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Some Recent Research on Random Wave Forces

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ABSTRACT

The present paper describes a selection of recent research relating to random wave forces acting on slender structural members. A brief review of prediction methods for random wave forces is initially given, and recent research into three specific aspects of random wave forces is then described. These relate to (i) the effects of multidirectional waves; (ii) the intermittent forces acting on sections near the water surface; and (iii) wave slamming forces on horizontal cylinders. For the first two cases, corresponding to multidirectional wave loading and to intermittent loading, comparisons are presented between available experimental data, numerically simulated data and theoretical predictions.

INTRODUCTION

The prediction of wave loads on offshore structures is an important component of offshore design. For structures comprised of slender members, wave force predictions are traditionally based on the Morison equation, in which the wave force at any section of a member is expressed directly in terms of the fluid kinematics which would occur at that section's location (Sarpkaya and Isaacson, 1981). The application of the Morison equation to regular waves is straightforward in principle and requires that the kinematics be obtained by an appropriate wave theory. For the case of random waves, the Morison equation may be applied to develop the statistical properties of the forces. A linearization of the Morison equation is generally carried out in order to estimate the spectral density of the force, whereas the assumption of a narrow-band spectrum is instead made in order to estimate the probability distribution of force maxima. A number of extensions to the fundamental case arise, and three such extensions are considered here. These relate to the effects of multidirectional waves; the intermittent forces acting on sections near the water surface; and wave slamming forces on horizontal cylinders near the free surface.

In the case of multidirectional waves, the estimation of forces on a structure is complicated because of the continuously changing direction of the incident flow kinematics associated with these waves. The spectral and probabilistic properties of the force taking this into account have been described by Isaacson and Nwogu (1989).

For a section of a vertical member located near the free surface, the intermittent submergence of the section gives rise to complications in estimating wave force statistics. For points near the free surface, the effects of intermittent submergence on the statistical properties of the water particle kinematics have been examined both theoretically (Tung, 1975b; Pajouhi and Tung, 1975), and experimentally, while the effects of intermittency on wave forces have been considered by Tung (1975a) and recently by Isaacson and Baldwin (1990a, b) and Isaacson and Subbiah (1991).

Horizontal structural members located close to the water surface are susceptible to large impulsive forces caused by wave slamming (Miller, 1980; Sarpkaya and Isaacson, 1981; Greenhow and Li, 1987). Isaacson and Subbiah (1990) have recently considered intermittency effects on the statistical properties of forces on such members due to random waves.

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THE MORISON EQUATION APPLIED TO RANDOM WAVES

The fundamental situation of unidirectional wave propagation past a submerged section of a vertical slender member is sketched in Fig. 1a. The horizontal force per unit length acting on such a section is given by the Morison equation as:

$$F = K_d\, u|u| + K_m\, a \tag{1}$$

where $K_d = (1/2)\rho D C_d$, $K_m = \rho(\pi D^2/4)C_m$, D is the diameter of the member, u and a are the horizontal water particle velocity and acceleration respectively, and C_d and C_m are empirical drag and inertia coefficients respectively.

In order to predict random wave forces, the Morison equation is generally applied in conjunction with linear wave theory. The statistical properties of the force which are of interest include the force spectra, the probability distribution of the force, the probability distribution of the force maxima, the probability distribution of the largest force maximum in a specified duration, and thereby the expected value of the largest force maximum in a specified duration. A brief summary of the corresponding development is given here, and for supporting details the reader is referred to the cited references and to reviews by Borgman (1972); Sarpkaya and Isaacson (1981); and Ochi (1982).

Spectral Density

The derivation of the force spectral density for the case of a fully submerged section was given by Borgman (1967) on the basis of a linearization of the nonlinear drag component. The Morison equation given by Eq. 1 is thus approximated as:

$$F = K_d\, \beta u + K_m\, a \tag{2}$$

where β is a drag linearization factor. With u taken to possess a Gaussian probability distribution, this factor is given as:

$$\beta = \sigma_u \sqrt{8/\pi} \tag{3}$$

where σ_u is the standard deviation of the velocity. This leads to a relatively straightforward expression for the force spectral density in terms of the spectral densities of the velocity and acceleration.

The force spectral density taking account of nonlinearities in the drag term is more difficult to develop, as the nonlinear drag term will introduce frequency changes between the velocity and the resulting drag force. Approaches which take this into account have been described by Eatock Taylor and Rajagopalan (1983) and Bendat and Piersol (1986).

Probability Density of Force

It is unrealistic to continue using a linearization of the Morison equation when deriving probability distributions of the forces, because the resulting normal distribution of wave force components would severely underestimate extreme force values. Thus, although the water particle velocity and acceleration each possess a Gaussian probability distribution and are uncorrelated, the force is itself non-Gaussian on account of the nonlinearity in the Morison equation. Closed form expressions for this have been derived (Pierson and Holmes, 1965).

Probability Density of Force Maxima

The probability distribution of the force maxima $\hat{F}$ is of particular interest. An expression for this may be derived by assuming that the wave spectrum is narrow-banded and concentrated near a single frequency ω_o. This assumption allows the peak force to be calculated deterministically for each wave, so that the Rayleigh distribution of wave heights may then be used to provide the corresponding probability density of the force maxima. The resulting expression, given by Borgman (1965), is:

$$p(\zeta)=\begin{cases}\zeta\exp\left(-\frac{1}{2}\zeta^2\right) & \text{for } \zeta<\zeta_c\\ \zeta_c\exp\left[-\frac{1}{2}\zeta_c(2\zeta-\zeta_c)\right] & \text{for } \zeta\geq\zeta_c\end{cases} \tag{4}$$

where

$$\zeta=\frac{2\sqrt{2}\hat{F}}{\omega_o^2 K_m H_{rms} G(z)} \tag{5}$$

$$\zeta_c=\frac{\sqrt{2}K_m}{K_d H_{rms} G(z)} \tag{6}$$

$$G(z)=\frac{\cosh[k(z+d)]}{\sinh(kd)} \tag{7}$$

and H_{rms} is the root-mean-square wave height. ζ_c is a measure of the relative contributions of inertia and drag forces.

A generalization to the probability density of force maxima for the case of an arbitrary wave spectrum is more difficult to develop, but alternative expressions for such a case have been obtained by Tung (1974); Tickell (1977); and Moe and Crandall (1978).

Single Largest Force Maximum

In engineering applications, it is often the single largest value of the force maxima which is of primary interest. The probability distribution function of the single largest value $\hat{F}m$ of the force maxima $\hat{F}$ which occur in a sample of N successive waves, considered independent and to occur in a specified duration, can be expressed as:

$$P\left(\hat{F}_m\right)=\left[P'\left(\hat{F}=\hat{F}_m\right)\right]^N \tag{8}$$

where $P'(\hat{F})$ may be developed from the probability density given in Eq. 4. The number of maxima N occurring within a specified duration τ is given as $N=\tau/T_z$, where T_z is the zero-crossing period of the waves. The corresponding probability density function of $\hat{F}_m$ and the expected value $E[\hat{F}_m]$ of the single largest force maximum may thereby be obtained numerically.

There are a number of refinements or extensions to the fundamental case summarized above (Naess, 1983; Lindgren, 1984). Three extensions reviewed here relate in turn to the effects of short-crested waves; the effects of intermittency near the free surface; and the effects of wave slamming on horizontal members. Corresponding definition sketches of these problems are included in Fig. 1.

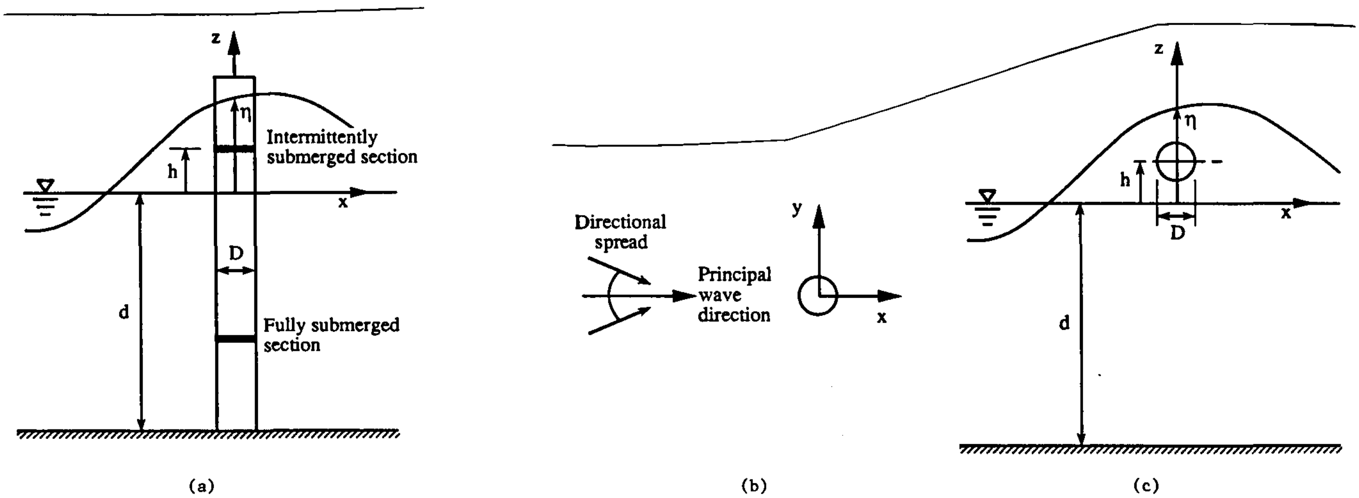

Fig. 1 Definition sketches. (a) random waves past fully and intermittently submerged sections of a vertical cylinder; (b) multidirectional random waves past a vertical cylinder; (c) random waves past a horizontal cylinder near the free surface.

SHORT-CRESTED WAVE FORCES

Short-crested waves correspond to an incident flow with a horizontal velocity and acceleration which are continuously changing direction (Fig. 1b). The Morison equation may still be applied in vector form, and it is then convenient to use the equation to provide the force components F_x and F_y in orthogonal horizontal directions, x and y. These are given as:

$$F_x = K_d qu + K_m \dot{u}$$
$$F_y = K_d qv + K_m \dot{v} \tag{9}$$

where q is the horizontal velocity magnitude, $q = \sqrt{u^2 + v^2}$, and u and v are the velocity components in the x and y directions respectively. Although extensive research has been carried out to investigate the force coefficients for the fundamental case of a uniform sinusoidal flow past a circular section (see, for example, Sarpkaya and Isaacson, 1981), the application of such force coefficients to the case of random short-crested waves is not obvious.

Short-crested random waves are usually described in terms of a directional wave spectrum $S(\omega,\theta)$ which may be expressed as the product of a unidirectional wave spectrum $S(\omega)$ and a directional spreading function $D(\omega,\theta)$. One parametric representation of $D(\omega,\theta)$ which is commonly used is the frequency independent cosine power spreading function which involves as parameters the principal direction of wave propagation θ_o and a spreading index s, such that $s \rightarrow \infty$ corresponds to unidirectional waves, and decreasing values of s corresponds to an increase in directional spreading.

The statistical properties of the force which are of interest now relate both to the in-line and transverse force components Fx and F_y, as well as to their horizontal resultant $F = \left[F_x^2 + F_y^2\right]^{1/2}$. These include the spectra of the in-line and transverse force components F_x and F_y; the probability distributions of F_x and F_y and of their horizontal resultant F; the probability distributions of the maxima of F_x, F_y and F; and the probability distributions of the largest of these maxima in a specified duration.

Spectral Density

As with unidirectional waves, expressions for the spectral densities of F_x and F_y may be obtained by first linearizing the Morison equation. The corresponding force spectra may then be expressed in terms of the spectra of velocity and acceleration, which can themselves readily be expressed in terms of the wave spectrum and directional spreading function (Isaacson and Nwogu, 1989).

Probability Distribution of Force Maxima

The probability distribution of the in-line and transverse force components may be obtained by retaining the full Morison equation and considering a transformation and integration of the joint distribution of the in-line and transverse velocities and accelerations. The corresponding derivation of the probability distributions of the force components and their maxima has been described by Nwogu (1989).

In many cases the horizontal resultant force F on each section, or on the total pile, is primarily of interest. The probability distribution of the maxima $\hat{F}$ of the resultant force may be obtained by considering the joint probability distribution of F_x and F_y and applying an appropriate transformation and integration. This procedure was described by Isaacson and Sinha (1986) for the case of large structures involving Gaussian force components. However, in the present case the force components are non-Gaussian on account of the nonlinearity of the Morison equation, and so in order to obtain reasonably tractable results, the assumption of a narrow-band wave spectrum is made. This gives rise to an expression provided by Isaacson and Nwogu (1986).

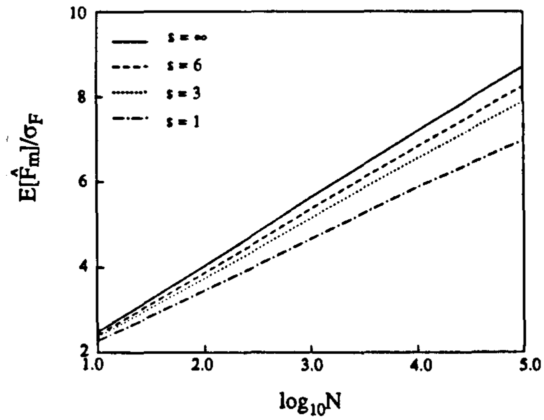

Fig. 2 Expected values of the largest force maximum as a function of N for long-crested and short-crested waves.

Probability Distribution of Largest Force Maximum

The cumulative probability of the single largest value $\hat{F}_m$ of the maxima $\hat{F}$ which occur in a sample of duration τ containing N successive maxima is given again by Eq. 8, where $P(\hat{F})$ now corresponds to the case of short-crested waves. The resulting distribution $P(\hat{F}_m)$ may now be used to obtain the expected value $E[\hat{F}_m]$ of the single largest force maximum.

Results

Selected results based on the above approach are reproduced here for the case of a still water depth d = 2 m and waves which possess a JONSWAP spectrum with peak period T_p = 2.0 s, significant wave height H_s = 0.3 m and peak enhancement factor g = 3.3. The forces acting on a 0.1 m high, fully submerged section of a circular cylinder of diameter D = 0.03 m are considered and force coefficient values of C_d = 1 and C_m = 2 have been used. Fig. 2 shows the expected value of $\hat{F}_m$ plotted against the number of waves N for long-crested waves and short-crested waves with different values of spreading index s, and clearly indicates how the expected value of the maximum resultant force is reduced in short-crested waves.

Numerically synthesized results for the same conditions have been obtained, and the probability distribution of the force maxima $\hat{F}$ based on the synthesized data and the theoretical predictions are compared in Fig. 3a for short-crested waves corresponding to s = 1. The agreement is rather good, particularly near the tail. Furthermore, it should be noted that the numerically synthesized values correspond to only one simulation, and the use of different set of random number seeds would produce a different set of maximum force values.

Experimental results have also been obtained in order to provide a comparison with the theoretical predictions (Nwogu and Isaacson, 1989). Experiments were carried out in the ocean engineering basin of the Hydraulics Laboratory of the National Research Council, Canada. The basin is 30 m wide and 19.2 m long, and is equipped with a 60-segment wave generator capable of producing regular and random, unidirectional and multidirectional waves. The water depth for the tests was set at d = 2 m. The test cylinder used has a diameter of 0.17 m and is 2.4 m high, with the upper 1.5 m divided into 9 segments. Each segment was fitted

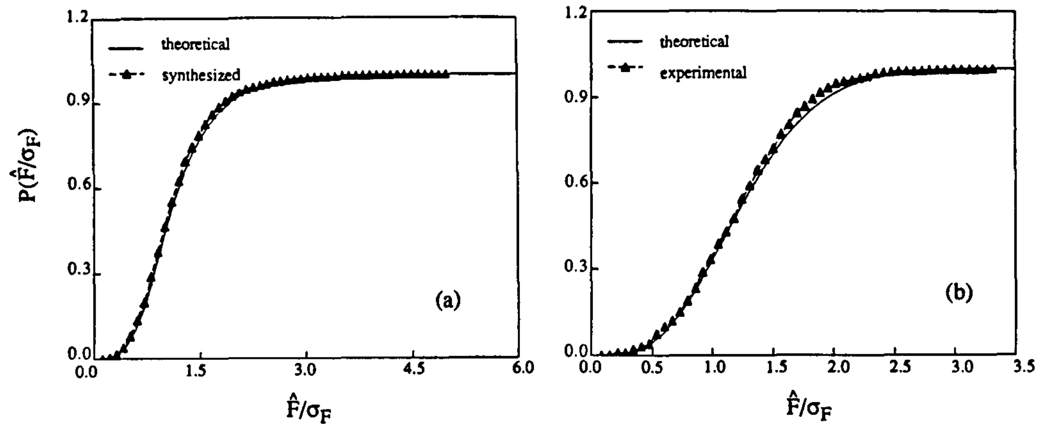

Fig. 3 Comparison of theoretical, synthesized and experimental probability distributions of force maxima for short-crested waves (s = 1). (a) theoretical and synthesized distributions; (b) theoretical and experimental distributions.

with two load cells oriented orthogonally so as to measure forces in-line and transverse to the incident wave direction. Fig. 3b compares the measured and predicted probability distributions of the force maxima acting on a 0.1 m high segment for short-crested waves corresponding to a JONSWAP spectrum with T_p = 3.03 s, H_s = 0.29 m and g = 3.3, and with s = 1. Once more the theoretical distribution is seen to fit the measured distribution reasonably well, particularly near the tail of the distribution. Results for these and other short-crested wave conditions tend to confirm the trend of decreasing values of $\hat{F}_m$ with an increasing degree of directional spreading, as predicted by the theory.

INTERMITTENTLY SUBMERGED SECTIONS

We consider now the effects of intermittent submergence on the force on a section of a vertical member which is close to the still water level. The general situation being considered is indicated in Fig. 1a. The intermittent flow field is taken to affect the statistical properties of the particle kinematics as described by Tung (1975b), but is considered not to affect the validity of the Morison equation itself.

Spectral Density

An approximate expression for the spectral density of the force acting on a structural section in the intermittent flow field may be obtained by applying the linearized form of the Morison equation (Eq. 2) to the case of an intermittent incident flow. However, the drag linearization factor β given by Eq. 3 was based on the assumption that u possesses a Gaussian probability distribution. In the present case, the distribution of u is non-Gaussian and a more general expression must be used. This is:

$$\beta = \frac{E\left[|u|^3\right]}{E\left[u^2\right]} \tag{10}$$

where E[ ] denotes the expected value. Substituting expressions provided by Pajouhi and Tung (1975) for the spectral densities of velocity and acceleration in the intermittent flow, a corresponding expression for the force spectral density is obtained (Isaacson and Baldwin, 1990a). It may be confirmed that, for sections far below the still water level, this reverts to that for fully submerged sections, so that the intermittency effects then vanish as expected. However, the expression indicates that, near the water surface, the intermittent submergence causes a significant reduction in the magnitude of the spectral density on account of the durations of zero force.

Probability Density of Force

The derivation of the probability density of the intermittent wave force is more difficult, as the full nonlinear drag term in the Morison equation should now be retained. Expressions for the complete force probability density have not been derived, although Tung (1975a) has obtained expressions for the mean and standard deviation of the wave force.

Probability Density of Force Maxima

As in the case of fully submerged sections, the probability density of the force maxima may be derived by assuming that the wave spectrum is narrow-banded, so that the loading within each wave may be considered to be deterministic. The Rayleigh distribution of wave heights may then be combined with the force wave height relationship to derive the probability density of the force maxima.

For sections at or below the still water level, the force maximum in each wave occurs when the section is submerged, and thus is unaffected by intermittency effects. Hence the expression given by Eq. 4 remains valid. For sections above the still water level, the maximum force may be affected by the intermittent submergence, and the corresponding probability density of the force maxima $\hat{F}$ is given as (Isaacson and Baldwin 1990a):

$$p(\zeta) = \begin{cases} \Gamma(\gamma)\delta(\zeta) & \text{for } \zeta = 0 \\ 0 & \text{for } 0 < \zeta < \gamma \\ (\zeta-\gamma)\exp\left[-\frac{1}{2}(\zeta-\gamma)^2 - \gamma\zeta_c\right] & \text{for } \gamma < \zeta < \zeta_c + \gamma \\ \zeta_c \exp\left[-\frac{1}{2}\zeta_c(2\zeta-\zeta_c)\right] & \text{for } \zeta \geq \zeta_c + \gamma \end{cases} \tag{11}$$

where δ is the Kronecker delta, ζ and ζ_c are defined in terms of $\hat{F}$ as in Eqs. 5 and 6, and

$$\gamma = \frac{4h^2}{\zeta_c H_{rms}^2} \tag{12}$$

Eq. 11 incorporates a finite probability $\Gamma(\gamma)$ at $\zeta = 0$, corresponding to force maxima of zero magnitude. $\Gamma(\gamma)$ is thus the probability that $H < 2h$, and is given by:

$$\Gamma(\gamma) = 1 - \exp(-\gamma\zeta_c) \quad (13)$$

Expressions for the mean μ_ζ and standard deviation σ_ζ of the force maxima may be obtained from Eq. 11 and are given by Isaacson and Baldwin (1990a). As h becomes large, the zero magnitude force maxima predominate, and both μ_ζ and σ_ζ tend to zero.

Single Largest Force Maximum

As in the other cases considered, the probability distribution function of the single largest value $\hat{F}_m$ of the force maxima $\hat{F}$ which occur in a sample of N successive waves can be evaluated by the application of Eq. 8. The corresponding expected value $E[\hat{F}_m]$ may thereby be obtained numerically.

Results

Selected results are reproduced here for the case of a random wave field described by a two-parameter Pierson-Moscowitz (or Bretschneider) spectrum in terms of H_s and T_p corresponding to $d = 40$ m, $T_p = 14.3$ s, and $H_s = 10$ m and a cylinder of diameter $D = 2.5$ m. The force coefficients C_m and C_d are taken as 1.9 and 0.6 respectively. Fig. 4 shows the vertical distribution above the still water level of the expected value $E[\hat{F}_m]$ of the largest force maximum for $N = 10$, 100 and 1000, corresponding to durations of approximately 2.4 min, 24 min and 4 hrs respectively. In the figure h is the sectional elevation above the still water level. Notable features of these results are that, before dropping off, this force value remains approximately constant with elevation above the still water level, particularly for higher values of N, and that the force may be significant at elevations approaching H_s.

The experiments described earlier were also used to provide a comparison for this situation (Isaacson and Baldwin, 1990b). Fig. 5 shows a comparison between measured and theoretical values of the single largest force maximum recorded on four 0.1 m high segments at different elevations above the still water level. Figs. 5a, 5b and 5c correspond in turn to three different wave conditions: $T_p = 3.13$ s, $H_s = 0.43$ m; $T_p = 2.44$ s, $H_s = 0.39$ m; and $T_p = 1.96$ s, $H_s = 0.31$ m. The agreement is generally quite reasonable. Observed discrepancies between theory and experiment may be attributed to a number of factors, including differences between the target and generated wave spectra, the assumption of a narrow-band spectrum, the finite heights of the segments, nonlinearities in the wave field, and finally to the difference between comparing experiments, which correspond to a single set of wave records, with theoretical predictions, which correspond to expected values obtained from many sets of wave records.

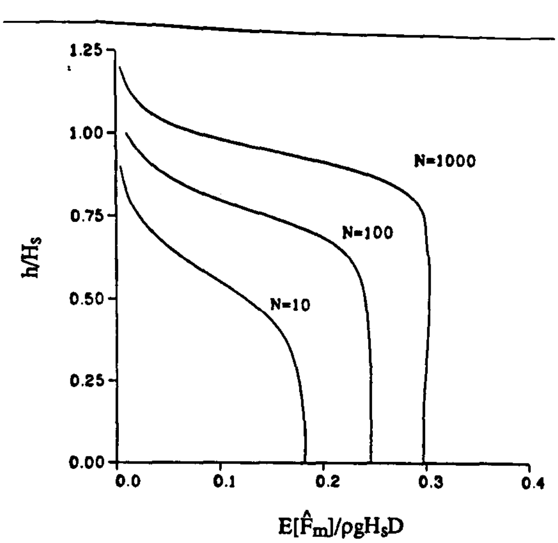

Fig. 4 Vertical distributions above the still water level of the expected value of the largest maximum of the sectional force on a vertical cylinder for a duration of N waves.

SLAMMING FORCES

Horizontal structural members located close to the water surface are susceptible to large impulsive forces caused by wave slamming. This situation is indicated in Fig. 1c. The slamming force F_s per unit length is usually calculated by:

$$F_s = K_s u^2 \quad (14)$$

where u is the (vertical) velocity of the water surface normal to the axis of the member, $K_s = (1/2)\rho D C_s$ and C_s is a slamming coefficient.

For a rigid circular cylinder, the theoretical maximum slamming force corresponds to a slamming coefficient of π and occurs at the instant of impact. However, measurements of the slamming

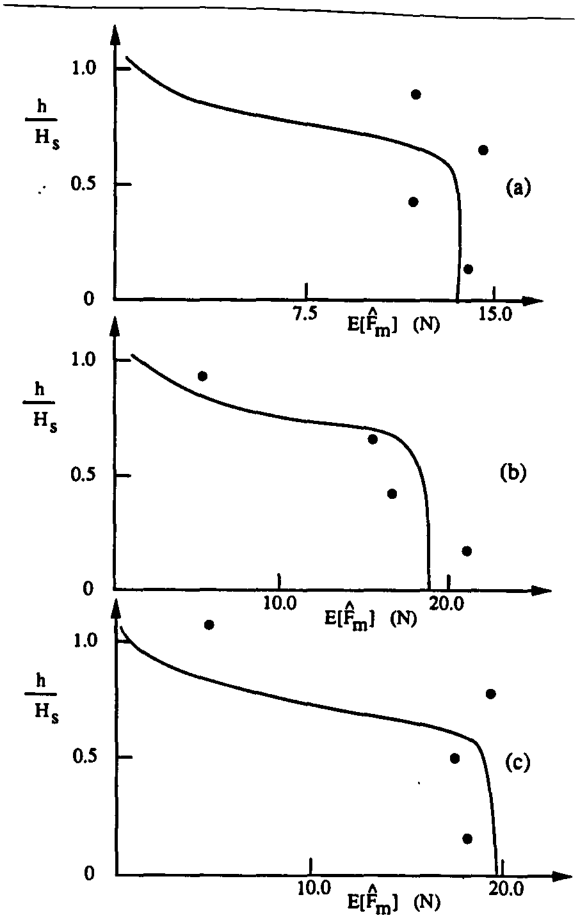

Fig. 5 Comparison of measured and predicted vertical distribution of the largest force maximum above the still water level for three wave conditions. (a) $T_p = 3.13$ s, $H_s = 0.43$ m; (b) $T_p = 2.44$ s, $H_s = 0.39$ m; (c) $T_p = 1.96$ s, $H_s = 0.31$ m. _____ , theoretical; •, measured.

coefficient indicate a slight delay before the slamming force reaches a maximum and a sensitivity of the maximum slamming force to a number of factors, including the dynamic response of the structural member, which is always present because of the high-frequency excitation of the impact loading, spray and air cushioning effects, free surface rise, and a slight slope of the member (Sarpkaya, 1978; Miller, 1980). Greenhow and Li (1987) have compared a number of alternative formulations for the added mass of a horizontal circular cylinder moving near the free surface, and have thereby described the variation of vertical force with immersion of the cylinder.

In addition to the impact force, other components of the vertical force acting on the cylinder include the buoyancy force, which is time-varying on account of the intermittent submergence of a member, and drag and inertia forces, which are given by the Morison equation during those periods when a member is fully submerged. Thus, when the cylinder is fully submerged, these three components combine in the form:

$$F_v = K_d u|u| + K_m a + \rho g \frac{\pi D^2}{4} \tag{15}$$

where u and a refer to the fluid vertical velocity and acceleration respectively.

For those durations when the cylinder is partly submerged, appropriate values of the various force coefficients are uncertain, but for the purpose of developing a random force model, a simplified approximation to Eq. 15 for the partially submerged case may be adopted. Such an approximation is not particularly critical when estimating the maximum force during passage of a wave, as this maximum will usually be due either to the slamming force, assumed to occur at the instant of impact, or to the other vertical force components, when the cylinder is fully submerged.

The effects of intermittency on the maximum vertical force due to random waves have been studied by Isaacson and Subbiah (1990). As in the cases described earlier, the probability distribution of force maxima may once more be derived by assuming that the wave spectrum is narrow-banded. The wave loading within each individual wave can then be considered deterministically, and the Rayleigh probability distribution of wave heights then enables the corresponding probability density of force maxima to be derived.

The maximum force during the passage of any one wave is assumed to be due either to the slamming force F_s and to occur at the instant of impact, or to the remaining force F_v indicated in Eq. 15. In the latter case, the maximum force may arise when the cylinder is fully submerged and be unaffected by the intermittent submergence; or if such a maximum does not occur when the cylinder is fully submerged, then the maximum force would instead correspond to that at the instant of complete submergence. For those waves which only partially submerge the cylinder, a simplified approximation to Eq. 15 is adopted. Whichever of the above cases arises, it turns out that the maximum force $\hat{F}$ may be expressed in terms of wave height H on the basis of linear wave theory in either of the following forms:

$$\hat{F} = aH - b \tag{16}$$

$$\hat{F} = \alpha H^2 - \beta \tag{17}$$

where a, b, α and β are parameters which may be derived from the different possible expressions for the maximum force. Consequently, alternative expressions for the maximum force arise, depending on the location of the cylinder relative to the still water level and on the wave height.

These expressions may be combined with the known Rayleigh distribution of wave heights to provide alternative expressions for the probability density of the force maxima, depending on the location of the cylinder. As in the case of a vertical cylinder, the probability density derived in this way is based on the assumption that one force maximum occurs per wave, even though this may be zero for some waves due to nonsubmergence of the cylinder. This represents the contribution due to individual waves which are not high enough to wet the cylinder.

Corresponding expressions for the mean and standard deviation of the force maxima may be obtained from the probability density expressions. Finally, the expected value of the single largest force maximum in a specified duration may be derived from the probability distribution in a similar manner to that for the case of a vertical cylinder considered earlier.

Results

Various numerical results relating to the maximum vertical force have been provided by Isaacson and Subbiah (1990). In particular, the single largest value $\hat{F}_m$ of the force maxima which occur within a specified duration is of particular interest. Fig. 6 shows the vertical distribution of the expected value $E[\zeta_m]$ of this extreme force expressed in dimensionless form for durations corresponding to N = 10, 100 and 1000. For the selected example with T_p = 14.3 s, the corresponding durations are approximately 2.4 min, 24 min and 4 hrs respectively. As expected, the figure indicates that, as the number of waves N is increased, $E[\zeta_m]$ at a given elevation increases, and that $E[\zeta_m]$ approaches zero at higher elevations. The variation of $E[\zeta_m]$ with elevation h is of particular interest for the two larger values of N. $E[\zeta_m]$ is almost constant with elevation for cylinder locations which are sufficiently below the still water level. Above this range, $E[\zeta_m]$ exhibits a notable increase with increasing h to a maximum value slightly above the still water level, and then eventually a decrease

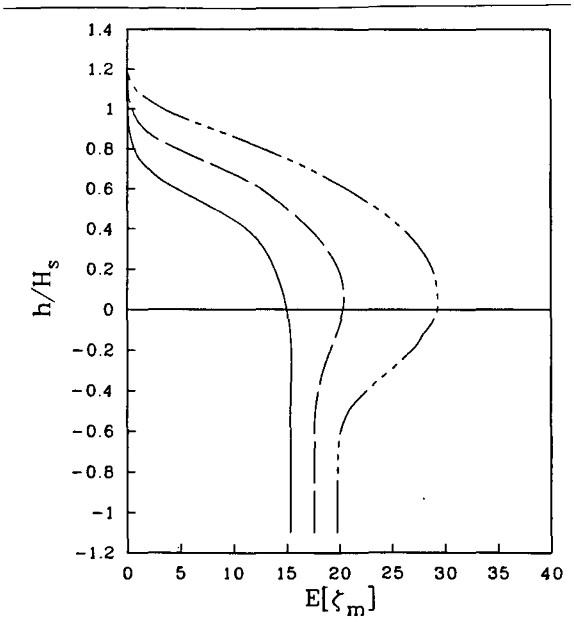

Fig. 6 Vertical distributions near the still water level of the expected value of the largest maximum E[ζ_m] of the vertical force on a horizontal cylinder for a duration of N waves. ——, N = 10; - - - , N = 100; ——-—, N = 1000.

towards zero as h is increased further. This feature is in marked contrast to Fig. 4, which relates to horizontal forces and which does not show such a maximum value near the still water level; Isaacson and Subbiah illustrate how the maximum of $E[\zeta_m]$ with h is attributed to the effects of wave slamming.

CONCLUSIONS

A selection of recent research relating to specific aspects of random wave forces acting on slender structural members is summarized. These relate to effects of directional spreading, the forces on intermittently submerged sections near the water surface, and the vertical forces due to wave slamming.

Theoretical results for forces due to short-crested waves are summarized, and comparisons with numerically simulated results and experimental results are favourable. An increase in directional spreading tends to reduce the magnitude of the largest force.

Theoretical results for forces on intermittently submerged sections of a vertical cylinder are also summarized, and comparisons with experimental results are favourable. Intermittent submergence markedly influences the statistics of the wave forces on such sections.

For horizontal members located near the still water level, wave slamming may dominate the wave loading and should be taken into account. A procedure is summarized for predicting the mean of the force maxima and the expected value of the single largest force maximum which occurs within a specified duration.

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