MOTION ANALYSIS AND MODEL STUDY OF A
GUYED TOWER STRUCTURE IN REGULAR WAVES

CENTRE FOR NEWFOUNDLAND STUDIES

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MOTION ANALYSIS AND MODEL STUDY OF A
GUOED TOWER STRUCTURE IN REGULAR WAVES

by


A thesis submitted in partial fulfillment of
the requirements for the degree of

Master of Engineering

Faculty of Engineering and Applied Science
Memorial University of Newfoundland

August 1981
The use of fixed platforms of either the gravity or jacket type in water depths exceeding three hundred and fifty meters would so escalate the size of these conventional platforms as to render recovery of oil uneconomical. Alternative platform concepts such as the guyed tower (Finn, 1976) take advantage of the effect of compliance to the wave action. However, such a concept introduces the main problem for deep-water platforms namely the dynamic interaction of waves and structure. Assuming the tower to be of uniform flexural rigidity and uniform weight per unit length, a modified Morison's equation was used to determine the horizontal wave loads on the tower. The equation of motion for the horizontal displacement of the deck was set up and a Crank-Nicholson finite-difference algorithm was employed to solve the equation of motion of the tower. Water particle velocity and acceleration used in the wave loading computation were obtained using linear diffraction theory (MacCamy and Fuchs, 1954). In the development of the computer model the tower was represented as an equivalent beam and the distributed wave load was resolved into concentrated nodal forces. Experimentally determined coefficients for damping, restoring and the mass of the tower were used for solving the equation of motion.

In order to compare the predictions of the computer model with the performance of a physical model, a model of the guyed tower was constructed and tested in a wave tank. The tower was supported by eight guy wires each having a model weight per unit length of 5.22 N/m. Deck displacements of the tower were monitored by means of rotary
transducers and the guy line tensions were monitored using ring transducers placed directly in the lines. The damping coefficient of the model was determined experimentally by displacing the model and using the logarithmic decrement obtained from a record of its free oscillation. The restoring coefficient was also determined experimentally by generating a plot of total restoring force versus deck offset of the model tower. Fairly good agreement between the computer model results and the physical model test results was found for the deck displacement.
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NOMENCLATURE

A - projected cross-sectional area
C - drag coefficient
D - diameter of cylinder
F - exciting wave force
H - wave height
H_n - Hankel function of first kind of order n
H_0 - Hankel function of first kind of order zero
J_n - Bessel function of first kind of order n
K - total restoring coefficient
L - length of mooring line
M - effective mass
P - load vector on tower
RAO - Response Amplitude Operator
T - total tension in mooring line
T_h - horizontal component of T
T_v - vertical component of T
J_n - Bessel function of second kind of order n
a - cylinder radius
c - damping coefficient
\theta - acceleration due to gravity
k - wave number, \sqrt{g/}\lambda
L - length of cylinder
M - mass

\eta - slope of mooring line characteristic curve of \eta/u versus \sqrt{u^2 + 1}
\eta_* - slope of mooring line characteristic curve of \eta/u versus T/T_{sw}
r - radial coordinate
w - weight per unit length of mooring line
x - horizontal distance from clump weight to tower position
x_h - horizontal component of water particle velocity
x_h - horizontal component of water particle acceleration
y - vertical component of water particle velocity
d - displacement vector
v - velocity vector
a - acceleration vector
z - vertical coordinate
\lambda - wave length
\rho - density of water
\beta - total velocity potential
\eta_0 - velocity potential of incident wave
\eta_r - velocity potential of reflected wave
1. INTRODUCTION

The large majority of ocean structures currently under study are related to activities in the offshore oil and gas industry. Present systems vary from the concrete bottom founded type in water depths of up to one hundred fifty meters to the dynamically positioned semisubmersible operating at depths up to three hundred meters. In the ongoing development of the ocean’s resources it is the responsibility of engineers to provide the industrial sector with safe and economical methods of design and analysis. Presently, the main technique for design and behavioural prediction is numerical modelling. Testing and verification of numerical models used to predict the behaviour of offshore structures is of increasing interest in the development of new structural concepts since there exists a number of basic hydrodynamic effects that lack adequate theoretical description. Traditionally these have been discarded in hydrodynamic experimental testing because their importance has been considered to be negligible, however the development of new deep water concepts demand a more sophisticated technology.

One deepwater concept for a water depth range of six hundred to eight hundred meters is the guyed tower (Finn, 1976). The guyed tower is a tall, relatively thin truss-framed compliant structure. The foundation of the guyed tower is usually of the spud can or pile configuration. The tower is held upright by a system of guylines, the ends of which are attached to clumped weights resting on the ocean floor. These weights are connected to anchors embedded in the floor or
to piles by means of a trailing line. Thus, when the tower
displacement exceeds a particular limit, this clumped weight will lift
off. An advantage of the guyed tower for deep water drilling as
compared to the jacket type structure is the economy in its structural
cost due to a considerable reduction in steel.

In the late 1960's Exxon Production Research Company began to
consider the guyed tower as a production platform and as a result in
1975 a 1/5th scale model was erected in the Gulf of Mexico. Finn
(1976) has presented the analytical results of wave loading on the
tower, wherein the wave-particle kinematics are computed using Airy's
wave theory. However, to date it appears that there have not been any
results concerning wave tank studies of such a structure published in
the open literature. The following thesis compares an analytical and
physical model of a guyed tower structure.

2. THEORETICAL DEVELOPMENT

Consider irrotational, inviscid, and incompressible two-
dimensional motion of water waves over a stable horizontal bottom,
which can be described by the Laplace differential equation

$$\nabla^2 \phi = \frac{\partial^2 \phi}{\partial x^2} + \frac{\partial^2 \phi}{\partial z^2} = 0$$

(1)

where, $\phi$ is the velocity potential.

and, $\frac{\partial \phi}{\partial x} = u_w$ and $\frac{\partial \phi}{\partial z} = v_w$

(2)

are the horizontal and vertical velocity components of the water
particles respectively.
Equation 1 is subjected to the following boundary conditions:

1) an impermeable bottom boundary condition described for a horizontal sea bed as:

\[ \frac{\partial \phi}{\partial z} = 0 \quad \text{at} \quad z = -h \]

where \( h \) = water depth

2) assuming that the incident wave height to length ratio is sufficiently small, all non-linear effects due to wave steepness may be neglected without significant error. Hence, the linear free surface boundary condition can be expressed as

\[ \bar{n} = \frac{1}{g} \frac{\partial \phi}{\partial t} \]

where \( \bar{n} \) is the free surface elevation at time \( t \) above still water line.

Under these conditions the velocity potential of the incident wave \( \phi_i \) may be written as

\[ \phi_i = \frac{gh}{2u} \cosh k(h + z) \cosh kh \ e^{i(kx - \omega t)} \]  

(3)

and transformed to polar coordinates \( r \) and \( \theta \) as,

\[ \phi_i = \frac{gh}{2u} \cosh k(h + z) \left[ \cos(kr \cos \theta) + i \sin(kr \cos \theta) \right] e^{-i\omega t} \]  

(4)

Equation 4 is obtained under the assumption that the particle kinematics is not affected by the presence of an object in a wave field. However, if the effect of the presence of an object on the particle kinematics is to be considered, the linear diffraction theory can be used. Although Airy's wave theory could be used for smaller \( 2a/\lambda \) ratios for design purposes, the use of linear diffraction theory for
estimating the hydrodynamic fluid loading on individual vertical cylinders could be a more complete analysis than Airy's wave theory. The diffraction theory requires that the total potential \( \phi \) can be expressed as the summation of incident wave \( \phi_i \) and the reflected wave potential \( \phi_r \).

Assuming that the reflected waves move outward with respect to the cylinder, the velocity potential for the reflected wave, \( \phi_r \), can be written as,

\[
\phi_r = \sum_{n=0}^{\infty} A_n \cos n\theta [J_n(kr) + iY_n(kr)] e^{-i\omega t}
\]

\[
= \sum_{n=0}^{\infty} A_n \cos n\theta [H_n(kr) e^{-i\omega t}]
\]

where \( J_n, Y_n \) are the Bessel functions of the first and second kind respectively, and \( H_n \) is the Hankel function of first kind.

It is implied here that the reflected wave potential satisfies the radiation boundary condition as expressed by

\[
\lim_{r \to \infty} \sqrt{r} \left[ \frac{\partial \phi_r}{\partial r} + ik \phi_r \right] = 0
\]

The total velocity potential satisfying eqn. (1) and the boundary conditions can be written after MacCamy and Fuchs (1954) as,

\[
\phi = -\frac{gH}{2u} \cosh k(h + z) \left[ J_o(kr) + 2 \sum_{n=1}^{\infty} i^n J_n(kr) \cos n\theta \right] e^{-i\omega t}
\]

\[
+ \sum_{n=0}^{\infty} A_n \cos n\theta [H_n(kr) e^{-i\omega t}]
\]
It should be mentioned here that although MacCamy and Fuchs have employed Hankel function of the second kind in their work for describing the reflected wave, Spring (1973) has pointed out that Hankel function of the first kind only describes the outgoing wave whereas the Hankel function of the second kind describes the incoming wave. Since, the scattered wave should be outgoing rather than incoming, the Hankel function of first kind is used here.

The coefficient $A_n$ is determined by setting the particle velocity normal to the cylinder, $\frac{\partial \phi}{\partial r}$, equal to zero at $r = a$, where $a$ is the cylinder radius.

$$A_0 = \frac{gh}{2\sigma} \cosh(k(h+z)) \frac{J_0'(ka)}{J_0'(ka)}$$

$$A_n = \frac{gh}{2\sigma} \cosh(k(h+z)) \frac{J_n'(ka)}{J_n'(ka)}$$

Substituting (7) into (6), the total velocity potential is

$$\phi = \frac{gh}{2\sigma} e^{-ist} \cosh(k(h+z)) \left(\frac{J_0'(ka)}{J_0'(ka)} - \frac{J_0'(ka)}{H_0'(ka)} H_0'(kr)\right)$$

$$+ 2 \sum_{n=1}^{\infty} \left[\frac{J_n'(ka)}{H_n'(ka)} H_n'(kr)\right] \cos n\theta$$

where $n = 1, 2, 3, \ldots$, and $J_n'(ka)$ and $H_n'(ka)$ denote the derivatives at $r = a$ of $J_n'(kr)$ and $H_n'(kr)$ respectively. The particle velocity in the horizontal direction is given by $u_w = \cos \theta \frac{\partial \phi}{\partial r} - \sin \theta \frac{\partial \phi}{\partial \theta}$.

Using the above described method, the particle kinematics on each of the vertical members in the model were determined.
2.1 Equation of Motion of Guyed Tower

The equation of motion of a compliant offshore structure can be defined as,

\[ M \ddot{x} + C \dot{x} + Kx = F \quad (10) \]

where \( M \) is the effective mass, \( C \) is the equivalent viscous damping coefficient, \( K \) is the restoring coefficient, \( F \) is the exciting force and \( x, \dot{x}, \ddot{x} \) are the displacement, velocity and acceleration vectors respectively.

Horizontal wave forces per unit length of a fixed structure can be calculated using Morison's equation (Morison et al., 1950),

\[ \Delta F = \frac{1}{2} C_D \rho D \left| u_W \right| u_W \dot{l} + C_m \rho \frac{\pi}{4} D^2 \dot{u} \quad (11) \]

All terms are defined in the nomenclature.

Equation 11 gives an estimate of the fluid loading on a structure with its bottom rigidly fixed. For this case the displacement of the cylinder is zero. Hence to calculate the fluid loading on a structure which has its own displacement, as in the case of a guyed tower, the relative motion between the water particle and the structure must be considered.

The relative horizontal wave particle velocity \( u \) and relative acceleration \( \ddot{u} \) are defined as,

\[ u = u_W - x \quad (12a) \]
\[ u = u_w - x \] (12b)

where \( u_w \) and \( u_x \) are the horizontal component of the water particle velocity and acceleration respectively. Fish et al. (1980) and Sunderland and Connor (1981) have defined the hydrodynamic loading per unit length of the vertical cylinder in a compliant structure as,

\[ \Delta F = C_D \frac{\rho}{2} \frac{D}{2} (u_w - x)(u_w - x) \]

\[ + (C_m - 1) \rho \frac{\pi}{4} D^2 (u_w - x) + \frac{\pi}{4} D^2 \rho u_w \] (13)

Equation 13 consists essentially of three terms. As in the case of the fixed vertical cylinder the drag and inertia forces are considered and an additional term known as the Froude-Krylov force introduced. This particular term is related to the undisturbed pressure field around the structure. For the present analysis particle velocities and accelerations are obtained from the linear diffraction theory as explained earlier.

After substitution of equation 13 into equation 10, it can be written as,

\[ x(M+a_m) + x(C+A_c) - \alpha_x x^2 + Kx = P \] (14)

where

\[ P = C_D \rho \frac{D}{2} u_w^2 + C_m \frac{\pi}{4} D^2 \rho \in u_w \] (15)

\[ a_m = \frac{\pi}{4} D^2 \rho \in (C_m - 1) \] (16)

\[ A_c = C_D \rho \in D u_w \] (17)
The values of effective mass, effective damping and stiffness for the tower were determined experimentally as described in section 5 and were used in the solution of the equation of motion of the tower. The coefficient $a_3$ stems from the relative velocity term in the equation of motion. It accounts for the drag induced by the motion of the structure in the waves.

The wave load on the structure is determined by using an equivalent vertical beam. In the case of long waves, spatial effects can be neglected and a single equivalent beam was used. However, for short wave lengths spatial variations can be treated using a number of vertical beams. The flexural properties of the tower can accurately be represented by an equivalent beam as shown in Figure 4. A single translational degree of freedom is used at each nodal point. Vertical displacements are relatively small and can be neglected. Each node has an attached lateral spring $k_1$. Concentrated forces at the nodes are determined by calculating the distributed forces at the mid-point, top and bottom of each equivalent element of length $l$.

The tower was modelled as a multi-degree-of-freedom system because the response of the tower such as the deck offset can be adequately described by the first node.

2.2 Method of Solution

Using the central point Crank-Nicholson finite difference method, the equation of motion (14) can be written as:

$$a_3 = C_D \rho \frac{D}{2}$$  \hspace{1cm} (18)
\[
M \frac{(x_{i+1} - 2x_i + x_{i-1})}{\Delta t^2} + \frac{(x_{i+1} - x_{i-1})}{2\Delta t} (C + A_c) + a_3
\]

\[
\frac{x_{i+1}^2 + x_{i-1}^2 - 2x_{i+1} x_{i-1}}{4\Delta t^2} + K \frac{(x_{i+1} + x_{i-1})}{2} = \frac{P_{i+1} + P_{i-1}}{2}
\]  

The equation of motion of the tower as represented by equation 14 is nonlinear. Hence, it was solved numerically using the Crank-Nicolson finite difference algorithm. This finite difference scheme is universally stable and has the advantages of smaller truncation error than the standard implicit or explicit finite difference scheme. Appendix 2 explains the flow diagram of the solution procedure for the solution of equation 19.

3. PROTOTYPE SCALING

The essential requirements of any model are that it provides an adequate representation of the design environment for a particular structure, the loading on the structure and the structure itself. Similarity between prototype and model when the behavior is dominated by the action of the waves and the inertia of the body is achieved using Froude scaling.

In order to scale from model to prototype, the laws of dynamic, geometric and kinematic similarity must be satisfied. Dynamic similarity is achieved by holding the ratio of the gravity force (assumed dominant for free surface flow) to inertia force constant. This results in a relationship between the model and prototype known as the Froude Number defined as,
\[ \sqrt{\frac{V_m^2}{g_m m}} = \sqrt{\frac{V_p^2}{g_p p}} \]  

(20)

where \( V \) is velocity, \( L \) is length, \( g \) is acceleration due to gravity and the subscripts \( m \) and \( p \) denote model and prototype respectively. Geometric similarity is achieved holding the ratio of model length to prototype length constant as follows:

\[ \frac{L_p}{L_m} = n \]  

(21)

Kinematic Similarity is achieved by holding the ratio of model velocity to prototype velocity constant. From the Froude relationship above

\[ \left( \frac{V_p}{V_m} \right)^2 = \frac{L_p}{L_m} = n \]  

(22)

From these relationships, the following scales are determined:

Length scale: \( L_p = nL_m \)  

(23)

Velocity scale: \( V_p = \sqrt{n}V_m \)  

(24)

Time scale: \( T_p = \sqrt{nT_m} \)  

(25)

Force scale: \( F_p = n^3F_m \)  

(26)

The choice of model scale depends mainly on the wave tank dimensions. In any case, the scale factor must allow accurate adjustment of such quantities as pretension in mooring lines, wave heights and wave periods and assume that model force and motion levels can be accurately measured and recorded.
4. GUYLINES ANALYSIS

The catenary stiffnesses of moving systems of articulated towers supported by guylines from the sea bed are of critical importance in the design of compliant structures such as the guyed tower since they greatly effect the response of the structure. Rothwell (1979) has presented a simple graphical approach to computing the stiffness of a catenary of a pretensioned or taut mooring line. In this analysis the slopes of a number of nondimensional curves are used to determine the stiffnesses of the free end mooring lines.

Define \( L \) as the length of cable from the clump weight to the end attached to the tower,

\[
\sin \varphi = \frac{1}{2} \frac{wv}{T} \left( \frac{L}{v} - \varphi \right) + \varphi
\]

(27)

where \( w \) is the weight per unit length of the mooring line, \( v \) is the vertical distance of the point in the cable to be analyzed (in this case the point at the tower) and \( T \) is the tension in the cable. The angle \( \varphi \) indicates the angle between the tangent at the specified point and the horizontal. The angle made by the catenary at the sea bed, \( \varphi_0 \), is defined as,

\[
\varphi_0 = \cos^{-1} \left( \frac{\cos \varphi}{1 - (wv/T)} \right)
\]

(28)

The horizontal and vertical components of the mooring line tension \( T_x \) and \( T_y \) respectively are defined as,

\[
T_x = T \cos \varphi
\]

(29)

\[
T_y = T \sin \varphi
\]

(30)
The horizontal distance, \( u_1 \), from the clump weight to the point of analysis in the line is defined as
\[
\frac{T_x}{w} \ln \left( \frac{\sec \psi + \tan \psi}{\sec \psi_0 + \tan \psi_0} \right)
\]
(31)

The corresponding stiffnesses may be determined as follows,
\[
\frac{\partial T_x}{\partial u_1} = \frac{w}{n_2}
\]
(32)
\[
\frac{\partial T_y}{\partial u_1} = \frac{n_1}{n_2} w
\]
(33)
\[
\frac{\partial T_x}{\partial v} = w \left( \frac{T_y}{wv} \right) - \frac{w}{n_2} \left( \frac{u - l}{v} \right)
\]
(34)
\[
\frac{\partial T_y}{\partial v} = w \left( \frac{T_y}{wv} \right) + n_1 \frac{\partial T_x}{\partial v} - \frac{T_x}{wv}
\]
(35)

The values \( n_1 \) and \( n_2 \) are the slopes of the curves \( T_x/wv \) versus \( T_y/wv \) and \( T_x/wv \) versus \((u_1 - l/v) + 1\). Clearly it can be seen that the cable stiffnesses are directly related to the weight per unit length.

5. EXPERIMENTAL PROCEDURE

A model of a guyed tower structure shown in Fig. 5, was constructed of polyvinyl chloride tubing. The tower is of no particular design but a Froude scale of 1/60 would represent a prototype structure with a height of one hundred and twenty meters, which is supported by eight guy wires in ninety meters of water. The physical properties of the tower and mooring system are given in Table 1. The value of \( w \) (weight per length of cable) was simulated by having lead weights in the lines which were made of 2 mm braided wire. Clump
weights were constructed of lead blocks resting on the tank floor. The rotational stiffness at the foundation was not modelled as the tower was mounted on a ball bearing assumed to have negligible friction.

All tests were conducted in the wave tank shown in Figs. 1 and 3 at a still water depth of 1.65 m. The facility construction and calibration is described in Nagera and Murray (1983). Fig. 2 shows the calibration results for both regular and irregular waves compared to those presented by Gilbert et. al., (1971). The tank structure is of reinforced concrete 61 m long, 4.5 m wide and 1 m deep. Waves are generated by means of a piston type analog controlled generator, thus generating regular and irregular water waves. Wave profiles are measured using resistance type probes. These probes consist of two parallel stainless steel wires 1.5 mm in diameter, 73.4 cm long and 1.25 cm apart. Voltage across the probe wires varies proportional to the depth of immersion. Model motions were measured using a system of rotary potentiometers. The associated circuits, as shown in Fig. 6 provide an accurate measurement of the horizontal displacement of the model.

Variations in the tension of the guy wires were monitored using ring transducers placed directly in the lines. Signals from each of the transducers were recorded on an eight channel analogue tape recorder while the deck offset and wave profile were recorded on a strip chart recorder as illustrated in Fig. 6.

The damping and restoring coefficients used in the equation of motion of the tower were determined experimentally. Fig. 7 shows the total restoring force for a range of deck displacements. This curve was generated by applying dead weight loads at the center of the tower deck and recording the resulting offset. The restoring coefficient used was determined from the portion of the graph before the clump weight lifts off. The damping coefficient was determined experimentally by using the logarithmic decrement of a free oscillation of the tower, resulting from offsetting the tower until the first clump weight lifted off and releasing the tower. The average of three such oscillations was used. Subsequently, the total mass, damping and restoring coefficients used in the computer model were 19.7 kN, 0.0 Mm/s and 7.0 N/m respectively.

Regular waves were generated for periods ranging from 0.57 sec to 5.00 sec. Table 2 shows the wave period and corresponding heights for all runs made during the model tests.

6. RESULTS AND DISCUSSION

Fig. 9 shows the deck offset for wave heights at wave periods of 0.60 sec, 1.00 sec and 2.25 sec. Good agreement was found for periods less than the natural period of the structure. Discrepancies between the computed and experimental values increase with increased value of wave period. This trend is also demonstrated in Fig. 10 which illustrates the Response Amplitude Operator (RAO) of the model. Once again, the results show fairly good agreement for periods up to the natural period of the structure, however above this (1.61 sec) value discrepancies increase with increasing period.
This discrepancies can be partially due to a higher value of added mass coefficient than the assumed value in the higher range of Keulegan-Carpenter numbers. In addition to this, the model mount although assumed to have negligible stiffness and damping characteristics, did in fact affect the tower response. Fig. 8 shows the measured tensions in two selected cables. The mooring line characteristics of a typical guylines are in Fig. 11. These curves were generated by use of the computer program "MOORING LINE ANALYSIS" found in Appendix 1. Characteristics shown in these curves are those pertaining to the section of mooring line between the clump weight and the tower itself for tension conditions from pretension 14.31 N to 24.05 N the tension corresponding to the lifting of the first clump weight. Observation of Fig. 8 and Fig. 11 shows some disagreement in the response of the mooring line.

This disagreement in results is due to the magnitude of the pretension in the mooring lines and the distribution of the weights within the line itself. The non-linear characteristic of a mooring line illustrated in Fig. 11 is due to the catenary of the line, however as the catenary approaches a straight line from the clumped weight to the point of connection on the tower the mooring system approaches a linear one. Under these conditions any change in the deck offset will result in a constant change in the line tension until the clumped weight lifts off. This behaviour is also illustrated in Fig. 7 where the total restoring coefficient is linear until the weight lifts off. Therefore the mooring line was not properly modelled for any particular
prototype since the weights were not placed in the line to simulate the correct catenary shape.

As may be inferred from the scaling factors in section 3, the weight per unit length of 5.21 N/m of the model cable, when scaled to prototype conditions would not be realistic. However these conditions may be qualified somewhat by the fact that the primary objective is to compare two methods of analysis of a structure response, i.e., a physical model with an analytical model. Also the mooring line stiffness and subsequently the resonant frequency conditions of the tower can be manipulated by the pretension and weight per unit length of the mooring line. It was of particular interest that the resonant conditions fell within the frequency range limitations of the wave generator.

Traditionally these stiffness characteristics have been simulated using a system of springs mounted in air and attached to the model at the proper point to simulate conditions realized by the structure as a mooring system. This method may pose questions as to the accuracy of the simulation of effects on the structure due to the hydrodynamic loading on the cables themselves.

7. SUMMARY AND CONCLUSIONS

A computer model for the analysis of a guyed tower has been developed using a modified form of Morison's equation for the calculation of fluid loading and resulting motion response of the structure. The equation of motion for the deck offset was set up by representing the tower as an equivalent beam and a Crank-Nicholson finite-difference
algorithm was employed to solve the equation. This particular method has shown to be an adequate means of solution where there are non-linear effects such as those introduced by the relative motion of the structure, since it does not impose restrictions on the time step.

A physical model of a guyed tower has been constructed, instrumented and tested for motion response in a range of regular wave frequencies. The model was supported by eight guylines, the stiffness characteristics of which have also been investigated and presented. The results of these tests have been compared to the computer models and good agreement was found.

Considering the errors that may have resulted from scaling effects, it can be concluded that the results obtained from the model tests could be used in the design and analysis of the guyed tower structure. Apart from a direct comparison with prototype information itself, which has obvious economic restrictions, the scaled model test is a suitable means of obtaining quantitative results concerning the response of the guyed tower provided the statistics of all anticipated extremes are applied.
REFERENCES


Fig. 1. Elevation and Plan Views of Wave Flume
FIG. 2. PISTON REGULAR AND RANDOM WAVE GENERATOR PERFORMANCE
FIG. 3. REGULAR WAVE IN WAVE TANK
FIG. 5. GUYED TOWER IN REGULAR WAVES
FIG. 6. DATA ACQUISITION EQUIPMENT
FIG. 7. TOTAL RESTORING FORCE OF MODEL TOWER
FIG. 10. RAO vs. WAVE PERIOD FOR REGULAR WAVES
FIG. 11 STIFFNESS CHARACTERISTIC CURVES FOR A TYPICAL CABLE.
<table>
<thead>
<tr>
<th>TABLE 1 - PHYSICAL PROPERTIES OF MODEL TOWER</th>
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<tr>
<td><strong>Height</strong></td>
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<tr>
<td><strong>Width</strong></td>
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<tr>
<td><strong>Total Weight</strong></td>
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<tr>
<td><strong>Damping Coefficient</strong> (at natural oscillation)**</td>
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<tr>
<td><strong>Total Restoring Coefficient</strong></td>
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<td><strong>Guylines</strong></td>
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<tr>
<td>total number</td>
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<tr>
<td>weight per unit length</td>
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<tr>
<td>pretension</td>
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<tr>
<td>Wave Period (Sec)</td>
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APPENDIX 1

MOORING LINE ANALYSIS PROGRAM
FLOWCHART FOR MOORING LINE ANALYSIS.
158 PRINT " LENGTH OF MOORING LINE ... ";
160 INPUT L;
170 PRINT " VERTICAL DISTANCE FROM OCEAN FLOOR ... ";
180 INPUT Y;
190 PRINT " DECREMENT OF TENSION; ";
200 INPUT D;
202 LET I=0
210 PRINT  " A  B  C  T  ANG  U";
220 REM CALCULATE AND OUTPUT TX/VW,TV/VW,U,(CU-L)/V+I,ANGEL,T,AND U.
250 FOR H=63 TO 1 STEP -1
260 LET S1=(C*(U*V)/T)*(L/V-(V/L))*(V/L)
265 LET C1=SORC(1-(S1**2))
270 LET C2=C1/(1-(V*V/T)).
272 LET S2=SORC(1-(C2**2))
275 LET ACMJ=(T*(V*V))/C1
280 LET BCMJ=(T*(V*V))/S1
285 LET F=(1/C1+S1/C1)/(1/C2+S2/C2)
287 LET U=(ACMJ*V)**LOG(F)
290 LET CMJ=(C-L)/V+1
295 LET R=ATAN(S1/C1)*180/3.1415
300 PRINT ACMJ;BCMJ;CMJ;T;R;U
310 LET HMJ=T
330 LET DEMJ=U
355 LET T=T-D
357 NEXT H
358 REM CHANGE ARRAYS A,B,C,AND C FROM FLOATING POINT TO INTEGER FORMAT.
360 PRINT " 
361 FOR K=63 TO 1 STEP -1
362 LET X=A[K]
363 LET Y=B[K]
364 LET Z=C[K]
365 CALL DPUT(EII,0CII,K,X,I)
366 CALL DPUT(FII,0CII,K,Y,I)
367 CALL DPUT(GII,0CII,K,Z,I)
368 NEXT K
1 CALL SCORE(7)
2 REM THIS PROGRAM WILL OPERATE ON A 5451B FOURIER ANALYZER
3 REM WITH A FOURIER BASIC CORELOAD, OPTION 720
4 REM PROGRAM NAME: "MOORING LINE ANALYSIS".
5 REM THE RESULTING ARRAYS OF DATA ARE STORED AS FOURIER DATA BLOCKS
6 REM IN THE TIME DOMAIN
7 REM TX/W, TY/W, AND \((U-L)/V\)+1 ARE LOCATED ON DISK IN FILE 1
8 REM RECORDS 0, 1, AND 2 RESPECTIVELY.
9 DIM D[64], H[64]
10 DIM A[64], B[64], C[64]
11 REM A IS TX/W, B IS TY/W, AND C IS \((U-L)/V\)+1
12 DIM E[64], F[64], G[64]
13 REM DATA BLOCK QUALIFIERS FOR FOURIER DATA BLOCK.
58 LET Q[1]=64
60 LET Q[2]=0
70 LET Q[3]=32767
80 LET Q[4]=13
90 LET Q[5]=0
91 CALL FIX0(Q[1])
92 FOR N=1 TO 64
93 LET A[N]=0
94 LET B[N]=0
95 LET C[N]=0
96 LET D[N]=0
97 LET E[N]=0
98 NEXT N
99 REM INPUT GUYED TOWER PARAMETERS
100 PRINT "MOORING LINE DESIGN PROGRAM"
101 PRINT "-----------------------------------"
102 PRINT
110 PRINT " WEIGHT PER UNIT LENGTH ... ";
120 INPUT W1
130 PRINT "UPPER LIMIT OF TENSION";
140 input T
359 PRINT "THIS IS A"
370 CALL DSYIPK(EI,OE,EI,63,0)
375 REM THIS SECTION DISPLAYS ARRAYS A, B, AND C ON THE SYSTEM DISPLAY.
380 PAUSE
390 CALL MODIS
395 PRINT
400 PRINT "THIS IS B"
410 CALL DSYIPK(EI,OE,EI,63,0)
420 PAUSE
430 CALL MODIS
440 PRINT
441 PRINT "THIS IS C"
450 CALL DSYIPK(EI,OE,EI,63,0)
460 PAUSE
470 CALL MODIS
475 REM WRITE THE ABOVE CALCULATED ARRAYS OF DATA ON DISK.
480 CALL DWRITK(EI,OE,EI,64,1)
490 CALL DWRITK(EI,OE,EI,1,64,1)
500 CALL DWRITK(EI,OE,EI,2,64,1)
520 LET N1=CB(E33)-BE(103)/(AE(103)-AC(103))
530 LET N2=CC(E33)-CC(103)/(AE(103)-AC(103))
531 REM CALCULATE STIFFNESSES.
535 LET S3=V1/N2
540 LET S4=(V1/N2)*W1
542 PRINT
545 PRINT "DTX/DU =",S3," DTY/DU =",S4
550 PRINT "T"
551 PRINT " T = DTY/DV"," DXY/DTV"," T"
560 FOR J=63 TO 1 STEP -1
570 LET SS=(V1*AE(J))-(V1/N2)*(OE(J-1)/V)
580 LET SG=(V1*BE(J))+(V1*(SS-(V1*AE(J))))
590 PRINT SS,SG,HE(J)
600 NEXT J
605 END
APPENDIX 2

EQUIVALENT BEAM ANALYSIS PROGRAM
INPUT PARAMETERS

CALCULATE M, C, K FOR EACH ELEMENT

SET i = Δt

CALCULATE WATER PARTICLE KINEMATICS Uw, Uẇ

CALCULATE FLUID LOADING AT EACH DEPTH. ESTIMATE NODEAL FORCE, P BY SIMPSON'S RULE

ASSUME INITIAL DISPLACEMENTS FOR ALL NODES x

CALCULATE DISPLACEMENTS FOR ALL NODES

SET \( \bar{x} = (\bar{x} + x) / 2 \)

ABS(\( \bar{x} - x \)) < \epsilon

YES

PRINT t, x
SET i = i + Δt

NO

YES

i < T

NO

END

FLOWCHART FOR EQUIVALENT BEAM ANALYSIS
NUMBER OF PRISMATIC BEAM ELEMENTS.

NUMBER OF DEGREES OF FREEDOM.

C = DAMPING COEFFICIENT OF ELEMENTS.

S = DAMPING COEFFICIENT OF ELEMENTS.

SM = MASS OF ELEMENTS.

WAVE LENGTH.

STILL WATER DEPTH.

WAVE PERIOD.

WAVE HEIGHT.

DRAG COEFFICIENT

MASS COEFFICIENT

DIAMETER OF VERTICAL MEMBERS.

PARTICLE VELOCITY IN VERTICAL DIRECTION.

PARTICLE VELOCITY IN HORIZONTAL DIRECTION.

PARTICLE ACCELERATION IN HORIZONTAL DIRECTION.

PARTICLE ACCELERATION IN HOVERTICAL DIRECTION.

WAVE VELOCITY.

DISPLACEMENT OF ELEMENT.

HEIGHT OF TOWER.

RMS VELOCITY OF UZ.


COMMON / FORNOD / FNODC, ACOND, SCOND, CCOND

COMPLEX CTME, CIP, CPR, SUMB, HOTD, HRTD, ETA, GBE

COMMON / CEXT1 / DT, SIZER, STEP, DES, TRI

COMMON / DISPLA / DSPN, DISPN, DISPNP, DISPNM

COMMON / CNPL1 / CTME, CI, CPR, SUMB, HOTD, HNTD, ETAD

COMMON / CHAR1 / T1, T2, T3, T4, T5, T6, T7, T8, T9, T10, T11, T12

COMMON / CHAR2 / PER, SWL, HT, AMP, EL, EX, WNO, WFR, PI, TIME, ETA, G, LO, SIGM, PHBL, CEL, PHBLCL

COMMON / SHT1, SHT, SHT2, SHT3, SHT4, CT1, CT3, CT4, SHT3

CH4T1, CH4T2, CH4T3, CH4T4, CH4T5, CH4T6, CH4T7, CH4T8, CH4T9

COMMON / FACTOR / RHO, ANO, CD, CM, DIA, FACT1, FACT2, AM2FR2, RHOG

COMMON / URM, RENO

COMMON / FORCE1 / UFSUM, UHSUM, AFSUM, AMSUM, EZ2

COMMON / A1 / FORCE1/00, MOMENT1/00, VZ/50, VDZ/50, UZ/50, UDZ/50

COMMON / A2 / ELEV1/00, PRES/50

COMMON / INCON1 / NZ, NZME, NZH, KK, NTH, NP

COMMON / FORCE / PX, PY, QX, QY, DELX, DELY, GB0, BOO, BOJ, BOJ, BOY, ATAL

COMMON / CHAR4 / AMPRES(20), FBE(6), GBE(6), FXS(50), FY(50), FXZ(50)

COMMON / BESS1 / BJJ, BY, B2J, B2Y, B1J, B1Y, GZ, FZ, FX, FY
DATA IR,JW / 5,6 /
1002 FORMAT ('/ WATER DEPTH = ',G10.3/
   1 ' WAVE PERIOD = ',G10.3/
   2 ' WAVE LENGTH = ',G10.3/
   3 ' WAVE HEIGHT = ',G10.3/
   4 ' WAVE NUMBER = ',G10.3/
   5 ' WAVE FREQUENCY = ',G10.3/
   6 ' CYLINDER SIZE = ',G10.3/
   7 ' WAVE STEEPNESS = ',G10.3/
1003 FORMAT (' SHALLOW WATER WAVE "SWL/EL" = ',G12.4)
1004 FORMAT (' DEEP WATER WAVE "SWL/EL" = ',G12.4)
1005 FORMAT (' TRANSITIONAL WAVE "SWL/EL" = ',G12.4)
1006 FORMAT (C6X,12610.3))
1007 FORMAT (C6X,10610.3))
2001 FORMAT (8E10.3)
2002 FORMAT (16I5)
3000 FORMAT (4G14.3)
READ (5,5) NP,NM,NPS
   5 FORMAT (3I5)
   6 READ (5,6) (GCI,I=1,NPS)
   7 FORMAT (8F10.0)
   8 READ (5,6) (AMASS(I),I=1,NPS)
   9 READ (5,6) (CCI,I=1,NM)
  10 WRITE (6,11)
  11 FORMAT (' THE STIFFNESS OF MEMBERS ')
  12 WRITE (6,12) (I,C(I),I=1,NPS)
  13 FORMAT (C5X,I3,E16.8)/
  14 WRITE (6,14)
  15 FORMAT (' DAMPING COEFFICIENT ')
  16 WRITE (6,12) (I,C(I),I=1,NPS)
  17 WRITE (6,13)
  18 FORMAT (' LUMPED MASSES ')
  19 WRITE (6,12) (I,AMASS(I),I=1,NPS)
  20 READ CIR,2001) SWL,PER,HT,TOWHT
  21 READ CIR,2002) NMEB,NP,NZ,NX,NTH
  22 READ CIR,2001) G,RH0,CD,CM,DIA,AND
  23 PI = 4.*ATAN1.0)
  24 ELLT = TOWHT/(NPS-1)
  25 FACT1 = CD*RHO*DIA/2.
  26 FACT2 = CM*RHO*PI*DIA*DIA/4.
  27 WFR = 2.*PI/PW
  28 SIGM = WFR**2./G
  29 LO = G*PER**2./PI
CALL WALGH
WNO = 2.*PI/EL
SIZEPR = WNO*DIA/2.
STEP = HT/EL
WRITE (JW, 1002) SWL, PER, EL, HT, WNO, WFR, SIZEPR, STEP
DES = SWL/EL
AMP = HT/2.
DT = PER/NP
TIME = -DT-
PHBL = PI*HT/EL
T2 = WNO*SWL
SHT2 = SINH(T2)
CHT2 = COSH(T2)
CH2T2 = COSH(2.*T2)
SHT2 = SINH(2.*T2)
SHT2 = SHT2**3.
SH4PT2 = SH3PT2*SHT2
TH2 = SHT2/CHT2
TRI = 5.+2.*CH2T2+2.*CH2T2*CH2T2
CEL = SQRT(G**TH2+1.*PHBL*PHBL*TRI/8./SH4PT2)/WNO
PHBLCL = PHBL**CEL
NZM = NZ-1.
EZ = SWL/NZM
AM2FR2 = RHO*AMP*AMP*WFR*WFR
RHOB = RHO*G
EX = 0.
GZ = RHOG*AMP/CHT2
FZ = GZ/RHOB/WFR
DISMNX = 0.
DISMXL = 0.
DO 27 I=1,NM
DISPM(I) = 0.
DISPN(I) = 0.
DISPNP(I) = 0.
DISPM(I) = 0.
DO 180 IT=1,NP
TIME = TIME+DT
CALL PARTIC (IT)
MEL = NZM/NM
DO 60 IM=1,NM
IT1 = (IM-1)*MEL+1
IF (IM.EQ.1.OR.IM.EQ.NM) GOTO 51
IT2 = IT1+MEL
GOTO 52.
51  IT2 = IT1+MEL/2
52  CONTINUE
   AL20 = CM*PI*RHO*DIA*DIA/4.0*ELLT
   AL40 = AL20*WFR
   AL30 = CD*RHO*DIA*ELLT
   C2W2 = C(IM)*C(IM)*WFR*WFR
   FXNOD(IM) = AL20*AFRMS+AL30*URMS
   SMFR2 = SC(IM)-AMASS(IM)*WFR*WFR
   AFACT0 = -AL30*URMS*(1.-SMFR2*SMFR2/(SMFR2*SMFR2+C2W2))/
         SQRT(C2W2)+AL40*URMS*SMFR2/(SMFR2*SMFR2+C2W2)
   BFACT0 = (AL30*URMS*SMFR2+AL40*URMS*SQRT(C2W2))/(SMFR2*SMFR2)
   +C2W2)
   DISP(IM) = AFACT0*COS(WFR*TIME)+BFACT0*SIN(WFR*TIME)
   DISP = DISP(IM)
   DISPNP(IM) = DISP(IM)
   CALL SUMINT(IT1,IT2,IM)
   EPS = 0.001
55  CONTINUE
   ANU1 = AMASS(IM)/DT/DT+C(IM)/2./DT+S(IM)/2.+AL30*DISPNP(IM)
   $ -2.*DISPNP(IM))/4./DT/DT
   ANU2 = AMASS(IM)/DT/DT-C(IM)/2./DT-AL30*DISPNM(IM-1)/4./DT/DT
   $ -SC(IM))/2.
   DISPNP(IM) = 1./ANU1*(FXNOD(IM)-DISPNP(IM)*(-2.*AMASS(IM))/DT/DT)
   $ DISPNP(IM)*=ANU2)
   DIF = ABS(DISPNP(IM)-DISPB)
   IF (DIF.LE.EPS) GOTO 59
   DISP = DISPNP(IM)
   GOTO 55
59  CONTINUE
60  CONTINUE
   DO 63 IM=1,NM
   DISPNP(IM) = DISPNP(IM)
   DISPNM(IM) = DISPN(IM)
   63  CONTINUE
   IF(DISPNP(IM).LE.DISMXN) GOTO 65
   DISMXN = DISPNP(NM)
   65  CONTINUE
   IF (DISP(NM).LE.DISMXL) GOTO 66
   DISMXL = DISP(NM)
   66  CONTINUE
   WRITE (6,3800) DISMXL,DISMXN,PER,HT
100  CONTINUE
STOP
END
SUBROUTINE PARTIC (IT)
COMPLEX CTME, CI, CPR, SUMB, HOTD, HNTD, ETAD, GBE
COMMON / EXTC1 / DT, SSIZEPR, STEP, DES, TRI
COMMON / CMPL1 / CTME, CI, CPR, SUMB, HOTD, HNTD, ETAD
COMMON / CHAR1 / T1, T2, T3, T4, T5, T6, T7, T8, T9, T10, T11, T12
COMMON / CHAR2 / PEP, SWL, HT, AMP, EL, EX, WNO, WFR, PI, TIME, ETA, G, LO,
      SIGM, PHBL, CEL, PHBL CL
COMMON / CHAR3 / SH1, CH1, SH2, CH2, SH3, CH3, SH4, CH4, SH5, CH5,
      SH6, CH6, SH7, CH7, SH8, CH8, SH9, CH9, SH10, CH10, SH11, CH11
COMMON / FACTOR / RHO, ANO, CD, CM, DIA, FACT1, FACT2, AM2FR2, RHOG,
      URMS, RENO
COMMON / FORCE1 / UFUSEM, UHUSEM, AFUSEM, AMUSEM, EZ2
COMMON / A1 / FORCEC(100), MOMENTC(100), VZC(60), VDZC(50), UZC(50), UDZC(50)
COMMON / A2 / ELEV(100), PRES(50)
COMMON / INCON1 / NZ, NZME, NZM, KK, NTH, NP
COMMON / FORCE / PX, PY, OX, OY, DELX, DELY, GBO, FBO, BOJ2, BOY2, ATAL
COMMON / CHAR4 / AMPRES(20), FECE(6), GECE(6), FEXC(50), FYC(50), FXZC(50)
DATA IR, JW / 5, 6 /
DLT = 0.02
T4 = WNO*EX-WFR*TIME
ST4 = SINC(T4)
CT4 = COS(T4)
C2T4 = COS(2.*T4)
S2T4 = SINC(2.*T4)
IF (HT/EL_LT.0.25E-01) GOTO 28
ETA = AMP*CT4+PHBL*HTC(2.+CH2T2)*CHT2*W2T4/SH2PT2/8.
GOTO 20
20 CONTINUE
ETA = AMP*ST4
20 CONTINUE
CALL FIXER
CALL WKNLR
URMS = SQRT(UFUSEM/CSWL+ETA)
RENO = URMS*DIA/ANO,
AFRMS = (AFUSEM/CSWL+ETA)
ELEV(30) = ETA
PHANG = C. WNO*EX-WFR*TIME)/3600./2./PI
1005 FORMAT (12G11.3)
RETURN
END
SUBROUTINE WALTCH
COMMON/ CHAR2 /PER, SWL, HT, AMP, EL, EX, WNO, WFR, PI, TIME, ETA, 6, LO,
                SIGM, PHBL, CEL, PHBLCL
               
               CALCULATE WAVE LENGTH
               T1 = WFR*W2, MSWL/6
               T2 = T1**2,
               T4 = T2**2,
               T5 = T4*T1
               RTERM = 1./(1.+0.6522*AT1+0.4622*AT2+0.0884*T4+0.0675*T5)
               ALTERM = 1./(CT1+RTERM)
               CEL2 = 6*SWL*ALTERM
               TRLK = SORT(WFR*W2./CEL2)
               EL = 2.*PI/TRLK
               CEL = SORT(CEL2)
               RETURN
END

SUBROUTINE WKNLR
COMMON/ A1 /FORCE(100), MOMENT(100), VZ(50), VDZ(50), UZ(50), UDZ(50)
COMMON/ A2 /ELEV(100), PRES(50)
COMMON/ CHAR1 /T1, T2, T3, T4, T5, T6, T7, T8, T9, T10, Y11, T12
COMMON/ CHAR2 /PER, SWL, HT, AMP, EL, EX, WNO, WFR, PI, TIME, ETA, 6, LO,
               SIGM, PHBL, CEL, PHBLCL
COMMON/ CHAR3 /SHT1, CHT1, SHT2, CHT2, SHT3, CHT3, ST4, CT4, SH2T2,
               CH2T2, THT2, SH4PT2, C2T4, S2T4, SHT3PT2, CH2T3, SH2T3
COMMON/ FACTOR /RHO, ANO, CO, CM, DIA, FACT1, FACT2, AM2FR2, RHOG,
               UMS, RENO
COMMON/ FORCE1 /UFSUM, UMNUM, AFSUM, AMSUM, EZ2
COMMON / INCON1 / NZ, NZME, NZM, KK, NTH, NP
DATA IJ, JW / 5, 6 /
PA = 0.
UFSUM = 0.
UMNUM = 0.
AFSUM = 0.
AMSUM = 0.
DO 59 IZ = 1, NZME
IF(CIZ.EQ.10) GOTO 50
EZ = FLOAT(KK-IZ)*SWL/NZM
GOTO 52
50 CONTINUE
EZ = ETA
52 CONTINUE
EZ1 = ABS(EZ)
T3 = WNO*(SWL+EZ)
CHT3 = COSH(T3)
SHT3 = SINH(T3)
CH2T3 = COSH(2*T3)
SHT2T3 = SINH(2*T3)

IF(HT/EL<LT.0.25E+01) GOTO 53

UZ(I) = PHBLC+CHT3*C4/SHT2+0.75*PHBLC*PHBLC+CH2T3*C24/SHT4*SH4PT2
VZ(I) = PHBLC*SH3T3*S4/SHT2+0.75*PHBLC*PHBLC*SH2T3*S24/SHT4*SH4PT2
UDZ(I) = PHBLC*WFR*CHT3*ST4/SHT2+1.5*PHBLC*PHBLC*WFR*CH2T3

S2T4/SH4PT2

VZ(I) = -PHBLC*WFR*SH3T3*CT4/SHT2-1.5*PHBLC*PHBLC*WFR*SH2T3

C2T4/SH4PT2

 PRES(I) = PA-RHOG*EZ-AM2FR2*SHT3/2./SHT2+RHOG*AMP*CHT3*CT4/CHT2
+AM2FR2*(3.*CH2T3/SHT2/SHT2-1.)*C2T4/4./SHT2

GOTO 54

53 CONTINUE

UZ(I) = AMP*WFR*CHT3*CT4/SHT2
VZ(I) = -AMP*WFR*SH3T3*CT4/SHT2
UDZ(I) = -AMP*WFR*WFR*/CHT3*CT4/SHT2

VZ(I) = -AMP*WFR*WFR*/SH3T3*CT4/SHT2

PRES(I) = PA-RHOG*ETA*CTH3/CHT2-EZ

1007 FORMAT (5X,10G10.3)
RETURN

END

SUBROUTINE SUMINT (IT1,IT2,IM)

COMMON / FORNOD / FXNOD(0),ANASS(0),SCB(0),CCD(0)

COMMON/ FORCE(1000),MOMENT(1000),VZ(0),VDZ(0),UZ(0),UDZ(0)

COMMON / Nz,Nzme,Nz,K,KNTH,NP

COMMON / FACTOR / RH0,ANO,CD,CH,DA,FI1,FACT2,AM2FR2,RH0G,

URMS,RENO

DO 00 IZ=1,NZME,2

Y10 = ABS(UZ(IZ))*UZ(IZ)

Y11 = ABS(UZ(IZ+1))*UZ(IZ+1)

Y12 = ABS(UZ(IZ+2))*UZ(IZ+2)

S0 = FLOAT(NZME-IZ)*EZ2

S1 = FLOAT(NZME-IZ-1)*EZ2

S2 = FLOAT(NZME-IZ-2)*EZ2

Y13 = ABS(UDZ(IZ))

Y14 = ABS(UDZ(IZ+1))

Y15 = ABS(UDZ(IZ+2))

UFSUM = UFSUM+EZ2*(Y10+Y11+Y12)/3.
UNSUM = UNSUM+EZ2*(Y10*S0+4.*Y11*S1+Y12*S2)/3.
AFSUM = AFSUM+EZ2*(Y13+4.*Y14+Y15)/3.
AMSUM = AMSUM+EZ2*(Y13*S0+4.*Y14*S1+Y15*S2)/3.

60 CONTINUE
FXNOC(I,M) = FACT1*UNSUM*FACT2*AFSUM
RETURN
END

SUBROUTINE FIXER
COMMON / CHAR1 / T1, T2, T3, T4, T5, T6, T7, T8, T9, T10, Y11, T12
COMMON / CHAR2 / PER, SWL, HT, AMP, EL, EX, WNO, WFR, PI, TIME, ETA, G, LO,
                  SIGN, PHBL, CEL, PHBL, CL
COMMON / CHAR3 / SHT1, CHT1, SHT2, CHT2, SHT3, CHT3, ST4, CT4, SH2T2,
                  CH2T2, THT2, SH4PT2, CT4, S2T4, SH3PT2, CH2T3, SH2T3
COMMON / INCON1 / NZ, NZME, NZM, KK, NTH, NP
T1 = WNO*(SWL+ETA)
SHT1 = SINH(T1)
CHT1 = COSH(T1)
IF(ETA.GE.0.00) GOTO 33
IF(ETA.LT.0.00) GOTO 35
I = 1
30 CONTINUE
IF(ETA.LE.FLOAT(I)*SWL/NZM) GOTO 32
I = I+1
GOTO 30
32 NZME = NZ+I
KK = I+1
GOTO 39
33 NZME = NZ
KK = I
GOTO 39
35 I = 1
36 CONTINUE
IF(ETA.LE.FLOAT(I)*SWL/NZM) GOTO 37
I = I+1
GOTO 36
37 NZME = NZ-I+1
KK = I
39 CONTINUE
RETURN
END

SUBROUTINE WKNNON (IT)
DIMENSION FXFC(18,20), FYFC(18,20)
COMPLEX CTME, CI, CPR, SUMB, HSTD, HNTD, ETAD, GBE, FRPRPH
COMMON/ CMPLX / CTME, CI, CPR, SUMB, HOTD, HTOTD, ETA
COMMON/ A1 /FORCE(100), MOMENT(100), VZ(50), VDZ(50), UZ(50), UDZ(50)
COMMON/ A2 /ELEV(100), PRES(50)
DIMENSION ZHC(50)
COMMON / INCON / NZ, NZME, NZM, KK, NTH, NP
COMMON/ CHAR1 / T1, T2, T3, T4, T5, T6, T7, T8, T9, T11, Y11, Y12
COMMON/ CHAR2 / PER, SWL, HT, AMP, EL, EX, WNO, WFR, PI, TIME, ETA, G, L0,
               SISM, PHBL, CEL, PHLCL
COMMON/ CHAR3 / SHT1, SHT2, SHT3, SHT2, SHT3, SHT4, CT4, SH2T2,
               CH2T2, CHT2, SH4PT2, C2T4, S2T4, SH3PT2, CH2T3, SH2T3
COMMON/ FACTOR / RHO, ANO, CD, CM, DIA, FACT1, FACT2, AMF2R, RHOG,
               URMS, RENO
COMMON / CHAR4 / AMPRES (20), FBE(6), GBE(6), FX(50), FY(50), FZ(50)
DATA IR, JH / 5, 6 /
CTME = CMPLX (0.0, -WFR*TIME)
CI = CMPLX (0, 1.0)
C
LINEAR DIFFRACTION THEORY
ARG = WNO*DIA/2.
TIMEFR = TIME/PER
AMOD1 = 1./SQRT((BJU-B2J)**2+(BYY-B2Y)**2.)
AMOD2 = 1./SQRT((B1Y-B1Y)**2+(B1J-B1J)**2)
ANG1 = WFR*TIME-ATAN((BJU-B2J)/(BYY-B2Y))
ANG2 = WFR*TIME-ATAN(B1Y/B1J)
FX = 8.*AMOD1*COSCANG1/PI/ARG
FY = 8.*AMOD2*COSCANG2/PI/PI/ARG
DO 76 IB=1,NTH
   TH = (IB-1)*PI/CNTH-1)
   TH = PI-TH
   SUMB = CMPLX(0.0,0.0)
DO 80 IBT=1,6
   SUMB = SUMB+CI**IBT*COSCIBT*TH)/GBE(IBT)
80 CONTINUE
   SUMB = 2.*SUMB
   HOTD = CMPLX (1.0,0.0)/CMPLX(-B1J,-B1Y)
   ETA = HT*CEXP(CTME)*<HOTD+SUMB>/PI/ARG
   ETA = (ETAD+CONJG(ETAD))/2.
   AMPRES(IB) = 2.*ETA/HT
   TH = TH*180./PI
   PHAN = 360.*TIME*WFR*180./PI
88 FORMAT ('2X,F10.1,5X,G10.3,5X,G12.5,5X,F10.1)
CALL FIXER
DO 72 IZ=1,NZME
IF (IZ.EQ.1) GOTO 62
EZ = FLOAT (KK-IZ)*SWL/NZM
GOTO 69
62
CONTINUE
EZ = ETA
63
CONTINUE
ZHCIZ = EZ/SWL
EZ1 = ABS(EZ)
TS = WNO*(SWL+EZ)
CHT3 = COS(CHT3)
FYCIZ = FYYMPI*DIAM*RH0*WFR*FZ*CHT3/2.
FXCIZ = 4.*RH0*HT*AMOD1*COS(CANG1)*CHT3/CHT2/WNO
PRESIZ = 6Z*CHT3*AMPPRES(IIB)
72
CONTINUE
IF (IB.GT.1) GOTO 900
SUMF = 0.
DO 75 ITX=2,NZME
FXFOCE = (FX(ITX)+FX(ITX-1))/2.
ABSZHT = (ABSCZH(ITX))/2.+ABSCZH(ITX-1))/2.*SWL
75
SUMFO = SUMFO+FXFOCE*ABSZHT
FXTOT = 4.*RH0*HT*HTT2*AMOD1*COS(CANG1)/WNO/WNO
FORCE(IIT) = FXTOT
FXF(IB,IZ) = FXCIZ
FYF(IB,IZ) = FYCIZ
76
CONTINUE
DO 93 IZ=1,NZME
SUME = 0.
93
CONTINUE
1000 FORMAT ('//,2X,3F10.2,/,5(1X,E10.3))
1010 FORMAT ('//,2X,3F10.3,/,6(1X,E10.3))
105 WRITE(*,105)
105 FORMAT ("NONLINEAR DIFFRACTION RANGE / PROGRAM NOT SUPPLIED")
900
CONTINUE
RETURN
END
SUBROUTINE BESGFE (AR6)
COMPLEX CTME,CI,CPR,SUMB,HOTD,HNTD,ETAD,GBE
COMMON/ CHPL1 / CTME,CI,CPR,SUMB,HOTD,HNTD,ETAD
COMMON / CHAR4 / AMRES(20),FBE8(8),GBE8(8),FX(80),FY(80),FXZ(80)
DATA IR,JW / 5,6 /
DO 4 IBT=1,6
IBTM1 = IBT-1
IBTP1 = IBT+1
CALL BESSJ (ARG,IBTP1,BJ2,0.01,IER)
CALL BESY (ARG,IBTP1,BY2,IER)
CALL BESSJ (ARG,IBTM1,BJ1,0.01,IER)
CALL BESY (ARG,IBTM1,BY1,IER)
IF (IBT.NE.2) GOTO 72
B1J = BJ1
B1Y = BY1
GOTO 73
72 CONTINUE
IF (IBT.NE.1) GOTO 73
B2J = BJ1
B2Y = BY1
B2J = BJ2
B2Y = BY2
73 CONTINUE
GBE(IBT) = COMPLX ((BJ1-BJ2)/2,(BY1-BY2)/2)
74 CONTINUE
RETURN
END