZ)
CLOSE (LUND)
READ (4,101) IDUM
READ (4,102) NRUN
IF (NRUN .GT. NEND) THEN
  CLOSE (4)
  IF (NCOD .EQ. 2) CLOSE (5)
  IF (NCOD .EQ. 3) CLOSE (6)
  IF (NCOD .EQ. 4) CLOSE (7)
  STOP
END IF
GO TO 333
Line# 1  7
  386  387  100  FORMAT (A, \`
  388  101  FORMAT (A)
  389  102  FORMAT (I5)
  390  104  FORMAT (2I5)
  391  106  FORMAT (4F8.3)
  392  111  FORMAT (6X,A, '/')
  393  121  FORMAT (6X,'Data File = ',A, '/' Deans Number = ',A, '/)
  394  151  FORMAT (2I6)
  395  161  FORMAT (F8.4)
  396  201  FORMAT (2A)
  397  313  FORMAT (F7.3,F7.2,2I5,6F6.3, '/)
  398  323  FORMAT (F7.3,F7.2,F7.3,6F6.2, '/)
  399  343  FORMAT (3F7.2,E8.3,9F7.2, '/)
  400  361  FORMAT (2F7.2,4F7.0,2F7.2)
  401  601  FORMAT (2I5)
  402  611  FORMAT (F8.3,E10.4,F8.3,E10.4)
  403  621  FORMAT (4F8.3)
  404  641  FORMAT (6F8.3)
  405  651  FORMAT (8F8.3)
  406  END

Name  Type  Offset  P Class
MH    REAL  16/FORE /
AFMV  REAL  32 /FORE /
AFNH  REAL  20 /FORE /
AFNV  REAL  36 /FORE /
AREA  REAL  8 /MAMO /
ATAN  INTRINSIC
      REAL
CALIB REAL  0 LARGE
CDF1  REAL  166
CDF2  REAL  174
CDL1  REAL  0 /LSQU /
CDL2  REAL  8 /LSQU /
CDM1  REAL  182
CDM2  REAL  190
CF1   REAL  198
CF2   REAL  202
CFHA  REAL  154
CFHP  REAL  150
CHVA  REAL  142
CHVP  REAL  138
CIF1  REAL  170
CIF2  REAL  178
CIL1  REAL  4 /LSQU /
CIL2  REAL  12 /LSQU /
CIM1  REAL  186
CIM2  REAL  194
_1    REAL  206
_2    REAL  210
CVMX  REAL  246
CWH   REAL  114
CP    REAL  110
DEAN  CHAR*3  42
SUBROUTINE READIN(LUN, NCHAN, ICHAN, VOLTS, NPTS, IBAD)

This subroutine will read from unit LUN. The data are converted to voltages and passed back in VOLTS.

The data file is assumed to be in 512 byte blocks of 256 points per block.

LUN .. Is the logical unit to read from.
NCHAN .. Is the number of channels of data in LUN
ICHRN .. Is the channel number to read
VOLTS .. Is the array of voltages returned to calling program
NPTS .. Is the number of points to read

COMMON/MANIP/ PI, TWOPI, GRAV, RHO, VIS, WP, DEP, FREQ, HOWO
DIMENSION ISUF(2560), VDLTS(NPTS)

Read in the data

IF(IBAD .EQ. 1)CALL BADPTS(IBUF,NPTS)

Convert bits to voltages

IF (HOWO.GT.0.45) THEN
    DO 18 I=1,NPTS
        VOLTS(I) = REAL((IBUF(I)) / 409.5 - 5.0)/10.0
    18
ELSE
    DO 20 I=1,NPTS
        VOLTS(I) = REAL(IBUF(I)) - 5.0
    20
Line# 1  7  
463    END IF 
464    RETURN 
465   100 FORMAT('0***** READIN ERROR AT IBLK.=',I4,':  ICHAN =',I4) 
466   101 FORMAT('0***** Number of points read for channel #',I3,': ', 
467       1   15,': There were ',I5,': points asked for. *****') 
468    END 

Name   Type   Offset P Class
      DEP  REAL    24 /MANP / 
      FREQ REAL    28 /MANP / 
      GRAV REAL    8 /MANP / 
      HOWO REAL    32 /MANP / 
      I  INTEGER*2  528 
      IBLK INTEGER*2  512 
      IBUF INTEGER*2  0 LARGE 
      ICHAN INTEGER*2  8 * 
      J  INTEGER*2  514 
      K  INTEGER*2  522 
      K1 INTEGER*2  518 
      K2 INTEGER*2  520 
      LUN INTEGER*2  0 * 
      NCHAN INTEGER*2  4 * 
      QINT INTEGER*2  526 
      NPTS INTEGER*2  16 * 
      PI REAL    0 /MANP / 
      RHO REAL    12 /MANP / 
      TWOPI REAL    4 /MANP / 
      VIS REAL    16 /MANP / 
      VOLTS REAL    12 * LARGE 
      WP REAL    20 /MANP / 

469 $PAGE
SUBROUTINE WAVCHA (INDEX, WLD, DWD, DGT2, CWP, CWH)

READS & Calculates Wave Characteristics

WK : Wave Number
WH : Wave Height
ISPI : Index of the Surface Profile chosen on screen
from Subroutine GETX

NPTC : Number of Points Considered

IPA-G: Reference index of wave surface profile

ISM : Index of Surface Profile Maximum

WLD : Wave Length Deep Water

WLD : Wave Length

C ---------------------------------------------------

COMMON/MANP/ PI, TWODI, GRAV, RHO, VIS, WP, DEP, FREQ, HOWO
COMMON/MANR/ READS (2560, 9)
COMMON/MAMD/ RGTH, DIA, AREA, VOL, DEL
COMMON/MANG/ NCOO, NRUN, NPTS, NPTI, NPTC, NAWVs, ISTART
COMMON/MWCA/ WL, WH, WK, WKD, WKD, WKNEW
COMMON/MWCC/ ETA(2560)
COMMON/MVCT/ IPA(S), IPB(9), IPC(9), IPD(9), IPE(9), IPF(9), IPS(S)
DIMENSION RMAX(9), RMIN(9), DIF(9)

Calculates Wave Number, WK, using Newton-Raphson Method
See Subroutine Wvlen of Hudspeth

IF (INDEX.EQ.1) GO TO 26
WKOD = (TWODI/WP)**2*DEP/GRAV

NN = 1
IF (((WKOD-TWODI).GT.0.) GO TO 24
WKD = WKOD

TH = TANH(WKD)
EPS = WKOD - WKD * TH
CH = COSH(WKD)
SLOPE = WKD/(CH**2) + TH
WKN = WKD NEW

IF (ABS(WKD-WKDN).LE.1.E-4) GO TO 26
IF (NN.GT.20) GO TO 22

WKD = WKDN

GO TO 20

WRITE (*,'(A)')

STOP

WKDNEW = WKD

GO TO 20

WRITE ('(A)',30)

30 STOP

READS in Surface Profile Data (ETA)
Determine the starting point (= wave crest of third wave)
of the data processing
DO 30 LP=1, NPTS

ETA (LP) = READG(LP,9)

CONTINUE

FMAX = ETA(513)

DO 35 K=513,768

IF (ETA(K).GT.FMAX) THEN
  FMAX = ETA(K)
  INDF = K
END IF

CONTINUE

ETA (513)

DO 36 K=769,1024

IF (ETA(K).GT.SMAX) THEN
  SMAX = ETA(K)
  INDS = K
END IF

CONTINUE

SMAX = ETA(769)

CONTINUE

FDIF = INDS - INDF

IF ((FDIF.LT.192).OR. (FDIF.GT.320)) THEN
  FMAX = ETA(577)
  DO 37 K=577,832
    IF (ETA(K).GT.FMAX) THEN
      FMAX = ETA(K)
      INDF = K
    END IF
  CONTINUE
END IF

END IF

ISPI = INDF

ISPI = ISTART

---------------------------------------------------------------

C Determines Individual Maximum Wave Height & its index

LWAVS = NWAVS + 1

DO 40 II=1, LWAVS

IPB(II) = (II-1) * 256 + ISPI

IPI(II) = IPB(II) - 256/4

IPA(II) = IPB(II) - 256/4

IPC(II) = IPB(II) + 256/4

IPD(II) = IPB(II) + 256/2

IPE(II) = IPC(II) + 256/2

IPF(II) = IPB(II) + 256

IPG(II) = IPC(II) + 256

RMAX(II) = ETA (IPA(II))

DO 42 JM=IPA(II), IPC(II)
  IF (ETA(JM).GT. RMAX(II) ) THEN
    RMAX(II) = ETA (JM)
    IBEGIN = JM
  END IF
CONTINUE

YMAX = ETA (IBEGIN)
DO 43 JP = IBEGIN , IPC(II)
IF ( ETA (JP) .EQ. YMAX ) THEN
IEND = JP
END IF
CONTINUE

ISAME = IEND - IBEGIN
IF (ISAME .GT. 32) THEN
WRITE (3,'***ERROR IN MAX SURFACE INDEX***')
ENDIF
ISM(II) = (ISAME) / 2 + IBEGIN
IF (ISM(II).GT.256) THEN
WRITE (3,'***ERROR IN SURFACE MAX INDEX***ISM',ISM(II))
ENDIF
CWRITE (3,'IBEGIN=',IBEGIN,' IEND=',IEND,' ISM=',ISM(II))
C ----------------------------------------------------------
C
Determines Individual Minimum Wave Height & its index
RMIN(II) = ETA ( IPC(II) )
DO 44 JN = IPC(II), IPE(II)
IF ( ETA (JN) .LT. RMIN(II) ) THEN
RMIN(II) = ETA (JN)
JBEGIN = JN
END IF
CONTINUE
YMIN = ETA (JBEGIN)
DO 46 JQ = JBEGIN, IPE(II)
IF ( ETA (JQ) .EQ. YMIN ) THEN
SEND = JQ
END IF
CONTINUE
JSAME = JEND - JBEGIN
IF (JSAME .GT. 32) THEN
WRITE (3,'***ERROR IN MIN SURFACE INDEX***')
ENDIF
ISN(II) = (JSAME) / 2 + JBEGIN
C -----------------------------------------
C
Standard Deviation of Wave Period & Wave Height
NPCT = 0.
DO 51 K = 1, NWAVS
NPC(K) = ISM(K + 1) - ISM(K)
NPCT = NPC(K)+NPCT
WPP = REAL(NPCT) / REAL(NWAVS)
SUM = 0.
DO 53 K=1, NWAVS
SUM = REAL(NPC(K))**2 + SUM
53 SDWP = SQRT((SUM/ REAL(NWAVS))-(WPP**2))
CWP = SDWP / WPP
HSUM = 0.
DO 61 J =1,NWAVS  
DIF(J) = RMAX(J) - RMIN(J)  
HSUM = HSUM + DIF(J)  
WH = HSUM / REAL(NWAVS)  
SUM = 0.  
DO 63 J=1,NWAVS  
SUM = DIF(J)**2 + SUM  
SDWH = SQRT((SUM/REAL(NWAVS))-(WH**2))  
CWH = SDWH / WH  
IF (CWP.GT.0.05) THEN  
WRITE (3,*)'*** CHECK CONSISTENCY OF WAVE PERIOD ***'  
END IF  
IF (CWH.GT.0.05) THEN  
WRITE (3,*>'*** CHECK CONSISTENCY OF WAVE HEIGHT ***'  
WRITE (3,207) (DIF(K),K=1,NWAVS)  
END IF  
C   
C Determines Wave Length  
WLD = (GRAV * (WP**2)) / TWOPI  
DWLD= DEP/WLD  
DGTE= DEP/(GRAV*(WP**2))  
WL = TWOPI / WK  
WL = WLD*SQRT(TANH(((PI**2)*DEP)/WLD))  
IPT = ISM(LWAVS) - 1  
NPTC = IPTE - ISM(1) + 1  
C Wave Characteristics  
WRITE (3,303) DEP,WP  
WRITE (3,307) NWAVS,ISM(1)  
WRITE (3,311) WH,WL  
N=NWAVS  
WRITE (3,*)' Wave Crest Index :'  
WRITE (3,201) (ISM(K), K=1,N)  
WRITE (3,251) SDWP,CWP  
WRITE (3,201) (NPC(K), K=1,N)  
WRITE (3,271) SDWH,CWH  
WRITE (3,207) (DIF(K), K=1,N)  
C WRITE (3,*)' Wave Number, WK = ',WK  
WDWL = DEP / WL  
IF (WDWL .GT. 0.5) THEN  
WRITE (3,*)' Deep Water :'  
ELSE IF (WDWL .GT. 0.05) THEN  
WRITE (3,*)' Intermediate Water :'  
ELSE  
WRITE (3,*)' Shallow Water :'  
END IF  
DIAWL = DIA/WL  
DIAWH = DIA/WH  
WRITE (3,401) WDWL,DWLD,DIAWL,DIAWH
LINE 1 7

630 IF (DIAWL .GE. 0.15) GOTO 222
691 IF (DIAWH .GE. 1.00) GOTO 222
692 GOTO 223
693 222 WRITE (3,*) '***Morison Equation Applicability ***'
694 223 CONTINUE

696 107 FORMAT (3F6.3)
697 201 FORMAT (8X,8I6)
698 251 FORMAT (8X,'Wave Crest Period : ', 'SDWP=', F5.2, 3X, 'CVWP=', F5.3)
699 271 FORMAT (8X,'Wave Height Amplit : ', 'SDWH=', F5.3, 3X, 'CVWH=', F5.3)
700 207 FORMAT (8X,8F6.2)
701 303 FORMAT (6X,'Water Depth (h) =', F6.1, ' ft', 3X, 'Wave Period (T) =', F16.3, ' sec', '/)
702 307 FORMAT (6X,'Waves Considered =', I4, 6X, 'Beginning Point =', I4)
703 308 FORMAT (6X,'Wave No.', I4, ' = ', F8.3)
704 311 FORMAT (6X,'Wave Height (H) =', F6.2, ' ft', 3X, 'Wave Length (L) =', F16.1, ' ft')
705 401 FORMAT (8X,'h/L =', F5.3, 3X,'h/Lo =', F5.3, 3X,'D/L =', F5.3, 3X,'D/H =', F5.3)
706 RETURN
707 END

Name    Type     Offset   P    Class
S     AREA     REAL     8       /MAMO /
       CH      REAL     714
COSH    REAL     20 *    /MAMO /
CWH     REAL     16 *    /MAMO /
DEL     REAL     16       /MAMO /
DEP     REAL     24       /MANP /
DGT2    REAL     12 *    /MAMO /
DIR     REAL     4        /MAMO /
DIAWH   REAL     834
DIAWL   REAL     830
DIF     REAL     0    LARGE
DWLD    REAL     8 *    /WVCR /
EPS     REAL     710
ETR     REAL     0        /WVCR /
FDIF    REAL     740
FMAX    REAL     726
FREQ    REAL     28       /MANP /
GRAV    REAL     8        /MANP /
HWO     REAL     32       /MANP /
HSLUM   REAL     806
IBEGIN  INTEGER*2  756
IEND    INTEGER*2  766
II      INTEGER*2  748
INDEX   INTEGER*2  0 *
IP      INTEGER*2  732
INDS    INTEGER*2  738
IPA     INTEGER*2  0    /WVCT /
IPB     INTEGER*2  18    /WVCT /
IPC     INTEGER*2  36    /WVCT /
SUBROUTINE CENFOR (RTDM,RTDN,RTAD)  

Computes Sum of horizontal & vertical forces and  
the Point of Interest, which is the distance from the bottom  
of the tank to the center of the horizontal force

FHM : Sum of horizontal forces, + Towards the beach  
- Towards the wave board
FVM : Sum of vertical forces, + up  
- down
FMD : Moment Horizontal
CFE : Center of Force Elevation
SCE : Sum of Center Elevation
PTEL : Avg Distance of the Point of Interest from Bottom
GAP : Distance between model bottom line and wave channel floor
DCFL : Distance from Center of Force divided by model vert length

COMMON/MANP/ P1, TWDP, GRAY, RHO, VIS, WP, DEP, FREQ, HOWO  
COMMON/MANR/ READG(2560,9)  
COMMON/MANO/ RTBM, DIA, AREA, VOL, DEL  
COMMON/MANG/ NCDI, NRUN, NPTS, NPTC, NWAY, ISTART  
COMMON/WVCC/ ISM(9), ISN(9), NPC(9), IPI(9)  
COMMON/CENF/ FHM(2560), FVM(2560)  
COMMON/CENO/ PTEL, COF  
DIMENSION F(6)  

Calculates Sum of Horz & Vert Meas Forces  
Finds the distance from the bottom to the center of force

DO 60 L = 1, NPTS  
DO 62 M = 1, 6  
F(M) = READG(L,M)  
FHM(L) = F(2) + F(4) + F(6)  
FVM(L) = F(1) + F(3) + F(5)  
CONTINUE  
FMOM = 0.  
FMOD = 0.  
IPTE = ISM(1) + NPTC - 1  
DO 10 I = ISM(1), IPTE  
DO 5 J = 1, 6
F(J) = READG(I,J)  
IF (NRUN .LT. 30) THEN  
FMD = (F(2)*5.325) + (F(4)*5.875) + (F(6)*46.063)  
ELSE IF (NRUN .LT. 65) THEN  
FMD = (F(2)*11.875) + (F(4)*4.875) + (F(6)*14.875)  
ENDIF  
FMOM = FMD
767   CFEM = FMOM / FHM(I)
768   END IF
769   IF (FM0 .LT. FM0N) THEN
770     FM0N = FM0
771   CFEN = FM0N / FHM(I)
772   END IF
773   CONTINUE
774   WRITE (3,*) CFEM,CFEN
775   IF (NRUN .LT. 31) THEN
776     PTEL = (RGTH / 2.) + 0.0312
777     ELSE IF (NRUN .LT. 65) THEN
778       PTEL = (DIA/ 2.) + 0.1042
779     ELSE IF (NRUN .LT. 83) THEN
780       PTEL = 2.2083 + ((3.25/2.)/12.)
781     ELSE
782       PTEL = 1.5417 + ((3.25/2.)/12.)
783   END IF
784
785   C-----------------------------
786   C Determines validity of PTEL &
787   C the max. and min. distance of center of force from model centroid
788   IF (NRUN .LT. 30) THEN
789     GAP = 0.0312
790     CNTE = ( RGTH/2.) + GAP
791     ELSE IF (NRUN .LT. 65) THEN
792       GAP = 0.1042
793     ELSE IF (NRUN .LT. 83) THEN
794     ELSE
795     GO TO 444
796   ENDIF
797   DMCR = (CFEM/12.) -CNTE
798   DNCR = (CFEN/12.) -CNTE
799   ADR = DMCR - DNCR
800   RTDM = DMCR/RGTH
801   RTDN = DNCR/RGTH
802   RTAD = ADR/RGTH
803   WRITE (3,202) PTEL
804   IF (NRUN .GT. 64) GO TO 444
805   WRITE (3,204) RTDM,RTDN,RTAD
806
807   FORMAT (8X, 'RTDM=' , F6.2, 3X, 'RTDN=' , F6.2, 3X, 'RTAD=' F6.2)
808
809   202 FORMAT ('* Model Centroid Elevation from bottom = ',F8.4)
810   204 FORMAT (8X,'RTDM=',F6.2,'RTDN=',F6.2,'RTAD=',F6.2)
811   444 RETURN
812   END

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SUBROUTINE VELACL (PKC2, REN2, CHVP, CHVA)

Velocity Variables

TAUV : Time Constant for Vert Velo of MM Current Meter
TAUH : Horz Velo
ELMM : Elevation of MM Current meter from channel bottom
UMES : Measured Horizontal Velocity
WMES : Measured Vertical Velocity
DOVL : Depth / Wave Length
UMMX : Meas Max Velo (absolute & averaged)
IHMV : Index of Max Velo
IHNV : Index of Min Velo
SMV : Sum of Absolute Max Horz Velo

Acceleration Variables

HACL : Calculated Acceleration (5 Points Slope)
HAAM : Calc Max Acc (absolute & averaged)
IHMA : Index of Max Acc
IHNA : Index of Min Acc
SMA : Sum of Absolute Max Acc
UAMX : Horiz Velo Absolute Maximum
AAMX : Absolute Max
ZURM : Index of Horiz Velo at Absolute Max
IRAM : Index of Horiz at Absolute Max

Time Constants for MM Current Meter (from J. Ramsden)
TAUV = 0.29
TAUH = 0.26

Velocity magnitude modifying factor
FACU = SQRT ((FREQ * TAUH)**2 + 1.0)
FACW = SQRT ((FREQ * TAUH)**2 + 1.0)
DOVL = DEP / WL
IF (NRUN .LT. 65) THEN
  ELMM = 34.25 / 12.
ELSE IF (NRUN .LT. 84) THEN
  ELMM = 46.375 / 12.
ELSE
  ELMM = 34.5 / 12.
ENDIF

IF (DOVL .LE. 0.05) THEN
  DO 40 3=1, NPTS
    U = READG(J,8) * FACU
    W = READG(J,7) * FACW
    UMES(J) = U
    WMES(J) = W * (PTEL/ELMM)
  40 CONTINUE
ELSE IF (DOVL .LE. 0.5) THEN
  CHUP = COSH ((TWOPI * PTEL)/WL)
  CHDW = COSH ((TWOPI * ELMM)/WL)
  CVUP = SINH ((TWOPI * PTEL)/WL)
  CVDW = SINH ((TWOPI * ELMM)/WL)
  DO 42 3=1, NPTS
    U = READG(J,8) * FACU
    W = READG(J,7) * FACW
    UMES(J) = U * (CHUP/CHDW)
    WMES(J) = U * (CVUP/CVDW)
  42 CONTINUE
ELSE
  EPUP = EXP ((TWOPI *(DEP-PTEL))/WL)
  EPDW = EXP ((TWOPI *(DEP-ELMM))/WL)
  DO 44 J =1, NPTS
    U = READG(J,8) * FACU
    W = READG(J,7) * FACW
    UMES(J) = U * (EPUP/EPDW)
    WMES(J) = W * (EPUP/EPDW)
  44 CONTINUE
ENDIF

Calculates Acceleration from Measured Velocity Readings
5 Points calculation
DO 50 K = 3, NPTS - 2
  KAF = K - 2
  KAT = K + 2
  HACL(K) = ( UMES(KAT) - UMES(KAF) ) / (WP/64.0)
50 CONTINUE
C Determines Max Horiz Velocity & its index

SMV = 0.
SWV = 0.
SMA = 0.
SUMP = 0.
SUMN = 0.
LWAVS = NWAVS + 1

DO 20 II=1, LWAVS

UMM(II) = UMES(IPA(II))
DO 22 MJ = IP1(II), IPD(II)
IF (UMES(MJ) .GE. UMM(II)) THEN
UMM(II) = UMES(MJ)
IBEGIN = MJ
END IF
22 CONTINUE

YMX = UMES(IBEGIN)
DO 24 MK = IBEGIN, IPD(II)
IF (UMES(MK) = YMX) THEN
IEND = MK
24 CONTINUE

IHMV(II) = (IEND - IBEGIN) / 2 + IBEGIN

WRITE (3,*) IPP(II), IPC(II)
WRITE (3,*) IEND, IBEGIN
WRITE (3,*) IHMV(II)

WMM(II) = WMES(IPD(II))
DO 35 KB = IPC(II), IPG(II)
IF (WMES(KB) .GT. WMM(II)) THEN
WMM(II) = WMES(KB)
35 CONTINUE

C Determines Min Horiz Velocity & its index

UMN(II) = UMES(IPC(II))
DO 23 ML = IPB(II), IPF(II)
IF (UMES(ML) .LE. UMN(II)) THEN
UMN(II) = UMES(ML)
JBEGIN = ML
END IF
23 CONTINUE

YMIN = UMES(JBEGIN)
DO 25 MM = JBEGIN, IPF(II)
IF (UMES(MM) = YMIN) THEN
JEND = MM
END IF
25 CONTINUE

IHNV(II) = (JEND - JBEGIN) / 2 + JBEGIN

WMN(II) = WMES(IPB(II))
DO 33 KA = IPA(II), IPE(II)
C.2

1. Line# 1    7

2. 979 IF ((WMES(KA)) .LT. WMN(II)) THEN
2. 980 WMN(II) = WMES(KA)
2. 981 END IF
2. 982 33 CONTINUE
1 983
1 984
1 985 C WRITE (3, *) 'UMM', UMM(1), UMM(2), UMM(3), UMM(4)
1 986 C WRITE (3, *) 'UMN', UMN(1), UMN(2), UMN(3), UMN(4)
1 987 C----------------------------------------------------------
1 988 C Determines Absolute Max Velo & its index
1 989 IF (ABS(UMM(II)) .GE. ABS(UMN(II))) THEN
1 990 UAMX(II) = UMM(II)
1 991 IUAM(II) = IHMV(II)
1 992 ELSE
1 993 UAMX(II) = ABS(UMN(II))
1 994 IUAM(II) = IHNV(II)
1 995 END IF
1 996
1 997 IF (BS(WMM(II)) .GE. BS(WMN(II))) THEN
1 998 WMM(II) = WMM(II)
1 999 ELSE
1 1000 WMM(II) = PBS(WMN(II))
1 1001 END IF
1 1002
1 1003 C==========================================================
1 1004 C Acceleration
1 1005 C Determines Min Calculated Acc & its index
1 1006 ANX (II) = HACL (IPB(II))
1 1007 DO 26 MW = IPA(II), IPE(II)
1 1008 IF (HACL(MW) .LE. ANX(II)) THEN
1 1009 ANX(II) = HACL(MW)
1 1010 KBEGIN = MW
1 1011 END IF
1 1012 26 CONTINUE
1 1013 IHNA(II) = KBEGIN
1 1014
1 1015 C----------------------------------------------------------
1 1016 C Determines Max Calculated Acc & its index
1 1017 AMX(II) = HACL (IPD(II))
1 1018 DO 28 MY = IPC(II), IPE(II)
1 1019 IF (HACL(MY) .GE. AMX(II)) THEN
1 1020 AMX(II) = HACL(MY)
1 1021 LBEGIN = MY
1 1022 END IF
1 1023 28 CONTINUE
1 1024 IHMA(II) = LBEGIN
1 1025
1 1026 C----------------------------------------------------------
1 1027 C Determines Absolute Max Acc & its index
1 1028 IF (ABS(ANX(II)) .GE. ABS(AMX(II))) THEN
1 1029 AAMX(II) = ABS(ANX(II))
1 1030 IAAM(II) = IHNA(II)
1 1031 ELSE
1 1032
AAMX(II) = AMX(II)
IAAM(II) = IHMA(II)
END IF
CONTINUE
C Sums individual values and calculates average values
DO 31 I=1,NWAVS
SMV = SMV + UPMX(I)
SWV = SWV + WAMX(I)
SUMP = SUMP + UMM(I)
SUMN = SUMN + UMN(I)
SMA = SMA + ARMX(I)
UMMX = SMV / REAL(NWAVS)
WMMX = SWV / REAL(NWAVS)
HAAM = SMA / REAL(NWAVS)
UMPO = SUMP / REAL(NWAVS)
UMNE = SUMN / REAL(NWAVS)
UMAV = (UMPO + ABS(UMNE))/2.0
C Standard Deviation of Measured Kinematics
DO 41 K=1,NWAVS
IUP(K) = IHMV(K+1) - IHMV(K)
TUV = REAL(IUP(K)) + TUV
AUP = TUV/REAL(NWAVS)
SUM = 0.0
DO 43 K=1,NWAVS
SUM = REAL(IUP(K))**2 + SUM
SDUP = SQRT((SUM/REAL(NWAVS)) - (AUP**2))
CHVP = SDUP/AUP
TUV = 0.0
DO 51 K=1,NWAVS
DUV(K) = UMM(K) - UMN(K)
TUV = DUV(K) + TUV
AUV = TUV/REAL(NWAVS)
SUM = 0.0
DO 53 K=1,NWAVS
SUM = DUV(K)**2 + SUM
SDUA = SQRT((SUM/REAL(NWAVS)) - (AUV**2))
CHVA = SDUA/AUV
IF (CHVP .GT. 0.05) THEN
WRITE (3,*)'*** CHECK CONSISTENCY OF VELOCITY PERIOD ***'
WRITE (3,206) (IUP(K),K=1,NWAVS)
END IF
IF (CHVA .GT. 0.05) THEN
WRITE (3,*)'*** CHECK CONSISTENCY OF VELOCITY AMPLITUDE***'
WRITE (3,207) (DUV(K),K=1,NWAVS)
END IF
272

Page 28
07-28-87
10:29:27

Microsoft FORTRAN77 V3.31 August 1985

Line# 1   7

1089 COMATIC FORTRAN77 V3.31 August 1985
1090 C WRITE (3,*) ' ETA UMES HACL WMES (1st Wave) '
1091 C DO 60 I=1,257,8
1092 C J = ISM(1) + I - 1
1093 C WRITE (3,601) ETA(J), UMES(J), HACL(J), WMES(J)
1094 C 60 CONTINUE
1095 C
1096 C---------------------------------------------------------
1097 C
1098 C Calculates Keulegan-Carpenter Number & Reynold's Number
1099 C with the Measured Max. Velocity
1100 C
1101 PKC2 = (ABS(UMMX) * WP) / DIA
1102 REN2 = (ABS(UMMX) * DIA) / VIS
1103 C WRITE (3,*),' * Meas & Calc Kines; Horz(+)=Beach, Vert(+)=Up'
1104 WRITE (3,205) SDUP,CHVP
1105 WRITE (3,215) (IUP(K), K=1,NWAVS)
1106 WRITE (3,225) SDUA,CHVA
1107 WRITE (3,235) (DUV(K), K=1,NWAVS)
1108 WRITE (3,512) UMPO,UMNE,UMAV,HAAM
1109 WRITE (3,516) WMMX
1110 WRITE (3,522) PKC2,REN2
1111 C 205 FORMAT (BX,'Max Hor. Velo Period : ','SDUP=',F5.2,'CVUP=',F5.3)
1112 206 FORMAT (616)
1113 201 FORMAT (3F6.3)
1114 207 FORMAT (6F6.3)
1115 215 FORMAT (8X,816)
1116 225 FORMAT (8X,'Max Hor. Velo Amplit : ','SDUA=',F5.3,'CVUA=',F5.3)
1117 235 FORMAT (8X,8F6.2)
1118 512 FORMAT (8X,'Um(+)=',F5.2,3X,'Um(-)=',F5.2,3X,'Uavg=',F5.2,3X,'Uacc'
1119 516 FORMAT (8X,'Wm(+)=',F5.2)
1120 522 FORMAT (8X,'K-C No. =',F6.1,4X,'Reyn No. =',E10.3)
1121 601 FORMAT (3X,4F8.3)
1122 RETURN
1123 END

Name Type Offset P Class

AAMX REAL 36 /VEAL /
ABS REAL INTRINSIC
AFMH REAL 16 /FORE /
AFNV REAL 32 /FORE /
AFNH REAL 20 /FORE /
AMX REAL 36 LARGE
ANX REAL 0 LARGE
AREA REAL 8 /MAMO /

Name Type Offset P Class


**SUBROUTINE** VLPH (DHVM)

**Determines the phase lag in the velocity & acceleration**

**VPVD**: Current Meter Velo Phase Shift (Vertical) in Degrees

**VPHD**: (Horizon )

**JVPV**: (Vertical) in Data Points

**JVPH**: (Horizon )

**JHUM**: Velo Phase Lag at Max Velo (each wave)

**JHUN**: at Min Velo (each wave)

**VPL**: at Max Velo by No. of Data Points

**DHVM**: at Max Velo by Degrees

---

**COMMON/MANP/ PI, TAOPI, GRAY, RHO, VIS, WP, DEP, FREQ, HOWO**

**COMMON/MANG/ NCOD, NRUN, NPTS, NPTZ, NPTC, NWAVS, ISTART**

**COMMON/UWCC/ ISM(9), ISN(9), NPC(9), IPI(9)**

**COMMON/VEAE/ IHMV(9), IHN(9), IHNA(9), IHMA(9)**

**COMMON/VEAR/ UMMX, HAM, WMXX, TAUV, TAUH, UMPO, UMNE, UMAV**

**COMMON/VEPH/ PHVM, PHVN**

**COMMON/VEPA/ JHUM(9), JHUN(9), JVPV(9), JVPH(9)**

---

**Velocity Phase Lag Due to M-M Current Meter**

**VPVD** = ATAN ((-FREQ * TAUV) / 57.2958)

**VPHD** = ATAN ((-FREQ * TAUH) / 57.2958)

**DO 5 I=1, NWAVS**

**JVPV(I)** = INT ((VPVD / 360.0) * REAL (NPC(I)))

**JVPH(I)** = INT ((VPHD / 360.0) * REAL (NPC(I)))

**CONTINUE**

**JHUMS** = 0

**JHUNS** = 0

**DO 10 I=1, NWAVS**

**JHUM(I)** = ISM(I) - IHMV(I) - JVPH(I)

**JHUN(I)** = ISN(I) - IHNV(I)

**JHUMS** = JHUMS + JHUM (I)

**JHUNS** = JHUNS + JHUN (I)

**CONTINUE**

**PHVM** = REAL (JHUMS) / REAL (NWAVS)

**PHVN** = REAL (JHUNS) / REAL (NWAVS)

**DHVM** = (PHVM/256.0) * 360.0

**WRITE (*, 303) VPVD**

**WRITE (3, 303) VPHD**

**WRITE (3, 404) DHVM**

**FORMAT(' 3. Current Meter Phase Shift =', F8.3, ' Degrees')**

**FORMAT(' Velocity Phase Shift =', F8.3, ' Degrees')**
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SUBROUTINE FORCES (CFHP, CFHA)

Determines the avg. horiz. force at wave crest, max & min velo,
max & min acceleration

SHWC : Horz Force at Wave Crest
SHWT : Horz Force at Wave Trough
SHMV : Horz Force at Max Velo
SHNV : Horz Force at Min Velo
SHMA : Horz Force at Max Accel
SHNA : Horz Force at Min Accel

FHWC : Force at Wave Crest
FHWT : Force at Wave Trough
FMV : Force at Max H Velo
FMH : Index of Max Horz Force
FHMA : Force at Max H Accel
FHNA : Force at Min H Accel
FVNV : Force at Min V Velo

FHNV : Force at Min H Velo
FHMA : Force at Max H Velo
FHNA : Force at Min H Velo

DIMENSION FMH(9), FNH(9), FMV(9), FNV(9), DFA(9)

Determines meas forces at various phases

DO 31 MT = 1, NWAVS
SHWC = SHWC + FHM(ISM(MT))
31 CONTINUE

DO 33 MD = 1, NWAVS
SHWT = SHWT + FHM(ISN(MD))
C Forces at Theoretical Horz Max & Min Velo
DO 43 MU = 1, NWAVS
   IM = IHMV(MU) + JVPH(MU)
   SHMV(MU) = FHM(IM)
   HMV = HMV + SHMV(MU)
CONTINUE
DO 45 MK = 1, NWAVS
   IN = IHNV(MK) + JVPH(MK)
   SHNV(MK) = FHM(IN)
   HNV = HNV + SHNV(MK)
CONTINUE
C Forces at Suppose-to-be Horz Max & Min Acceleration
C also Forces at Vert Max & Min Velocity
DO 53 MP = 1, NWAVS
   IM = IHMA(MP) + JVPH(MP)
   SHMA(MP) = FHM(IM)
   HMA = HMA + SHMA(MP)
   SVMV(MP) = FVM(IM)
   VMV = VMV + SVMV(MP)
CONTINUE
DO 55 MS = 1, NWAVS
   IN = IHNA(MS) + JVPH(MS)
   SHNA(MS) = FHM(IN)
   HNA = HNA + SHNA(MS)
   SVNV(MS) = FVM(IN)
   VNV = VNV + SVNV(MS)
CONTINUE
C Determines Horz Max (+) & Min (-) meas forces
LWAVS = NWAVS + 1
DO 70 K = 1, LWAVS
   FMH(K) = FHM(ISM(K))
   FNH(K) = FHM(ISM(K))
   J = ISM(K) + 276 - 1
   DO 72 LM = ISM(K), J
       IF (FHM(LM) .GE. FMH(K)) THEN
           FMH(K) = FHM(LM)
           IFMH(K) = LM
       ENDIF
DO 74 LN = ISM(K), J
    IF (FHM(LN) .LE. FNH(K)) THEN
      FNH(K) = FHM(LN)
      IFNH(K) = LN
    ENDIF
  74 CONTINUE

DO 77 K =1,NWVS
  SFMH = SFMH + FMH(K)
  SFNH = SFNH + FNH(K)
  DO 80 K =1, NWVE
    FMV(K) = FVM(ISM(K))
    FNV(K) = FVM(ISM(K)+ NPC(K) - 1)
    DO 82 JM = ISM(K), 3
      IF (FVM(JM) .GE. FMV(K)) THEN
        FMV(K) = FVM(JM)
        IFMV(K) = JM
      ENDIF
    82 CONTINUE
    DO 84 JN = ISM(K), 3
      IF (FVM(JN) .LE. FNV(K)) THEN
        FNV(K) = FVM(JN)
        IFNV(K) = JN
      ENDIF
    84 CONTINUE
  80 CONTINUE

DO 91 M=1,NWPVS
  IFP(M) = IFMH(M+1) - IFMH(M)
  TDF = REL(IFP(M)) + TDF
  FHP = TDF/REAL(NWVS)
  SUMO = SUMO. + REL(IFP(M))**2
  SDFHP = SQRT((SUMO/REAL(NWPVS)) - (FHP**2))
1350 CFHP = SDFHP/AFHP
1351  
1352 TDF = 0.
1353  
1354 DO 95 M=1,NWAVS
1355  
1356 DFA(M) = FMH(M) - FNH(M)
1357  
1358 SUM=0.
1359  
1360 DO 97 M=1,NWAVS
1361  
1362 SDFHA = SQRT((SUM/REAL(NWAVS))-(AFHA**2))
1363  
1364 IF (CFHP.GT.0.05) THEN
1365 WRITE (3,*)'*** CHECK CONSISTENCY OF FORCE PERIOD ***'
1366 WRITE (3,206) (IFP(K), K=1,NWAVS)
1367 END IF
1368 IF (CFHA.GT.0.05) THEN
1369 WRITE (3,*)'*** CHECK CONSISTENCY OF FORCE AMPLITUDE***'
1370 WRITE (3,207) (DFA(K), K=1,NWAVS)
1371 END IF
1372  
1373 AFMH = SFMH / REAL(NWAVS)
1374 AFNH = SFNH / REAL(NWAVS)
1375 AFH = (AFMH + ABS(FNH))/2.0
1376  
1377 AFMV = SFMV / REAL(NWAVS)
1378 AFNV = SFNV / REAL(NWAVS)
1379 AFV = (AFMV + ABS(AFNV))/2.0
1380  
1381 WRITE (3,*)' * Measured Forces; Horz(+)=Beach, Vert(+)=Up'  
1382 WRITE (3,205) SDFHP, CFHP
1383 WRITE (3,215) (IFP(K), K=1,NWAVS)
1384 WRITE (3,225) SDFHA, CFHA
1385 WRITE (3,235) (DFA(K), K=1,NWAVS)
1386 WRITE (3,314) FHWC, FHWT
1387 WRITE (3,316) FHMV
1388 WRITE (3,318) FHNV
1389 WRITE (3,314) FHMA
1390 WRITE (3,316) FNHA
1391 WRITE (3,312) AFMH, AFNH, AFH
1392 WRITE (3,316) AFMV, AFNV, AFV
1393  
1394 205 FORMAT (8X,'Max Hori Force Period : ','SDFP=',F5.2,3X,'CVFP=',  
1395 1 F5.3)
1396 206 FORMAT (6E16)
1397 207 FORMAT (6E16.3)
1398 215 FORMAT (8X,617)
1399 225 FORMAT (8X,'Max Hori Force Amplit : ','SDFA=',F5.3,3X,'CVFA=',  
1400 1 F5.3)
1401 235 FORMAT (6X,8F7.2)
1402 314 FORMAT (8X,'At Wave Crest =',F8.3,4X,'At Wave Trough =',F8.3)  
1403 416 FORMAT (8X,'Force at Max Velo =', F8.3)
Line# 1 418  FORMAT (8X,'Force at Min Velo =',F8.3)
1406 514  FORMAT (8X,'Force at Max Accel =',F8.3)
1407 516  FORMAT (8X,'Force at Max Accel =',F8.3)
1408 612  FORMAT (8X,'FHm(+) =',F6.2,3X,'FHm(-) =',F6.2,3X,'FH avg =',F6.2)
1409 712  FORMAT (8X,'FVrn(+) =',F6.2,3X,'FVrn(-) =',F6.2,3X,'FV avg =',F6.2)
1410  RETURN
1411  END

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**SUBROUTINE LWT (PKC1, REN1)**

Wave Kinematics Predicted by Linear Wave Theory

\[ \eta = \left( \frac{H}{2} \right) \cos(kx - \omega t) \]

\[ \phi = -\left( \frac{H}{2} \right) \frac{\omega}{k} \frac{\cosh(ks)}{\sinh(kd) \sin(kx - \omega t)} \]

\[ u = \frac{-d\phi}{dx} = \left( \frac{H}{2} \right) \frac{\omega^2}{k} \frac{\cosh(ks)}{\sinh(kd) \sin(kx - \omega t)} \]

\[ w = -\frac{d\phi}{dz} = \left( \frac{H}{2} \right) \frac{\omega^2}{k} \frac{\sinh(kd) \sin(kx - \omega t)}{\cosh(ks)} \]

\[ \dot{u} = \dot{u} + u \frac{d\dot{u}}{dx} + w \frac{d\dot{u}}{dz} \]

\[ \dot{w} = -\dot{u} + u \frac{d\dot{u}}{dx} + w \frac{d\dot{u}}{dz} \]

\[ \text{From Continuity: } \frac{d\dot{u}}{dx} = -\frac{d\dot{w}}{dz} \]

\[ \text{Irrationality: } \frac{d\dot{u}}{dz} = \frac{d\dot{w}}{dx} \]

**COMMON/MNP/ PI, TWOPI, GRAY, RHO, VIS, WP, DEP, FREQ, HOWO**

**COMMON/MANO/ RGT, DIA, AREA, VOL, DEL**

**COMMON/MANG/ NCOD, NRUN, NPTS, NPTZ, NPTC, NWAVS, ISTART**

**COMMON/WSVA/ WL, WH, WK, WDKD, WDKDNEW**

**COMMON/CENADO/ PTEL, COF**

**COMMON/FORE/ FMV, FHNV, FHMA, FHNA, AFNH, FMV, FVMV, FVNV, AFMV, AFNV**

**COMMON/LWTO/ U(257), W(257)**

**COMMON/LWTR/ UDOT(257), WDOT(257), DUDT(257), DWDT(257)**

**DIMENSION**

**THETA(257), ETA(257), ANGLE(257), SP(257)**

**DIMENSION**

**COSN(257), SINE(257), DUDX(257), DUDZ(257)**

**OMEGA = TWOPI/WP**

**DTHERA = TWOPI/REAL(NPTZ)**

**CREM = 360.0/REAL(NPTZ)**

**VELCON = WH * OMEGA/(2.0 * SINH(WK*DEP))**

**ACCCON = VELCON * OMEGA**

**CH = COSH(WK*PTEL)**

**SH = SINH(WK*PTEL)**

**UCT = VELCON * CH**

**WCT = VELCON * SH**

**WRITE(3,*) 'THETA', ETA, U, W, UDOT, WDOT, DUDT**

**DO 45 I = 1, 257, 8**

**ANGLE(I) = (REAL(I-1)) * (-DTHERA)**

**THETA(I) = (REAL(I-1)) * (-CREM)**

**ETA(I) = (WH/2.0) * COS(ANGLE(I))**

**COSN(I) = COS(ANGLE(I))**

**SINE(I) = SIN(ANGLE(I))**

**U(I) = UCT * COSN(I)**
**Line# 1**  
1468 W(I) = WCT * SINE(I)  
1469 UDOT(I) = ACCCON * CH * SINE(I)  
1470 WDOT(I) = - ACCCON * SH * COSN(I)  
1471 DUDX(I) = - VELCON * WK * CH * SINE(I)  
1472 DUDZ(I) = VELCON * WK * SH * COSN(I)  
1473 DUDT(I) = UDOT(I) + U(I) * DUDX(I) + W(I) * DUDZ(I)  
1474 DWDT(I) = WDOT(I) + U(I) * DUDZ(I) - W(I) * DUDX(I)  
1475 WRITE (3, '(8F8.2)') THETA(I), ETA(I), U(I), W(I), UDOT(I), WDOT(I), DUDT(I), DWDT(I)  
1476 48 CONTINUE  
1477  
1478 C -------------------------------------------------  
1479 C Finds the Max Horz Velocity  
1480 UMAX = 0.0  
1481 DO 70 I = 1,257  
1482 IF ( U(I) .GT. UMAX ) THEN  
1483 UMAX = U(I)  
1484 END IF  
1485 70 CONTINUE  
1486 C -------------------------------------------------  
1487 C Finds the Maximum Acceleration  
1488 UDDTM = 0.0  
1489 DO 72 I = 1, 257  
1490 IF ( UDOT(I) .GT. UDDTM ) THEN  
1491 UDDTM = UDOT(I)  
1492 END IF  
1493 72 CONTINUE  
1494 C -------------------------------------------------  
1495 C Finds the Max Vert Velocity  
1496 WMX = 0.0  
1497 DO 60 I = 1,257  
1498 IF ( W(I) .GT. WMX ) THEN  
1499 WMX = W(I)  
1500 END IF  
1501 60 CONTINUE  
1502 C -------------------------------------------------  
1503 C Finds Max Hcir Displacement & Disp/Diameter Ratio  
1504 DISP = 0.
DO 74 I=1,237
   IF (DSP(I) .GT. DISP) THEN
      DISP = DSP(I)
   ENDIF
74 CONTINUE

DPDIA = DISP/DIA

C ----------------------------------------------------------
C Calculates Keulegan-Carpenter Number & Reynold's Number

PKC1 = (UMAX * WP)/DIA
REN1 = (UMAX * DIA)/VIS

WRITE (3,*), 'Kinematics Predicted by Linear Wave Theory'
WRITE (*,312) PTEL
WRITE (3,312) PTEL
WRITE (3,320) UMAX,UDOTM
WRITE (3,112) UMAX
WRITE (3,212) DISP,DPDIA
WRITE (3,314) PKC1,REN1

RETURN

END

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**SUBROUTINE LSQ**

**Least Square Method**

**L1 : Velo (LWT), Acc1 (LWT), Force (Meas)**

**L2 : Velo (Meas), Acc1 (Calc), Force (Meas)**

**COMMON/MANP/ PI, TWDPI, GRAV, RHO, VIS, WP, DEP, FREQ, HOWO**

**COMMON/MAND/ RGTH, DIA, AREA, VOL, DEL**

**COMMON/MANG/ NCOD, NRUN, NPTS, NPTZ, NPTC, NWAVS, ISTART**

**COMMON/WWCC/ ISM(9), ISN(9), NPC(9), IPI(9)**

**COMMON/CENF/ FHM(2560), FVM(2560)**

**COMMON/VEAC/ UMES(2560), WMES(2560), HAEL(2560)**

**COMMON/VEAE/ IHMV(9), IHNV(9), IHNA(9), IHMA(9)**

**COMMON/VEPA/ JHUM(9), JHUN(9), JVPV(9), JVPH(9)**

**COMMON/LWTE/ U(257), W(257)**

**COMMON/LWTO/ UMX, UDOTM**

**COMMON/LWTR/ UDOT(257), WDOT(257), DUDT(257), DWDT(257)**

**COMMON/LSQU/ CDLI, CIL1, CDL2, CIL2**

**DIMENSION S1(300), S2(300)**

**SCDL1 = 0.**

**SCIL1 = 0.**

**SCDL2 = 0.**

**SCIL2 = 0.**

**DO 20 K = 1, NWAVS**

**JS = ISM(K)**

**JU = ISM(K) - JVPH(K)**

**JU = IHMV(K)**

**WRITE(3,*)'FHM(JSM),FHM(JUM),U(I),UMES(JUM)'**

**DO 21 I = 1, NPC(K)**

**JSM = JS + I - 1**

**JUM = JU + I - 1**

**S1(I) = FHM(JSM) * (U(I)) * ABS(U(I))**

**S2(I) = FHM(JSM) * (UMES(JUM) * ABS(UMES(JUM)))**

**WRITE(3,*) FHM(JSM), FHM(JUM), U(I), UMES(JUM)**

**CONTINUE**

**CALL SUMMA(NPC(K),S1,SUMD1)**

**D1 = SUMD1**

**CALL SUMMA(NPC(K),S2,SUMD2)**

**D2 = SUMD2**

**DO 22 I = 1, NPC(K)**

**JS = JS + I - 1**

**JUM = JU + I - 1**

**S1(I) = U(I) * ABS(U(I))**

**S2(I) = (UMES(JUM) * ABS(UMES(JUM)))**

**CONTINUE**
CALL SUMMA (NPC(K), S1, SUMA1)
A1 = ((RHO * AREA) / 2.) * SUMA1
CALL SUMMA (NPC(K), S2, SUMA2)
A2 = ((RHO * AREA) / 2.) * SUMA2

WRITE (3, *) 'DUDT(I), HACL(JUM), ABS(U(I)), ABS(UMES(JUM))'
DO 23 I = 1, NPC(K)
JSM = JS + I - 1
JUM = JU + I - 1
S1(I) = DUDT(I) * (U(I) * ABS(U(I)))
S2(I) = HACL(JUM) * (UMES(JUM) * ABS(UMES(JUM)))
WRITE (3, *) DUDT(I), HACL(JUM), ABS(U(I)), ABS(UMES(JUM))
CONTINUE

CALL SUMMA (NPC(K), S1, SUMB1)
B1 = RHO * VOL * SUMB1
CALL SUMMA (NPC(K), S2, SUMB2)
B2 = RHO * VOL * SUMB2

DO 24 I = 1, NPC(K)
JSM = JS + I - 1
JUM = JU + I - 1
S1(I) = DUDT(I) ** 2
S2(I) = HACL(JUM) ** 2
CONTINUE

CALL SUMMA (NPC(K), S1, SUMF1)
F1 = (2. * RHO * (VOL**2)/(AREA)) * SUMF1
CALL SUMMA (NPC(K), S2, SUMF2)
F2 = (2. * RHO * (VOL**2)/(AREA)) * SUMF2

DO 25 I = 1, NPC(K)
JSM = JS + I - 1
JUM = JU + I - 1
S1(I) = FHM(JSM) * (DUDT(I))
S2(I) = FHM(JSM) * HACL(JUM)
CONTINUE

CALL SUMMA (NPC(K), S1, SUMG1)
G1 = 2. * VOL/(AREA) * SUMG1
CALL SUMMA (NPC(K), S2, SUMG2)
G2 = 2. * VOL/(AREA) * SUMG2

SCDL1 = (G1*B1-D1*F1)/(B1**2-A1*F1) + SCDL1
SCIL1 = (D1*B1-G1*A1)/(B1**2-A1*F1) + SCIL1
SCDL2 = (G2*B2-D2*F2)/(B2**2-A2*F2) + SCDL2
SCIL2 = (D2*B2-G2*A2)/(B2**2-A2*F2) + SCIL2
CONTINUE

CDL1 = SCDL1 / REAL (NWAVS)
CIL1 = SCIL1 / REAL (NWAVS)
CDL2 = SCDL2 / REAL (NWAVS)
CIL2 = SCIL2 / REAL (NWAVS)
IF (CDL1 .GT. 9999.999) CDL1 = 9999.999
IF (CDL2 .GT. 9999.999) CDL2 = 9999.999

WRITE (3, *) '61=', El, ' B1=', 51, ' D1=', D1, ' F1', Fl, ' A1=', R1
WRITE (*,*) ' 6. Least Square M. (1: LWT, 2: Meas Kinematics)'  
WRITE (3,*) ' 6. Least Square M. (1: LWT, 2: Meas Kinematics)'  
WRITE (3,*) ' L1 : Velo (LWT), Acci (LWT), Force (Meas)'  
WRITE (3,*) ' L2 : Velo (Meas), Acci (Calc), Force (Meas)'  
WRITE (3,*)  
WRITE (3,*)  
WRITE (3,104) CDL1, CIL1  
WRITE (3,104) CDL2, CIL2  
104 FORMAT (8X,'CD.L1 =',F8.3,4X,'CI.L1 =',F8.3)  
105 FORMAT (8X,'CD.L2 =',F8.3,4X,'CI.L2 =',F8.3)  
RETURN  
END  

Name Type Offset P Class  
A1 REAL 3074  
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ABS REAL 8 /MAMO /  
AREA REAL 3092  
B1 REAL 3100  
B2 REAL 0 /LSQU /  
CDL1 REAL 8 /LSQU /  
CDL2 REAL 4 /LSQU /  
L1 REAL 12 /LSQU /  
LIL2 REAL 3056  
D1 REAL 3064  
D2 REAL 16 /MAMO /  
DEL REAL 24 /MANP /  
DIA REAL 4 /MAMO /  
DUDT REAL 2056 /LWTR /  
DWDT REAL 3084 /LWTR /  
F1 REAL 3110  
F2 REAL 3118  
FHM REAL 0 /CENF /  
FREQ REAL 28 /MANP /  
FVM REAL 10240 /CENF /  
G1 REAL 3128  
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GRAV REAL 8 /MANP /  
HACL REAL 20480 /VEAC /  
HOWO REAL 32 /MANP /  
I INTEGER*2 3044  
IHMA INTEGER*2 54 /VEAE /  
IHM INTEGER*2 0 /VEAE /  
IHNA INTEGER*2 36 /VEAE /  
IHNV INTEGER*2 18 /VEAE /  
IP1 INTEGER*2 54 /WVCC /  
IPM INTEGER*2 0 /WVCC /  
J INTEGER*2 18 /WVCC /  
ISTART INTEGER*2 12 /MANG /  
JHUM INTEGER*2 0 /VEPA /  
JHUN INTEGER*2 18 /VEPA /  
JS INTEGER*2 3040
SUBROUTINE SUMMA (NPC, S, SUM)

DIMENSION S(300)

SUM = 0.

DO 12 I = 1, NPC
  SUM = SUM + S(I)
12 CONTINUE

RETURN

END
SUBROUTINE FOUAVG (CDF1,CIF1,CDF2,CIF2)

Computes CD & CI by Fourier Averaged Method
F1 : Velo(LWT), Force(Meas)
F2 : Velo(Meas), Force(Meas)

COMMON/MANP/ PI,TWOPI,GRAV,RHO,DISP,DP,DQ,HO
COMMON/MAMO/ RGTH,DIA,AREA,VOL,DEL
COMMON/MANG/ NCD,NA,NTS,NPT,NCWVS,ISTART
COMMON/MVCN/ ISM(9), ISBN(9), NPC(9), IPI(9)
COMMON/VEAR/ UMMX,UMMX,TAUV,TAUH,UMPO,UMNE,UMAV
COMMON/CENF/ FHN(2560),FVM(2560)
COMMON/LWT/ UMAX, UDDTM

DIMENSION T1(300), T2(300), ANGLE(300), COSN(300), SINE(300)

CD1 = 0.
SCI1 = 0.
SCD2 = C).
SCI2 = 0.

DO 10 L=1, NWAVS
JS = ISM(L)
DO 12 I=1, NPC(L)
JSM = .36 + I - 1
DTHETA = TWOPI/ REAL (NPC(L))
ANGLE(I) = (REAL (I-I)) * (-DTHETA)
COSN(I) = COS (ANGLE(I))
SINE(I) = SIN (ANGLE(I))
T1(I) = FHM(JSM) * COSN(I)
T2(I) = FHM(JSM) * SINE(I)
12 CONTINUE
CD1 = T1*ST1
CIF1 = T2*ST2

10 CONTINUE
CDF1 = CDF1 / REAL(NWAVS)
CIF1 = CIF1 / REAL(NWAVS)
CDF2 = CDF2 / REAL(NWAVS)
CIF2 = CIF2 / REAL(NWAVS)

IF (CDF1 .GT. 9999.999) CDF1 = 9999.999
Line# 1 7  Microsoft FORTRAN77 V3.31 August 1985
1746 1747 1748 1749 1750 C 1751 C 1752 1753 1754 1755 1756 1757 1758 1759 1760
1746 IF (CDF2 .GT. 9999.999) CDF2 = 9999.999
1747 1748 WRITE (*,*)' 7. Fourier Averaged Method'
1749 WRITE (3,*)' F1: Velo (LWT), Acci (LWT), Force (Meas)'
1750 C WRITE (3,*)' F2: Velo (Meas), Acci (Calc), Force (Meas)'
1751 C WRITE (*,107) CDF1, CIF1
1752 WRITE (3,*), CIF1
1753 WRITE (3,107) CDF1, CIF1
1754 WRITE (3,109) CDF2, CIF2
1755 1756 107 FORMAT (8X,'CD.Fl =',F8.3,4X,'Cl.F1 =',F8.3)
1757 109 FORMAT (8X,'CD.F2',F8.3,4X,'CI.F2 =',F8.3)
1758 1759 RETURN
1760 END

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**SUBROUTINE INTGRT (TWOPI,NPC,Y,SINTG)**

**C**

27-JUL-83 NCEL CYL VERSION

**C** Numerical Integration of Y(T)*DTHETA from 0 to TWOPI

**DIMENSION Y(300)**

**C**

**SUM1 = 0**

**DTHETA = TWOPI / REAL (NPC)**

**N = NPC - 1**

**DO 11 I=2, N, 2**

**SUM1 = SUM1 + Y(I-1) + 4. * Y(I) + Y(I+1)**

**CONTINUE**

**SINTG = (SUM1 * DTHETA)/3.**

**RETURN**

**END**

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1783 $PAGE
SUBROUTINE MAXVPL (CDM1,CIM1,CDM2,CIM2)

Calculates CD & CI using Maximum Value Method

M1: Velo (LWT), Accl (LWT), Force (Meas)
M2: Velo (Meas), Accl (Calc), Force (Meas)

AHFV: Absol Horz Force at Max Horz Velo
AHFA: Absol Horz Force at Max Horz Accel
AVFV: Absol Vert Force at Max Horz Velo

COMMON/MANP/ PI, TWOPI, GRAV, RHO, VIS, WP, DEP, FREQ, HDWO
COMMON/MAMP/ RGTH, DIA, AREA, VOL, DEL
COMMON/MANG/ NCOD, NRUN, NPTS, NPTZ, NPTC, NWAVS, ISTART
COMMON/VEAC/ UMES(2560), WMES(2560), HACL(2560)
COMMON/VEAR/ UMMX, UMAW, UMMX, TAUV, TAUN, UMPD, UMNE, UMAV
COMMON/VEAE/ IHMV(9), IHNV(9), IHMA(9), IHMA(9)
COMMON/FORE/ FHMV, FHNV, FHNA, AFMH, AFNH, FVMV, FVNV, AFMV, AFNM
COMMON/FORS/ SHMV(9), SHNV(9), SHMA(9), SHNA(9), SVMV(9), SVNV(9)
COMMON/LWTO/ UMAX, UDDTM
COMMON/MXVL/ AHFV, AHFA, AVFV

Using LWT Kinematics

IF (ABS(FHMV) .GE. ABS(FHNV)) THEN
   AHFV = ABS(FHMV)
ELSE
   AHFV = ABS(FHNV)
ENDIF

IF (ABS(FHMA) .GE. ABS(FHNA)) THEN
   AHFA = ABS(FHMA)
ELSE
   AHFA = ABS(FHNA)
ENDIF

IF (ABS(FVMV) .GE. ABS(FVNV)) THEN
   AVFV = ABS(FVMV)
ELSE
   AVFV = ABS(FVNV)
ENDIF

CDM1 = AHFV / ((RHO / 2.0) * AREA * (UMAX ** 2))

Using Meas Kinematics

SCDVM = 0.
SCDVN = 0.
DO 22 K=1, NWAVS
1843 CDMV = SHMV(K) / (( RHO / 2.0 ) * AREA* UMES(IHMV(K))*2)
1844 CDNV = SHNV(K) / (( RHO / 2.0 ) * AREA* UMES(IHNV(K))*2)
1845
1846 C WRITE (3,*) SHMR(K),HPCL(IHMR(K)),IHMR(K)
1847 C WRITE (3,*) SHNR(K),HRCL(IHNA(K)),IHNAU()
1848 CIMR = SHMR(K) / ( RHO * VOL * ABS(HACL(IHMR(<))))
1849 CINA = SHNA(K) / ( RHO * VOL * ABS(HACL(IHNA(K))))
1850
1851 SCDVM = SCDVM + RBS(CDMV)
1852 SCDVN = SCDVN + RES(CDNV)
1853 SCIRM = SCIRM + RBSCCIMR)
1854 SCIAN = SCIAN + ABS(CINA)
1855 CONTINUE
1856 IF (ABS(SCDVM) .GE. ABS(SCDVN)) THEN
1857 SCDM = ABS(SCDVM)
1858 ELSE
1859 SCDM = ABS(SCDVN)
1860 ENDIF
1861
1862 IF (ABS(SCIAM) .GE. ABS(SCIAN)) THEN
1863 SCIM = ABS(SCIAM)
1864 ELSE
1865 SCIM = ABS(SCIAN)
1866 ENDIF
1867
1868 C Determines which force to use for lift force coeff
1869 IF (UMMX .LT. 0.) THEN
1870 F = FVNV
1871 ELSE
1872 F = ABS(FVMV)
1873 ENDIF
1874
1875 C------------------------------------- ---------
1876 CDM2 = SCDM / REAL(NWAVS)
1877 CIM2 = SCIM / REAL(NWAVS)
1878 CLM2 = ( F * 2.0 * (UMMX**2)) / (RHO * DIA)
1879 IF (CDM1 .GT. 9999.999) CDM1 = 9999.999
1880 IF (CDM2 .GT. 9999.999) CDM2 = 9999.999
1881
1882 WRITE (*,*) ' 8. Maximum Value Method '
1883 WRITE (3,*) ' 8. Maximum Value Method '
1884 C WRITE (3,*) ' M1 : Velo (LWT), Acc1 (LWT), Force (Meas)'
1885 C WRITE (3,*) ' M2 : Velo (Meas), Acc1 (Calc), Force (Meas)'
1886 C WRITE (*,117) CDM1, CIM1
1887 WRITE (3,117) CDM1, CIM1
1888 WRITE (3,117) CDM2, CIM2
1889 IF (CDM1 .GT. 9999.999) CDM1 = 9999.999
1890 IF (CDM2 .GT. 9999.999) CDM2 = 9999.999
1891
1892 117 FORMAT (8X,'CD.M1 =',F8.3,4X,'CI.M1 =',F8.3)
Line 1    7    Microsoft FORTRAN77 V3.31 August 1985
1894 119  FORMAT (8X,'CD..M2 =',F8.3,4X,'CI..M2 =',F8.3)
1895 205  FORMAT (2F8.3)
1896 207  FORMAT (2I5)
1897      RETURN
1898      END

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SUBROUTINE MXFCEF (CF1,CF2,CL1,CL2)

Calculates the max force coefficients (both horz & lift force)

CF1: Velo (LWT), Max H. Force
CL1: w/ Max V. Force

CF2: Velo (Meas), Max H. Force
CL2: w/ Max V. Force

COMMON/MANP/ PI, TWDPI, GRAV, RHO, VIS, WP, DEP, FREQ, HOWO
COMMON/MAMO/ RGTH, DIA, AREA, VOL, DEL
COMMON/MANG/ NCOD, NRUN, NPTS, NPTZ, NPTC, NWAVS, ISTART
COMMON/VEAL/ UAMX(9), AAMX(9)
COMMON/VEAR/ UMMX, HAMM, WMMX, TAUH, TAUH, UMPO, UMNE, UMAV
COMMON/CENO/ PTEL, COF
COMMON/FORE/ FHMV, FHNV, FHMA, FHNA, AFMH, AFNH, FVMV, FVNV, AFMV, AFNV
COMMON/LWTO/ UMAX, UDOTM
COMMON/MXCF/ FMH, FMV

IF (ABS(AFMH) .GE. ABS(AFNH)) THEN
  FMH = ABS(AFMH)
ELSE
  FMH = AFNH
ENDIF

IF (ABS(AFMV) .GE. ABS(AFNV)) THEN
  FMV = ABS(AFMV)
ELSE
  FMV = AFNV
ENDIF

CF1 = ABS(FMH) / ((RHO/2.) * AREA * (UMAX)**2)
CF2 = ABS(FMH) / ((RHO/2.) * AREA * (UMMX)**2)
CL1 = ABS(FMV) / ((RHO/2.) * AREA * (UMAX)**2)
CL2 = ABS(FMV) / ((RHO/2.) * AREA * (UMMX)**2)

WRITE (*,*), 9. Max Force Coeff (Use Velo & Forces)!
WRITE (3,*), 9. Max Force Coeff (Use Velo & Forces)!
WRITE (*,102) CF1, CF2
WRITE (3,102) CF1, CF2
IF (NRUN .LT. 31) GO TO 444
WRITE (3,104) CL1, CL2

FORMAT (8X,'CF1 =',F8.3,4X,'CF2 =',F8.3)
FORMAT (8X,'CL1 =',F8.3,4X,'CL2 =',F8.3)
RETURN
END
SUBROUTINE FRPP

Determines Force Phase Lags & Relative Force Ratios

FTPH : Total Force (Horz Force) Phase Lag
FLPH : Lift Force (Vert Force)
FDPH : Draf Force
FIPH : Inertia Force

COMMON/MANP/ PI, TWOPI, GRAV, RHO, VIS, WP, DEP, FREQ, HOWD
COMMON/MAMO/ RGTH, DIA, AREA, VOL, DEL
COMMON/MANG/ NCOD, NRUN, NPTS, NPTZ, NWAVS, ISTART
COMMON/WVCC/ ISM(9), ISN(9), NPC(9), IPI(9)
COMMON/VEAE/ IHMV(9), IHNV(9), IINH(9), IINM(9)
COMMON/VEAD/ IUAM(9), IAAM(9)
COMMON/FRd/ IFMH(9), IFNH(9), IFMV(9), IFNV(9), IFP(9)
COMMON/LWTO/ UMAX, UDOTM
COMMON/MXVL/ AHFV, AHFA, AVFV
COMMON/FRPH/ FTPH, FLPH, FDPH, FIPH, FDIL, FDIM, FVFH
COMMON/LSQD/ CDL1, CIL1, CDL2, CIL2

DIMENSION IFT(9), IFL(9), IFD(9), IFI(9)

ITFT = 0
ITFL = 0
ITFI = 0
ITFD = 0

DO 10 I=1,NWAVS
1 IF(ABS(AFMH).GE.ABS(AFNH)) IFT(I) = ISM(I)-IFMH(I)
1 IF(ABS(AFNH).GE.ABS(AFMH)) IFT(I) = ISM(I)-IFNH(I)
1 ITFT = ITFT +IFT(I)
1 IF(ABS(AFMV).GE.ABS(AFNV)) IFL(I) = ISM(I)-IFMV(I)
1 IF(ABS(AFNV).GE.ABS(AFMV)) IFL(I) = ISM(I)-IFNV(I)
1 ITFL = ITFL +IFL(I)
1 IFD(I) = ISM(I)-IUAM(I)
1 ITFD = ITFD + IFD(I)
1 IFI(I) = ISM(I)-IAAM(I)
1 ITFI = ITFI + IFI(I)

10 CONTINUE

FTPH = (REAL(IFTF)/REAL(NWAVS))/256.0*360.0
FLPH = (REAL(IFLT)/REAL(NWAVS))/256.0*360.0
FDPH = (REAL(IFD)/REAL(NWAVS))/256.0*360.0
FIPH = (REAL(IFI)/REAL(NWAVS))/256.0*360.0

C--------------------------------
C Force Ratios

FDI = 0.5 * CDL1 * RHO * AREA * (UMAX*(ABS(UMAX)))
FII = CIL1 * RHO * VOL * UDOTM
FDIL = FDI / FII
FDIM = AHFV / AHFA
FVFH = AFMV / AFMH
Line# 1  7
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2010  RETURN
2011  END

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APPENDIX C.

LIST OF NOTATIONS & SYMBOLS

The following symbols are used in this paper:

\( A \) = projected area of model (\( \text{ft}^2 \))

\( A_i \) = actual velocity amplitude

\( A_0 \) = measured velocity amplitude by current meter

\( C_D \) = drag coefficient

\( C_F \) = maximum force coefficient

\( C_I \) = inertia force coefficient

\( C_L \) = lift force coefficient

\( C_M \) = added mass coefficient

\( D \) = diameter

\( e_t, e_1, e_2, e_3 \) = distance from wave channel bottom

\( E_F \) = center of force elevation

\( E_M \) = current meter elevation

\( F \) or \( F_{HT} \) = total force (=total horizontal force)

\( F_D \) or \( F_D \) = drag force

\( F_{H1}, F_{H2}, F_{H3} \) = individual horizontal force

\( F_I \) or \( F_I \) = inertia force

\( F_L \) or \( F_L \) = lift force (=vertical force)

\( \text{FORI} \) = Fourier method

\( f_n \) = noise frequency

\( g \) = gravitational acceleration (= 32.174 \( \text{ft/sec}^2 \))

\( H \) = wave height (ft)

\( h \) = water depth (ft)
\( K = \) static sensitivity of current meter (fps/volt)
\( k = \) wave number (\( = 2\pi/L \))
\( KC \) or \( K-C = \) Kulegan-Carpenter number
\( L = \) wave length (ft)
\( L_0 = \) wave length in deep water
\( LSQ = \) least square method
\( LWT = \) linear wave theory
\( MXVL = \) maximum value method
\( n = \) noise constant
\( Re = \) Reynolds number (\( = U_mD/\eta \))
\( T = \) wave period
\( U_i = \) actual velocity in field
\( U_0 = \) measured velocity from current meter
\( U_m = \) maximum horizontal velocity
\( V = \) enclosed volume of test model
\( \nu = \) kinematic viscosity of water
\( = 1.25 \times 10^{-5} \text{ ft}^2/\text{sec at } 54^\circ F \)
\( \rho = \) density of water
\( = 1.939 \text{ slugs/ft}^3 \text{ at } 54^\circ F \)
\( \sigma = \) wave frequency
\( \omega = \) angular frequency \( (=2\pi/T) \)
\( \tau = \) time constant of current meter (sec)
\( \phi = \) phase angle
\( f = \) function