WAVE FORCES ON SPACE FRAME STRUCTURE

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ABSTRACT

In this study a simple method is presented to take into account; the effect of the inclination of the members on the response, the angle between the members and the direction of wave propagation,the effect of neglecting the variation in water surface elevation in computing wave forces. It is shown that, this variation has a pronounced effect on the distribution of the forces. The importance of using relative velocities and accelerations in calculating the forces on space frame offshore structure is demonstrated, too.

INTRODUCTION

The discovery of large deposit of oil and gas in offshore areas has resulted in the construction of large drilling and production platforms, which often have to withstand severe environmental conditions in inhospitable areas.

In calculating the response of a jacket type platform it is usual to use Morison equations to find out the applied forces. The computed wave forces by Morrison equation consists of two parts ; drag force and inertia force. The drag force is proportional to the square of the water particles' velocities, while the inertia force is proportional to the water particles' accelerations.

To be able to calculate the response of the structure using the frequency domain method, a linearization of the drag force is required.

The relative importance of the following factors; members orientation, variation in water surface, using relative velocities and accelerations on computing wave forces is a function of the dimensions and stiffness of the structure and wave characteristics.

For compliant structure, we need to compute the structure response U in order to compute wave force.

The finite element method is used to model the structure and to construct the mass and stiffness matricesThe structure damping matrix is taken proportional to the stiffness matrix. We also, considered the hydrodynamic damping. The response of a structure may be calculated using either quasi static or dynamic analysisBoth approaches may be based on using deterministic or non-deterministic methods of analysis.

The mathematical analysis of the platform results in a system of equations governing the structure motionThese equations were solved numerically in time and frequency domains to compute the structure response The statistics of wave forces, moments are discussedThe time series of wave forces have shown deviation from Gaussian distribution even when the surface elevation is normally distributed.

EQUATION OF MOTION

The general equation of motion for any linear elastic structure, assuming viscous damping is given by:

$$[M]\,\ddot{U} + [C]\dot{\boldsymbol{U}} + [K]\,\boldsymbol{U} = \boldsymbol{F} \quad (1)$$

where a letter written in bold face means a vector quantity, and

[M], [C], [K] are the mass, the damping, and the stiffness matrices, respectively. **F** is the force vector

and

U, $\dot{U}$, $\ddot{U}$ are displacement, velocity and acceleration vectors respectively

If the stiffness and mass matrices are constructed using the same shape functions then they are said to be consistent. In offshore engineering, it is a common practice to use a lumped mass matrix.

Since little is known about the nature of the damping matrix, then it is usual to assume a damping matrix as a combination of both the mass and stiffness matrices. A form that leads to a proportional damping matrix is given by

$$[C]=[M]\sum_b a_b \left[[M]^{-1}[K]\right]^b \qquad (2)$$

where the values of b can lie anywhere in the range $-\infty < b < +\infty$ but in practice it is desirable to select values as near to zero as possible and the existing terms must be equal in number to the number of the known modal damping ratios [1].

In this paper we use a damping matrix that satisfies equation (2) with b = 1

$$[C] = a_1 [K] \qquad (3)$$

where

$$a_1 = \frac{2\epsilon_1}{\omega_1} \qquad (4)$$

where

ϵ_1 is the damping ratio of the first mode
ω_1 is the undamped natural frequency of the first mode

In the analysis of offshore structures subjected to wind, current and wave forces, it is clear that the applied load vector consists of surface forces only. In offshore engineering it is usual to define the load vector as a set of concentrated loads which are statically equivalent to the distributed loading.

The inline wave force affecting a unit length of vertical flexible pile of diameter D is given by the modified Morison equation in the form [2].

$$F = .50\,\rho\,C_D\,D\,|u_x-\dot{U}_x|\,(u_x-\dot{U}_x)$$
$$+.25\,\pi\,\rho\,D^2\,\dot{u}_x \qquad (5)$$
$$+.25\,\pi\,\rho\,(C_M-1)\,D^2\,(\dot{u}_x-\ddot{U}_x)$$

where

F is the total hydrodynamic force per unit length
C_D is the drag force coefficient
C_M-1 is the added mass coefficient
$\dot{U}_x$ and $\ddot{U}_x$ are the velocity and acceleration of the structure in x direction
u_x and $\dot{u}_x$ are the velocity and acceleration of the fluid particles in x direction

FORCE ON INCLINED MEMBERS

Morison's equation is used to find the force affecting a vertical cylinder. To extend the result to the case of an arbitrary oriented cylinder, the independence principle is introduced. The independence principle states that the inline forces on an inclined cylinder may be expressed in terms of the normal velocity and acceleration, and the tangential velocity and acceleration components can be neglected [3]. Then a generalized vectorial form of equation (5) is given by [4]

$$F(s) = .50\,\rho\,C_D\,D\,|\,u_n(s)-\dot{U}_n(s)\,|\,(u_n(s)-\dot{U}_n(s))$$
$$+ .25\,\pi\,\rho\,C_M\,D^2\,\dot{u}_n(s) \qquad (6)$$
$$-\, .25\,\pi\,\rho\,(C_M-1)\,D^2\,\ddot{U}_n(s)$$

where (s) is variable dimension along the member measured from one of its ends (see Figure 1-a), u(s) and $\dot{u}$(s) are the instantaneous water particles velocity and acceleration at location s. $u_n(s)$ and $\dot{u}_n(s)$ are their normal components respectively. U(s), $\dot{U}$(s), and $\ddot{U}$(s) are the displacement, velocity and acceleration of the member at location (s) $U_n(s)$, $\dot{U}_n(s)$, $\ddot{U}_n(s)$ are their normal components respectively.

The velocity vector of the water may be written in the form:

$$u(s) = u_x\,i + u_y\,j + u_z\,k \qquad (7)$$

where u_x, u_y, u_z are the velocity components in x,y and z directions, and i,j,k are unit vectors in x, y, z directions, respectively.

Assume S is a unit vector coinciding with the member axis [see Figure (1-b). Then S is given by

$$S = S_x\, i + S_y\, j + S_z\, k \qquad (8)$$

where S_x, S_y and S_z are the direction cosines of the memberThe normal components of $u, \dot{u}, U, \dot{U}, \ddot{U}$ are given by

$$u_n(s) = [N]\, u(s)$$

$$\dot{u}_n(s) = [N]\, \dot{u}(s) \qquad (9)$$

$$\dot{U}_n(s) = [N]\, \dot{U}(s)$$

$$\ddot{U}_n(s) = [N]\, \ddot{U}(s)$$

here [N] is given by [4]

$$[N] = [I] - S\, S^t = \begin{bmatrix} 1-S_x^2 & -S_x S_y & -S_x S_z \\ -S_x S_y & 1-S_y^2 & -S_y S_z \\ -S_x S_z & -S_y S_z & 1-S_z^2 \end{bmatrix} \qquad (10)$$

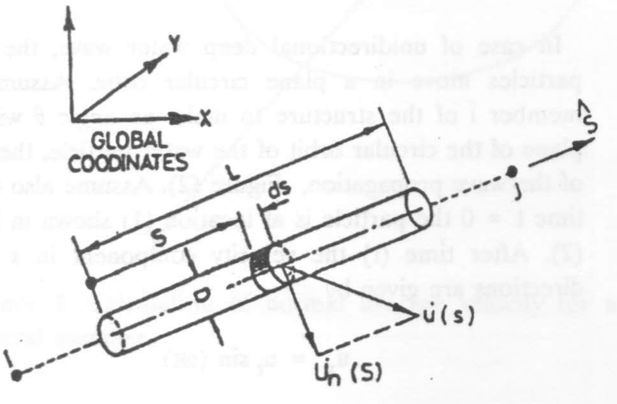

Figure 1-a. Water particle velocity along member i.

If we assume the flow to lie in the X-Y plane ; that is u_z equal zero, then the equations introduced may be reduced to those given by Chakrabarti [5].

LINEARIZATION OF WAVE FORCES

The velocity squared term in equation (6) may be approximated by

$$| u_n(s) |\, u_n(s) - 2\, | u_n(s) |\, \dot{U}_n(s) \qquad (11)$$

because $u_n(s) >> \dot{U}_n(s)$

using equations (9) and (11) then equation (6) becomes

$$\begin{aligned} F(s) = &\ .5\ \rho\ C_D\ D\ |\ [N]\ u(s)\ |\ [N]\ u(s) \\ & -\rho\ C_D\ D\ |\ [N]\ u(s) | . [N] \dot{U}(s) \\ & +.25\ \pi\ \rho\ C_M\ D^2\ [N]\ \dot{u}(s) \\ & -.25\ \pi\ \rho\ (C_M - 1)\ D^2\ [N]\ \ddot{U}(s) \end{aligned} \qquad (12)$$

The vector function $F_i(s)$ along any member i with length l and diameter D can be divided into a 12 component force vector F_i corresponding to the 12 nodal displacements at I and J, see Figure (1-b). This is given by

$$\begin{aligned} F_i = &\ .5\ \rho\ C_D\ D\ l\ |\ [N_T] u\ |\ [N_T] u \\ & -\rho\ C_D\ D\ l\ | [N_T] u\ |\ [N_T]\ \dot{U} \\ & +.25\ \pi\ \rho\ C_M\ D^2 [N]\ \dot{u}(s) \\ & -.25\ \pi\ \rho\ (\ C_M - 1\ )\ D^2 l [N_T]\ \ddot{U} \end{aligned} \qquad (13)$$

where $u, \dot{u}, \dot{U}, \ddot{U}$ are the 12 - component vector in the member's nodal coordinates and $[N_T]$ is the 12 X 12 matrix given by

$$[N_T] = 0.5 \begin{bmatrix} N & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & N & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \qquad (14)$$

where the matrix N is defined by equation (10).

Defining an effective volume matrix and an effective drag area matrix as

$$[V] = .25\ \pi\ D^2\ l\ [N_T] \quad (12{*}12) \qquad (15)$$

$$[A] = D\ l\ [N_T] \quad (12{*}12) \qquad (16)$$

then we write equation (13) in the form

$$F_i = .5\rho C_D \mid [N_T]u \mid [A]u - \rho C_D \mid [N_T]u \mid [A]\dot{U} + \rho C_M [V]\dot{u} - \rho(C_M - 1)[V]\ddot{U} \tag{17}$$

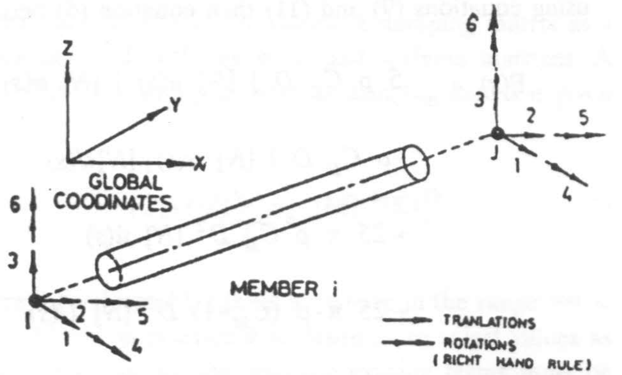

Figure 1-b. Nodal displacement component at nodal points I and J of member i.

The above equation defines the 12 component nodal hydrodynamic force vector for one member, member i.

The vector F of the hydrodynamic forces in equation (1) is given by

$$F = \sum_{i=1}^{m} F_i \tag{18}$$

where m is the number of members, and the hydrodynamic forces are to be summed vectorially. From the above we can write

$$[M_T]\ddot{U} + [C_T]\dot{U} + [K]U = [F_M]\dot{u} + [F_D]u \tag{19}$$

where, $\ddot{U}, \dot{U}, U, \dot{u}$ and $\dot{u}$ are n-dimensional vectors, and

$$[F_M] = \sum_{i=1}^{m} \rho\, C_M\, [V_i] \tag{20}$$

$$[F_D] = \sum_{i=1}^{m} .5\, \rho\, C_D\, |[N_{Ti}]\, \dot{u}_i\, [A_i] \tag{21}$$

$$[M_T] = [M] + \sum_{i=1}^{m} \rho(C_M - 1)[V_i] = [M] + [M_a] \tag{22}$$

where $[M_a]$ is the added mass matrix

Approximating $|[N_{Ti}]u_i|$ by its time average $<|[N_{Ti}]u_i|>$ we get

$$[C_T] = [C] + \sum_{i=1}^{m} \rho\, C_D < | [N_{Ti}] | \dot{u}_i > [A_i] \tag{23}$$

F_D may be given by

$$F_D = \sum_{i=1}^{m} .5\, \rho\, C_D < | [N_{Ti}]\, u_i | > [A_i] \tag{24}$$

A mathematical expression for the time average $<|[N_{Ti}] u_i|>$ must be introduced for both deterministic and stochastic analysis. In case of deep water (d/L> 0.5) we may write

$$\cosh(ky) = \sinh(ky) = 0.5 \exp(ky) \tag{25}$$

then the total velocity of the wave particle is given by

$$u_t = \sqrt{u_x^2 + u_Y^2} = \frac{k}{\sqrt{2}} \frac{ag}{\omega} \frac{\exp(ky)}{\cosh(kd)} \tag{26}$$

In case of unidirectional deep water wave, the water particles move in a plane circular orbit. Assume any member i of the structure to make an angle θ with the plane of the circular orbit of the water particle, the plane of the wave propagation, Figure (2). Assume also that at time t = 0 the particle is at location (1) shown in Figure (2). After time (t) the velocity component in x and y directions are given by

$$u_x = u_t \sin(\omega t)$$

$$u_y = u_t \cos(\omega t) \tag{27}$$

the component u_x is normal to the member i, and the component u_y has a component normal to the member i which is given by

$$u_{yn} = u_t \cos(\omega t) \cdot \sin(\theta) \tag{28}$$

then the total normal component at time t is given by

$$u_n = u_t \sqrt{\sin^2(wt) + \sin^2(\theta)\cos^2(wt)} \tag{29}$$

and the time average of (u_n) may be given by

$$u_{n.av} = \frac{2u_t}{\pi} \int_0^{\pi/2} \sqrt{\sin^2(\omega t)+\sin^2(\theta)\cos^2(\omega t)}\ d(\omega t) \quad (30)$$

The integration given in equation (30) can be approximated using numerical methods to take the form

$$\int_0^{\pi/2} \sqrt{\sin^2(\omega t)+\sin^2(\theta)\cos^2(\omega t)}\ d(\omega t) = 1+(1-\frac{2}{\pi})\theta \quad (31)$$

from which equation (30) takes the form

$$u_{n.av} = \frac{2\ u_t}{\pi}\ [1+(1-\frac{2}{\pi})\theta] \quad (32)$$

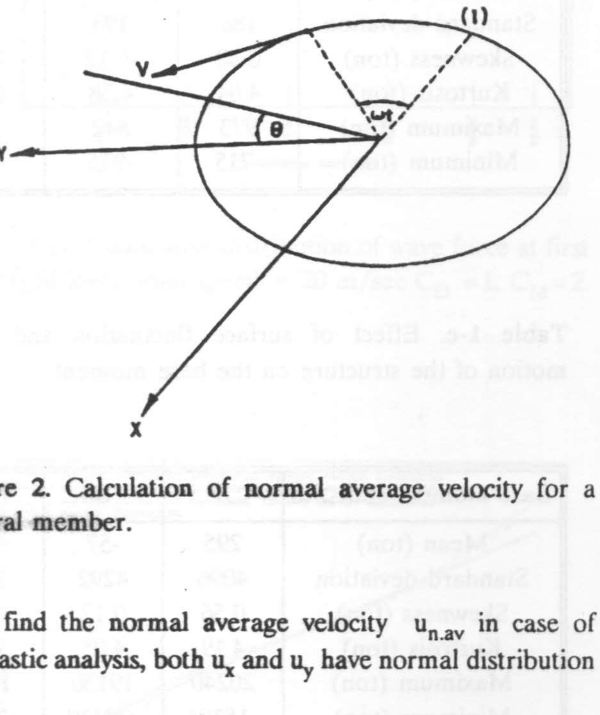

Figure 2. Calculation of normal average velocity for a general member.

To find the normal average velocity $u_{n.av}$ in case of stochastic analysis, both u_x and u_y have normal distribution [6].

If two random variables x and y are normal, independent with zero mean and equal variance, then the function

$$z = \sqrt{x^2 + y^2} \quad (33)$$

has a Rayleigh distribution , and its expected value is given by

$$E(z) = \sigma \sqrt{\frac{\pi}{2}} \quad (34)$$

then we can write,assuming that the u_x and u_y are normal independent variables with zero mean and equal variance

$$E(u_t) = \sigma \sqrt{\frac{\pi}{2}} \quad (35)$$

PARAMETRIC STUDY

The effects of the following parameters on the forces experienced by a jacket type offshore structure are studied under different values of the drag and inertia coefficients and wave energy. The parameters are (a) fluctuation in water surface due to the passage of waves, (b) structure motion relative to the flow, and (c) non linear form of the drag force

To study the effect of the above mentioned parameters, the frame shown in Figure (3) is considered. Each leg of the frame is supported by a single pile.

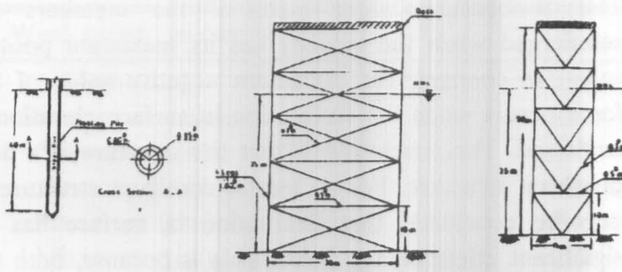

Figure 3. Short and long sides of the space frame and details of the pile foundation.

Throughout the analysis, only long crested waves are considered. The direction of the wave propagation is assumed parallel to the short side of the frame. The effect of lift force (transverse force) is neglected. Finally, it is assumed that, the sea state may be described by a P-M spectrum, given by

$$S_{nn}(\omega) = \frac{\alpha g^2}{\omega^5}\ EXP[-\beta(\frac{g}{\omega W})^4]$$

where

g is the gravity acceleration
W is the wind speed at 20 m above mean water level
ω is the wave frequency in radian per second
α and β are given by
α = 0.0081
β = 0.74

CHARACTERISTICS OF WAVE FORCES

In this paper, the effect of the different parameters (a, b, c) mentioned above, on the statistics of wave forces in the direction of the wave are studied.

The frame is subjected to a random wave train using wind speed 20 m/sec. for the three cases a, b, and c. The drag and inertia coefficients are kept constant at 1, and 2 respectively. The results of the analysis are shown in Tables (1-a) through (1-d) and Figures (4-a) through (4-c). Table (1-a) shows the effect of the factors a, b, and c on the force at the first submerged level. From this table it can be shown that, in all cases, the force has nearly the same standard deviation. The fluctuation in water surface and the motion of the structure with respect to the flow have no effect on the Kurtosis. The maximum positive force is larger in case of considering surface fluctuation This is because larger parts of the members are submerged when the velocity has its maximum positive value. In contrast, the maximum negative value of the force occurs when the fluctuation in surface elevation is neglected. The conclusion is that the structure is a drag dominant structure. For an inertia dominant structure, it may be concluded that fluctuation in surface has no significant effect on the force. This is because, both the maximum positive and the maximum negative accelerations occur when the surface elevation coincides with the mean water level. In case of drag dominant structure, the surface fluctuation has a significant effect on the force. This is because the maximum positive velocity coincides with the crest of the wave, while the maximum negative velocity coincides with the trough of the wave That means a big difference in the area of the submerged members in the two cases, which leads to a corresponding big difference between the positive and the negative forces. The difference between the positive and the negative values of the forces in case a, and c, Table (1-a) explains the shift in the skewness toward a large positive value.

Table 1-a. Effect of surface fluctuation and relative motion of the structure on the force at first submerged level

Wave force statistics	A	B	C
Mean (ton)	10..8	-1.28	10.8
Standard deviation	85	88	85
Skewness (ton)	0.953	-0.215	0.988
Kurtosis (ton)	4.75	4.72	4.945
Maximum (ton)	454	420	486
Minimum (ton)	-213	-425	-206

Table 1-b. Effect of surface fluctuation and relative motion of the structure on the base shear.

Base shear statistics	A	B	C
Mean (ton)	9.2	-2.46	9.11
Standard deviation	186	193	177
Skewness (ton)	0.38	-0.12	0.31
Kurtosis (ton)	4.04	4.38	0.04
Maximum (ton)	973	842	809
Minimum (ton)	-715	-915	-700

Table 1-c. Effect of surface fluctuation and relative motion of the structure on the base moment.

Base moment statistics	A	B	C
Mean (ton)	295	-57	297
Standard deviation	4096	4292	3900
Skewness (ton)	0.56	0.12	0.49
Kurtosis (ton)	4.19	4.05	4.20
Maximum (ton)	20240	19130	19150
Minimum (ton)	-15301	-20439	-14264

Figure (4-a) shows the distribution of the force at the first submerged level for the cases a, b, and c compared with the normal distribution. From the figure it is shown that the effect of relative motion on the distribution is minimum.

Tables (1-c) and (1-d) show the effect of the surface fluctuation and relative motion on the base shear and base moment. The standard deviation, skewness, kurtosis, and the mean of both; the base shear and the base moment seem to be controlled by the behavior of the force at the first submerged level.

Figures (4-b) and (4-c) show the distribution of the base shear and base moment. Again, they seem to follow that of the force at the first submerged level.

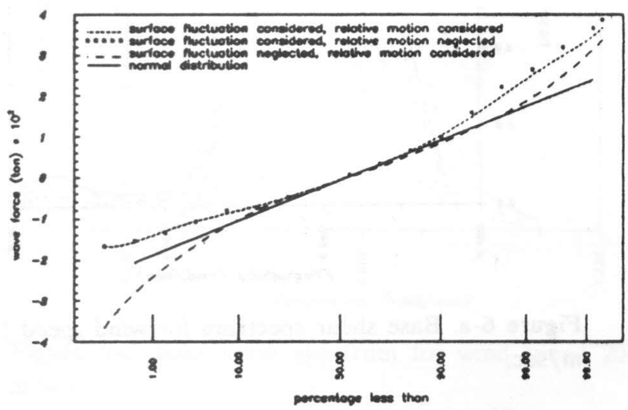

Figure (4-a). Cumulative distribution of wave force at first submerged level, wind speed = 20 m/sec C_D = 1, C_M = 2.

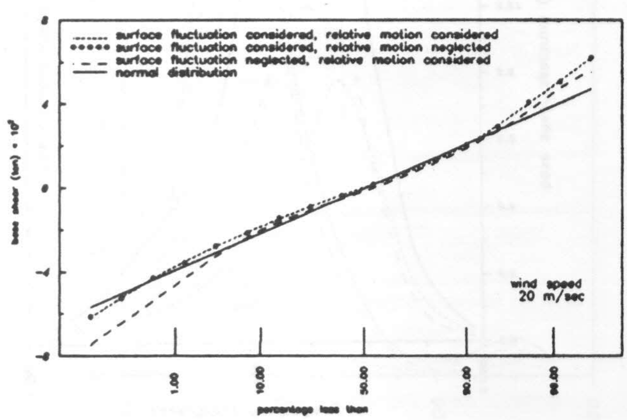

Figure 4-b. Cumulative distribution of base shear, wind speed = 20 m/sec C_D = 1, C_M = 2.

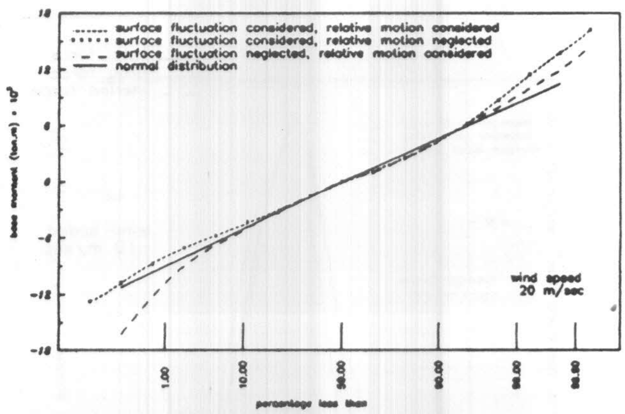

Figure 4-c. Cumulative distribution of base moment, wind speed = 20 m/sec C_D = 1, C_M = 2.

Table (2) shows the statistics of wave force at first submerged level, using wind speeds 10, 15, and 20 m/sec, respectively. In all cases, both water surface fluctuation and relative motion are considered. The standard deviation of the surface elevation for wind speeds 10, 15, and 20 m/sec are 0.53, 1.2 and 2.14 m respectively with significant wave heights 2.12, 4.8, and 8.56 m respectively.

Table 2. Statistics of wave force at first submerged level

Wind speed m/sec	10	15	20
Mran (ton)	0.20	2.13	10.8
Standard deviation	17	42.0	85.
Skewness (ton)	1.73E-3	0.35	0.95
Kurtosis (ton)	2.71	3.4	4.75
Maximum (ton)	55.	182	454.
Minimum (ton)	-54	-117	-213

From Table (2), it may be noted that, the effect of surface fluctuation is less with reducing wind speed It becomes less pronounced at wind speed 15 m/sec, and insignificant at wind speed 10 m/sec.

It is mentioned before that the effect of surface fluctuation becomes less important when the structure is inertia dominant structure. To examine this assumption, the force spectrum is introduced. Figures (5-a) through (5-c) show the force spectra at the first submerged level for wind speeds 10, 15, and 20 m/sec. Together, with the overall force spectrum, the spectra for both the drag and inertia forces are shown.

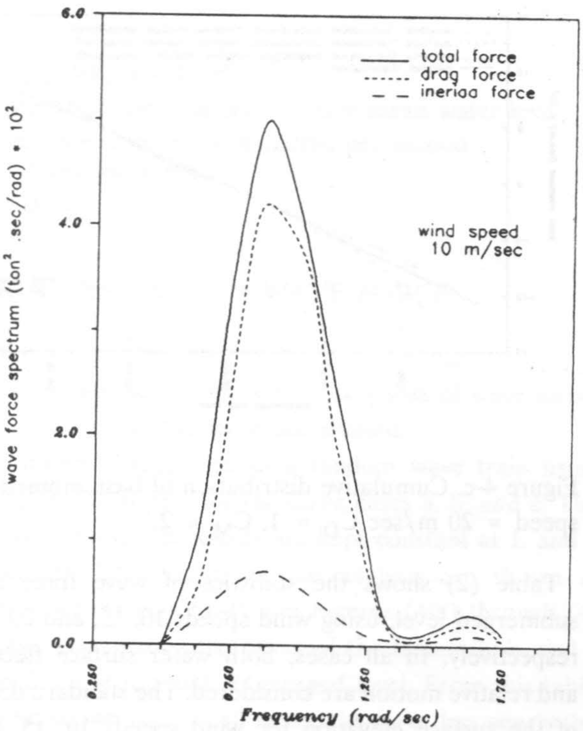

Figure (5-a). Wave force spectrum for wind speed 10 m/sec.

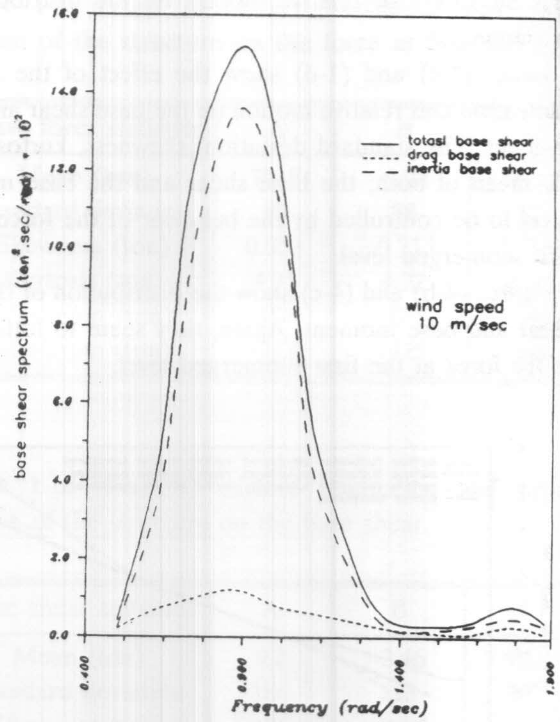

Figure 6-a. Base shear spectrum for wind speed 10 m/sec.

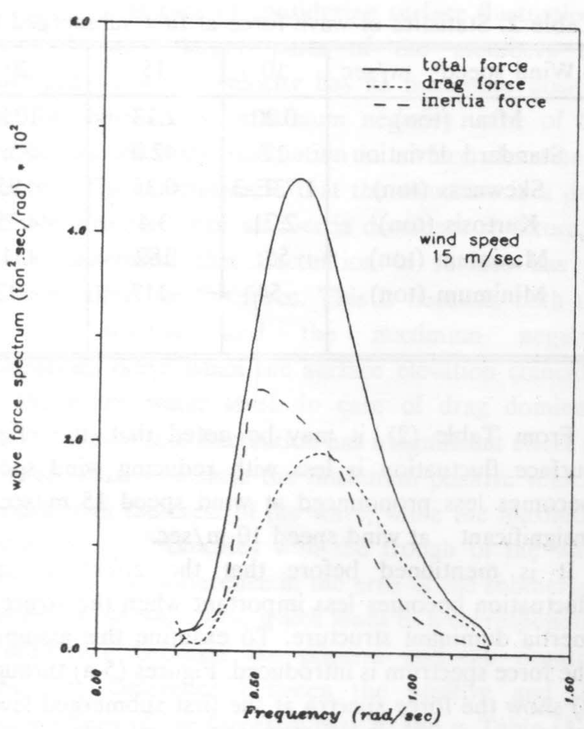

Figure (5-b). Wave force spectrum for wind speed 15 m/sec.

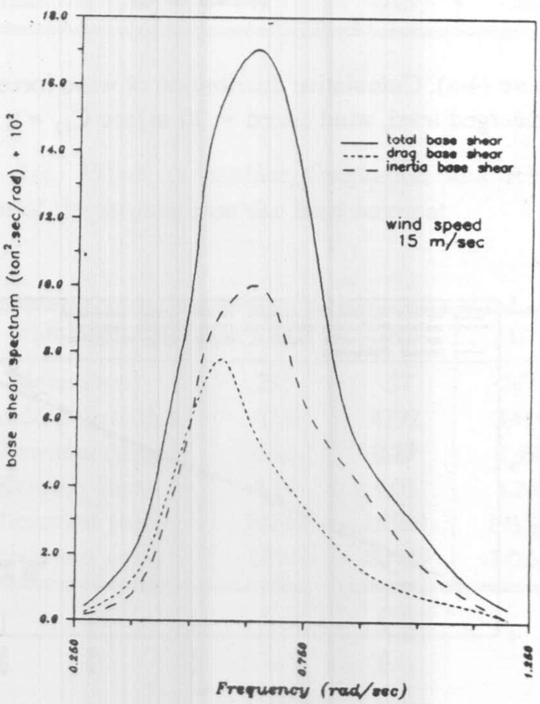

Figure (6-b). Base shear spectrum for wind speed 15 m/sec.

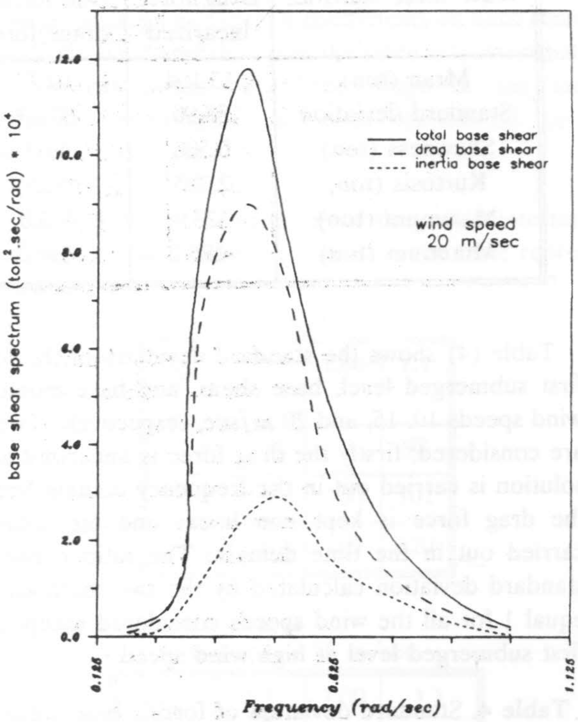

Figure 6-c. Base shear spectrum for wind speed 20 m/sec.

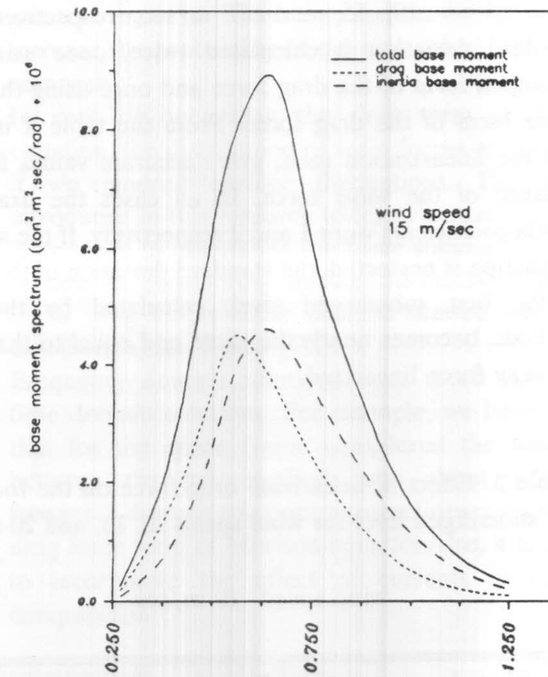

Figure 7-b. Base moment spectrum for wind speed 15 m/sec.

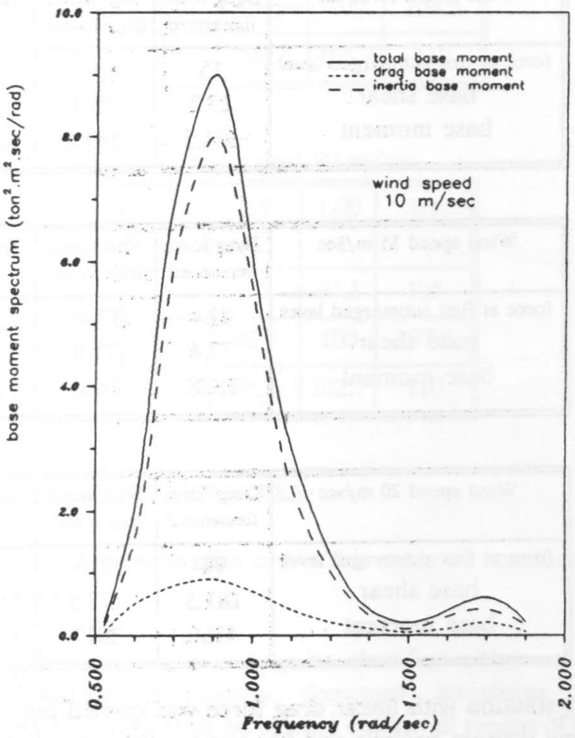

Figure 7-a. Base moment spectrum for wind speed 10 m/sec.

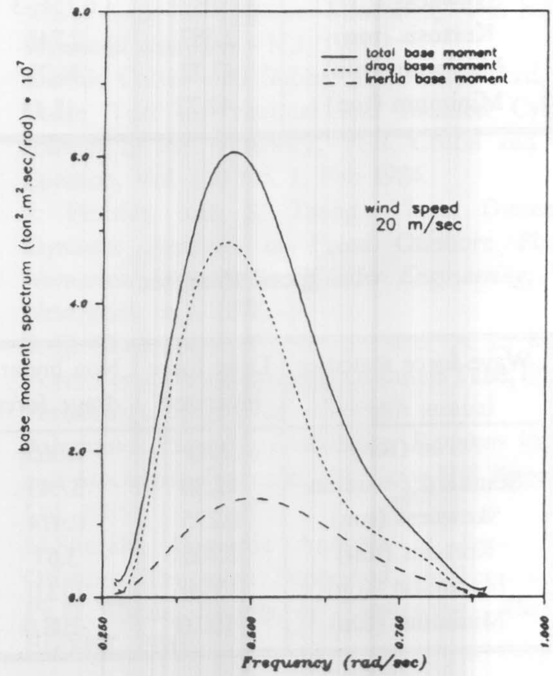

Figure 7-c. Base moment spectrum for wind speed 20 m/sec.

Table (3) shows the standard deviation of the force at the first submerged level calculated in the time domain for wind speeds 10, 15, and 20 m/sec, respectively. the standard deviation is calculated twice, once using the linearized form of the drag force and once using the non-linear form of the drag force. From the table it is clear that the linearization used, give accurate values for the variance of the wave force. In all cases the drag and inertia coefficients were 1 and 2 respectively. If the surface fluctuation is neglected, the standard deviation of the force at the first submerged level, calculated by the two methods, becomes nearly the same and equal to that with the drag force linearized.

Table 3. Effect of linearizing drag force on the force at first submerged level for wind speed 10, 15, and 20 m/sec

wind speed 10 m/sec

Wave force statistics	Drag force lnearized	Non linear drage force
Mran (ton)	0.28	0.193
Standard deviation	15.00	14.63
Skewness (ton)	1.4E-3	6.15E-3
Kurtosis (ton)	2.587	2.745
Maximum (ton)	47.22	46.72
Minimum (ton)	-42.72	-45.13

wind speed 15 m/sec

Wave force statistics	Drag force lnearized	Non linear drage force
Mran (ton)	2.85	2.065
Standard deviation	42.30	37.43
Skewness (ton)	0.275	0.414
Kurtosis (ton)	2.705	3.67
Maximum (ton)	153.0	173.0
Minimum (ton)	-100.0	-108.0

wind speed 20 m/sec

Wave force statistics	Drag force lnearized	Non linear drage force
Mran (ton)	13.104	10.97
Standard deviation	88.90	80.80
Skewness (ton)	0.506	1.07
Kurtosis (ton)	2.705	5.25
Maximum (ton)	323.0	465.0
Minimum (ton)	-186.0	-198.0

Table (4) shows the standard deviation of the force at first submerged level, base shear, and base moment for wind speeds 10, 15, and 20 m/sec, respectively. Two cases are considered; firstly the drag force is linearized and the solution is carried out in the frequency domain Secondly, the drag force is kept non linear and the solution is carried out in the time domain. The ratio between the standard deviation calculated by the two methods nearly equal 1 for all the wind speeds considered except for the first submerged level at high wind speed.

Table 4. Standard deviation of forces, base shear, and base moment using non linear and linear forms of the drag force for wind speed 10, 15, and 20 m/sec.

Wind speed 10 m/sec	Drag force linearized	Non linear drag force	ratio
force at first submerged level	15	14.6	1.03
base shear	23.2	23.9	0.97
base moment	601.5	589.5	1.02

Wind speed 15 m/sec	Drag force linearized	Non linear drag force	ratio
force at first submerged level	42.4	37.43	1.13
base shear	77.4	71.9	1.08
base moment	1828	1666	1.10

Wind speed 20 m/sec	Drag force linearized	Non linear drag force	ratio
force at first submerged level	91	80.8	1.13
base shear	181.5	177.5	1.02
base moment	4160	3917	1.06

* solution with linear drag force was carried out using time domain analysis and has same values obtained using frequency domain analysis

Table (5) introduces a sensitivity analysis of the effect of variation of drage and inertia coefficients on base moment for differnt wind speeds. From the table it is clear that the error in calculating either the drage or the inertia coefficient overweights the error introduced by the linearization process.

Table 5. Effect of variation of drage and intertia coefficient on base moment. Values in the table represent precentage of the values with $C_D = 1$ and $C_M = 2$.

wind speed 15 m/sec.

C_M / C_D	0.9	1.00	1.1
1.8	90	91	92
2.0	99	100	101
2.2	108	109	110

wind speed 15 m/sec.

C_M / C_D	0.9	1.00	1.1
1.8	90	94.5	99.4
2.0	95.5	100	104.5
2.2	101.5	105.7	110

wind speed 20 m/sec.

C_M / C_D	0.9	1.00	1.1
1.8	90	97.5	105
2.0	92.7	100	107.0
2.2	95.7	102.7	110

CONCLUDING REMARKS

From the results obtained in this study we conclude the following :

1. Offshore structures may be classified either as drag dominant or inertia dominant structures. The classification must be carried out for all ranges of wind speeds.
2. The non-linear drag term of Morison equation causes a deviation of the forces distributions from Gaussian, as indicated by Kurtosis value, for these distributions greater than 3. Thus the non-linear drag forces increase the probability of extreme values of structure response.
3. In case of linearizing the drag term of Morison equation, the distribution of wave forces are Gaussian, if we ignored surface fluctuations. The method introduced in this research to linearize the drag forces is accurate in calculating the force standard deviation.
4. In case of considering surface fluctuations, the non-linear drag forces cause positive skewed wave force distribution, see figure (4-a).
5. Frequency domain solutions were much faster than time domain solutions. For example, we have noticed that for the space frame considered the time ratio between the two methods was about 1:30. The frequency domain solutions require linearization of the drag force term of Morison equationAlso, it is difficult to incorporate the effect of currents in response computation.

REFERENCES

[1] Ray W. Clough, Joseph Penzien, *Dynamic of Structures* McGraw-Hill Kogakushua Ltd., 1975.

[2] Turgut Sarpkaya and Michael Isaacson, *Mechanics of Wave Force on Offshore Structures*, Van Nostrand Reinhold company - N.J, 1981.

[3] Dennis Cotter and Subbrata K. Chakrabrti, Wave Force Test on Vertical and Inclined Cylinders, *Journal of the Waterway*, Port, Costal and Ocean Division, Vol. 110 No. 1, Feb 1984.

[4] J. Penzien and S. Tseng, Three Dimensional Dynamic Analysis of Fixed Offshore Platform, *Numerical Methods in Offshore Engineering*, Wiley, New York ch.7, 1978.

[5] S. K. Chakrabarti, W. A. Tam and A. L. Wolbert, Wave Force on a Randomly Oriented Tube, *Offshore Technology Conference* - Seventh annual

[6] Athanasios Papoulis, *Probability, Random Variable, and Stochastic Processes*, McGraw-Hill Kogakusha. Ltd, 1965.

[7] M.Sharaki, Dynamic Analysis of Space Frame Offshore Structures Supported on Vertical Piles, Ph.D Thesis, *Faculty of Engineering, Alex Uni.*, EGYPT, 1990