LARGE SCALE EXPERIMENTS DATA ANALYSIS FOR ESTIMATION OF HYDRODYNAMIC FORCE COEFFICIENTS PART 1: TIME DOMAIN ANALYSIS

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Abstract This paper describes various time-domain methods useful for analyzing the experimental data obtained from a circular cylinder force in terms of both wave and current for estimation of the drag and inertia coefficients applicable to the Morison's equation. An additional approach, weighted least squares method is also introduced. A set of data obtained from experiments on heavily roughened circular cylinders in waves and simulated current has been analyzed by all these techniques. The resulting force coefficients are then used to predict the force from separate experiments-results that have not been used in the analysis. The root mean squares error and bias in the estimation of maximum force in each wave cycle is used as a measure of predictive accuracy and as a basis for comparing the analysis techniques. It is found that no single method is consistently better under all circumstances but on average weighted least squares method generally gives the best predictive accuracy by a small margin. The force coefficients obtained by the various methods significantly decrease when current is added to waves.

Key Words Morison's Equation, Weighted Least Squares, Drag and Inertia Coefficients, Ocean Waves

چكيده اين مقاله روشهای مختلف در حوزه زمانی را که برای استفاده در آناليز داده‌ها به منظور تخمين ضرايب هيدروديناميکی درگ و اينرسی در معادله موريسون بر استوانه‌های واقع در امواج و جريانات پايا بکار مي‌رود، تشريح مي‌کند. علاوه بر آن، روش حداقل مربعات وزني نيز معرفي مي‌گردد. داده‌هاي بدست آمده از آزمايش بر سيلندرهاي استوانه‌اي با سطح کاملاً زبر واقع در امواج و جريانات شبيه سازي شده توسط اين روشها آناليز گرديده‌اند؛ سپس ضرايب بدست آمده از اين آناليز بر يک سري داده‌هاي ديگر بکار گرفته شده اند. براي مقايسه روشهاي مختلف آناليز در هر سيکل، موج از جذر ميانگين مربعات (RMSE) و ميانگين خطای نرمال (MNE) استفاده شده است. ملاحظه گرديد که هيچ روشی بتنهايی نمی‌تواند، با در نظر گرفتن تمام شرايط، بهتر از ديگری ارزيابی گردد. اما در مجموع روش حداقل مربعات وزنی دقت بيشتری با مقداری پراکندگی نشان می‌دهد و نيز ملاحظه گرديد که وقتی جريان به امواج اضافه می‌گردد، ضرايب هيدروديناميکی بدست آمده توسط روشهای مختلف بطور قابل توجهی کاهش می‌يابد.

INTRODUCTION

There has been a considerable volume of experimental research undertaken to estimate the force coefficients in Morison's equation [1]. Much of the early work was undertaken at small scale but the experiments described and discussed in this paper were undertaken in a large 2-D wave flume.

Offshore current may augment the wave particle kinematics. In the laboratory this can be simulated either by circulating the water in the wave flume or by attaching the test cylinder to a moving carriage. In the experiments described in this paper the later approach has been used.

In the laboratory it is possible to measure the wave particle velocity beside the cylinder. These measurements can be differentiated with respect to time to find the corresponding wave particle acceleration. It is these measurements together with the measured force on the cylinder that is generally used when estimated the drag and the inertia coefficients (Cd and Cm) for Morison's equation [1].

A variety of procedures have been used to analyze the experimental data in the context of Morison's equation and to predict Cd and Cm. The methods used in time domain analysis are described in third section of this paper.

Sometimes experimenters have justified their choice of analysis on the basis of how well the predicted Morison force compares with the measured force. However as the force coefficients are derived from the measured force one would expect the reconstruction of force time histories to be quite satisfactory, provided that Morison's equation was a suitable model. This is not an independent test.

By splitting the experimental data from a random wave experiment into two parts, a more demanding test can be devised. The first part of the time history is analyzed to obtain predictions for Cd and Cm. These values are then used with particle kinematics measured in the second part to predict the force time series measured in the second part. This provides a more independent assessment of predictive accuracy.

In order to estimate predictive accuracy a measure is needed of how well the predicted force maps onto the independently measured force. One measure would be the root mean squares error normalized by some function of the magnitude of the measured signal. This would measure the quality of the mapping at all points of the time series. However it is the maximum magnitude of the force involving a single extreme wave, which is of interest in the ultimate limit state design assessment.

In the fatigue limit state it is the range of the force produced by each wave, which is of concern, and in particular that produced by the larger waves. In this paper the root mean squares error in the prediction of the maximum and minimum (maximum negative) force normalized by the measured force is used as one measure of predictive accuracy. To avoid the influence of irrelevant small waves only the fit to waves of above average height are considered. The normalized mean bias in this fit is used as the other measure of predictive accuracy.

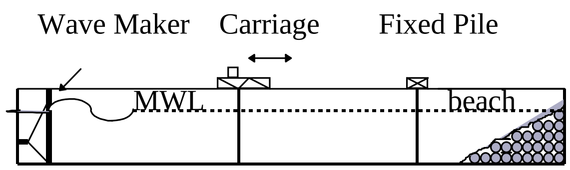

Figure 1. Schematic fixed and mobile cylinders in the large wave flume.

The next section of the paper describes the experiments. The third section describes the various methods for the prediction of force coefficients from experiment data. The fourth section presents the discussion of the results from the analysis of the experiment data. Finally some conclusions are drawn.

DESCRIPTION OF THE EXPERIMENTS

A series of experiments were made to examine the wave loading on two large-scale circular cylinders in the Delft Hydraulic Laboratory's Delta wave flume in the Netherlands [2].

Figures 1 and 2 show a schematic longitudinal section of the flume with a cylinder mounted on the moving carriage, a fixed cylinder, the beach, the wave-maker and the force sleeves' positions.

The details of the six experiment runs considered here are given by [3] from which it can be found that there were experiments with both the small and large cylinders stationary, with a current in the wave direction and a current opposing the wave direction. The currents were achieved by translating the cylinder on the moving carriage away from the wave maker and towards the wave maker respectively.

METHODS FOR ESTIMATING FORCE COEFFICIENTS

There are many methods for estimating force coefficients from the data produced from experiments in waves, wave and current and other oscillatory flows. The methods used in time domain analysis are explained briefly. Also the weighted least squares method that has been developed by the author is considered.

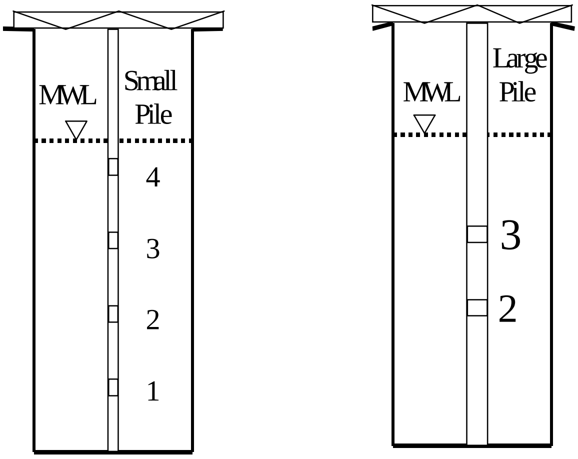

Figure 2. Schematic cylinders in the flume with the force sleeves' positions.

Trough-Crest Linear Theory Fitting One approach to evaluating the hydrodynamics force coefficients is to assume that the velocity and acceleration are 90 degrees out of phase, so when the velocity is maximum, the acceleration is zero and vice versa, thus there are specific locations where the force is purely drag and purely inertial, and Morison's equation can be written at these two points as below and then the coefficients may be easily determined [4].

$$f = K_D \; u_0^2 \; |\sin\Theta|\sin\Theta + K_M \; u_0 \; \omega \cos\Theta \qquad (1)$$

where

$$K_D = 0.5\rho \, D C_d \qquad K_M = 0.25\rho\pi \, D^2 C_m \qquad (2)$$

Θ = wave phase
where ρ = mass density of water, D is the diameter of the cylinder and C_m and C_d are the inertia and drag force coefficients, respectively.

The Fourier Averages Method Keulegan and Carpenter [5] introduced a method that they used for relatively low Reynolds numbers through measurements on a horizontal cylinder and a sphere in an experiment with standing waves.

According to this method, the force applied to a cylinder submerged in waves can be expressed by considering linear theory described by Equation 1 and the inertia and drag force coefficients can, respectively, be determined over one cycle using Fourier averaging [6].

The method of Fourier averaging has been developed and used by many authors including Bearman et al. [7,8], Bishop [9] and Davies [10].

In the method used by Bearman et al. [7], the Morison's equation is multiplied once by u and then by $\dot{u}$ and in each case time averaged over a complete wave cycle. The hydrodynamic coefficients can then be determined from the following equations:

$$C_d = \frac{< fu >}{0.5\rho D < |u|^3 >} \qquad C_m = \frac{< f\dot{u} >}{0.25\rho\pi D^2 < \dot{u}^2 >} \qquad (3)$$

where u and $\dot{u}$ are the horizontal components of water particle velocity and acceleration, respectively and <> indicates time averaging of the enclosed quantity.

In the method used by Klopman and Kostense, the Morison's equation is multiplied first by $u|u||$ and then by $\dot{u}$ and again time averaged on each occasion over each complete wave cycle to give new equations which can be solved to give the following results:

$$C_d = \frac{< fu|u| >}{0.5\rho D < u^4 >} \qquad C_m = \frac{< f\dot{u} >}{0.25\rho\pi D^2 < \dot{u}^2 >} \qquad (4)$$

If the assumption is made that u and $\dot{u}$ both have zero mean value normal distributions, then:

$$< |u|^3 > = \sigma^3 \sqrt{\frac{8}{\pi}} \qquad < u^4 > = 3\sigma_u^4 \qquad < \dot{u}^2 > = \sigma_{\dot{u}}^2 \qquad (5)$$

In the case that waves are combined with current, then considering the terms $< \dot{u} \; u|u| >$ $< \dot{u} u >$ and $< \dot{u}u \, | u | >^2$ are very small [11] compared with the other terms Equation 3 can be written as:

$$C_d = \frac{< fu >< \dot{u}^2 > - < f\dot{u} >< u\dot{u} >}{0.5\rho\ D(<|u|^3 >< \dot{u}^2 >)}$$

$$C_m = \frac{< f\dot{u} ><|u|^3 > - < fu >< \dot{u}u|u|>}{0.25\rho\ \pi\ D^2 (< \dot{u}^2 ><|u|^3 >)} \quad (6)$$

and Equation 4 as:

$$C_d = \frac{< fu|u|>< \dot{u}^2 > - < f\dot{u} >< u|u|\dot{u} >}{0.5\rho\ D(< u^4 >< \dot{u}^2 > - < \dot{u}u|u|>^2)}$$

$$C_m = \frac{< f\dot{u} >< u^4 > - < fu|u|>< \dot{u}u|u|>}{0.25\rho\ \pi\ D^2 (< \dot{u}^2 >< u^4 > - < \dot{u}u|u|>^2)} \quad (7)$$

where u is the horizontal components of water particle velocity when a steady current exists.

Mean Squares Method The mean squares method derived by Bishop [12] is yet another way to determine hydrodynamic coefficients in time domain analysis.

Bishop [13] has given a brief review of mean squares theory and Shipway. He has obtained the following results applicable to a random sea:

$$\frac{< F^2 >}{< \dot{u}^2 >} = A^2 \frac{< u^4 >}{< \dot{u}^2 >} + B^2 \quad (8)$$

in which, <.> denotes the expected value of the random quantity enclosed in the <> estimated from whole time series and F^2 is the mean squares value of the force and

$$A = 0.5C_d\ \rho\ D \qquad B = 0.25C_m\ \rho\ \pi\ D^2 \quad (9)$$

Davies [10] has discussed the problems of using this method in detail.

Method of Moments Applied to the Force Time History Pierson and Holmes [11] have used moment generating function-derived equations to determine hydrodynamic force coefficients. They assumed that u and $\dot{u}$ are independent normal random variables with mean values of zero. Muga and Wilson [14] used this method and found the values of C_m and C_d according to the following equations:

$$\mu_2 = 3K_D^2\sigma_u^4 + K_M^2\sigma_{\dot{u}}^2$$
$$\mu_4 = 105K_D^4\sigma_u^8 + 18K_D^2\sigma_u^4K_M^2\sigma_{\dot{u}}^2 + 3K_M^4\sigma_{\dot{u}}^4 \quad (10)$$

In these equations, σ_u^2 and $\sigma_{\dot{u}}^2$ are estimated from the experimental data and μ_2 and μ_4 are defined by:

$$\mu_2 = \frac{1}{n}\sum_{i=1}^{n} f_i^2 \quad and \quad \mu_4 = \frac{1}{n}\sum_{i=1}^{n} f_i^4 \quad (11)$$

The coefficients of Equation 10 are obtained from the following definitions:

$$K_M = \sqrt{\frac{(\mu_4 - 3\mu_2^2)^{0.5}}{\sqrt{78}\sigma_u^4}}$$

$$K_D = \sqrt{\frac{\mu_2 - 3\sqrt{\frac{\mu_4 - 3\mu_2^2}{\sqrt{78}}}}{\sigma_{\dot{u}}^2}} = \sqrt{\frac{\mu_2 - 3K_M^2\sigma_u^4}{\sigma_{\dot{u}}^2}} \quad (12)$$

Least Squares Method One of the most straightforward methods for estimating the coefficients is the least squares method. In this method the coefficients can be estimated by minimizing the sum of the squares of the difference (measured at each small time interval) between the time series of the measured and predicted forces. This method can be used either for each individual wave cycle, defined between successive zero up-crossings or for whole wave records (i.e. about 20 minutes of data).

Correspondingly, it is assumed that C_m and C_d are both constant during each wave cycle or for the whole set of wave data and are given by:

$$C_d = \frac{\sum fu|u|\sum \dot{u}^2 - \sum f\dot{u}\sum u|u|\dot{u}}{0.5\rho D(\sum u^4 \sum \dot{u}^2 - (\sum \dot{u}u|u|)^2)} \quad (13)$$

$$C_m = \frac{\sum f\dot{u}\sum u^4 - \sum fu|u|\sum \dot{u}u|u|}{0.25\rho \pi D^2(\sum \dot{u}^2 \sum u^4 - (\sum \dot{u}u|u|)^2)}$$

If we consider the waves to be linear and use the data from a single whole wave cycle, then:

$$\sum u|u|\dot{u} = 0 \quad (14)$$

and Equation 16 are simplified to:

$$C_d = \frac{\sum fu|u|}{0.5\rho D(\sum u^4)} \qquad C_m = \frac{\sum f\dot{u}}{0.25\rho\pi D^2(\sum \dot{u}^2)} \quad (15)$$

This method was developed by [15] He showed that depending on the wave and cylinder characteristics, data can be well or poorly-conditioned for resolving C_d and C_m. He presented a criterion for evaluating the suitability of data for determining C_m and C_d as "reliability ratio"

$$R = \frac{2}{\pi D}\sqrt{\frac{< u^4 >}{< \dot{u}^2 >}} \quad (16)$$

Dean [15] suggested that data will be well-conditioned for evaluating both C_m and C_d together when *0.25<R<4* and for C_m only when *0<R<0.25* and for C_d only when *R>4*

Weighted Least Squares Method A weighted least squares analysis, which has been introduced by [3] can also be applied to the data. Using such an approach the author has found a noticeable reduction is achieved in the error between fitted and measured values at the peaks of the force time series for waves with heights of more than the root-mean-squares wave height $(H > H_{rms})$. This approach may have a significant affect when extreme value and peak-to-peak range of Morison force are required. This is the case for estimating extreme collapse loading and fatigue loading respectively of offshore jacket structures. The weighted least squares formulation is:

$$e_f = f - f_e = f - (0.5\rho DC_d u|u| + 0.25\rho \pi D^2 C_m \dot{u})$$

$$e_f f^k = f^k(f - f_e) \qquad E = \frac{1}{N}\sum e_f^2 f^{2k}$$

$$\frac{\partial E}{\partial C_m} = 0 \qquad \frac{\partial E}{\partial C_d} = 0 \quad (17)$$

where k is an arbitrary positive number and the terms e_f, f_e, E, N define the error of the estimated force, the estimated force, mean squares error and number of data from which the coefficients are evaluated respectively. The parameter k is considered as a constant that can be selected to minimize the error in the critical peak force areas.

The coefficients are then obtained as below:

$$C_d = \frac{\sum f^{2k} fu|u|\sum f^{2k}\dot{u}^2 - \sum f^{2k} f\dot{u}\sum f^{2k}u|u|\dot{u}}{0.5\rho D(\sum f^{2k}u^4\sum f^{2k}\dot{u}^2 - (\sum f^{2k}\dot{u}u|u|)^2)}$$

$$C_m = \frac{\sum f^{2k} f\dot{u}\sum f^{2k}u^4 - \sum f^{2k} fu|u|\sum f^{2k}\dot{u}u|u|}{\rho\frac{\pi}{4}D^2(\sum f^{2k}\dot{u}^2\sum f^{2k}u^4 - (\sum f^{2k}\dot{u}u|u|)^2)}$$

(18)

All the parameters in these equations are defined above. It has been found that the constant the k can be optimized in an iterative manner to give a minimum predictive error in the peak force regions.

DISCUSSION OF RESULTS

The principal objective of this paper is to examine the efficiency of the various methods of analysis rather than to present a very extensive set of experimental data and so only a subset of a larger project is considered. The experiments considered here all had heavy (artificial marine) roughness on them. The results of the other experiments in the same project, on smooth cylinders and those with slight roughness are presented in Mackwood, et al. [16].

Effect of Keulegan Carpenter Number Before examining the efficiency of the various methods for estimating Cd and Cm from random wave data it is interesting to look at plots of Cf against KC (Cf is a root mean squares force coefficient); see Bearman, et al. [7],

$$Cf = \frac{f_{rms}}{0.5\rho D u_{rms}^2}$$

where f_{rms} is root mean squares value of in-line force, u_{rms} is root mean squares value of horizontal water particle velocity, D is the diameter of the cylinder and ρ is mass density of water. The results obtained with no current are shown in Figure 3 for the large cylinder. These results have been obtained by analyzing each wave in the random wave train separately. Figure 4 shows that the effect of introducing a positive current is to reduce not only the scatter in Cf at low KC values but also its average magnitude. A negative current reduces the average magnitude even further and across a wider range of KC as can be seen in Figure 5. The inference that can be drawn is that at low KC without current a large number of correspondingly small waves are needed to estimate a mean value of Cf, and also Cd and Cm, with statistical accuracy.

This variation in scatter with KC is also seen in some cases after the total force is split into drag and inertia components as can be seen in Figure 6. Here Cd and Cm have been estimated using the wave-by-wave least squares method (WWLSM). Interestingly for the larger pile in the no current condition the Cd shows most of the scatter at low KC and Cm has lower scatter, which is apparently

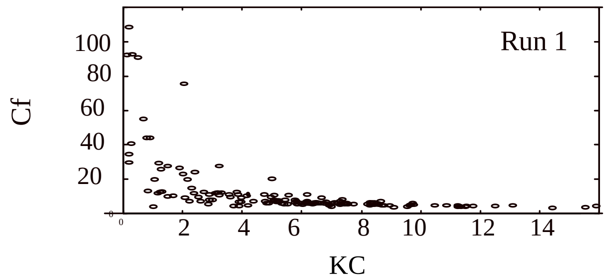

Figure 3. Variation of Cf with KC in the random waves (fixed large pile).

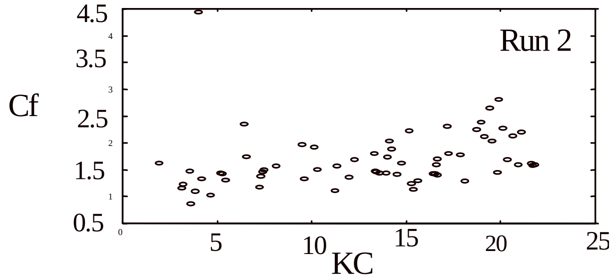

Figure 4. Variation of Cf with KC in the random waves (mobile large pile, = +1m/sec).

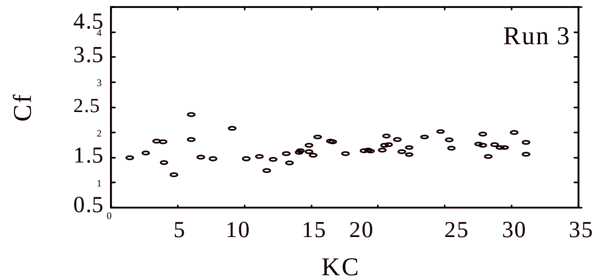

Figure 5. Variation of Cf with KC in the random waves (mobile large pile, U=-1m/sec).

independent of KC, as is seen in Figure 6. For the smaller pile on the other hand the scatter in both Cd and Cm is similar. This is reflected in Dean's "reliability coefficient" R (Figures 7 and 8). In all cases there is at least some tendency for the scatter to reduce as the KC in creases but there is very little variation in the average value of either Cd or Cm above a KC of around 7 for both the with and without current cases. Because of this average results for Cd and Cm are considered hereafter in this paper.

Assessing Predictive Accuracy In a statistical sense a good estimator should be unbiased and of minimum variance. This is equally important when estimating the forces on offshore structures and in this paper two corresponding parameters are used to assess how well a predicted force time series compares with the corresponding measured force time series. These parameters are the mean normalised error (MNE) and root mean squares error (RMSE) are given by:

$$MNE = \frac{100}{N}\sum_{i=1}^{N}\frac{(f_m)_i-(f_e)_i}{(f_m)_i}$$

$$RMSE = 100\sqrt{\frac{1}{N}\sum_{i=1}^{N}\left[\frac{(f_m)_i-(f_e)_i}{(f_m)_i}\right]^2} \qquad (19)$$

where f_m is maximum of absolute value of measured force, f_e is the same as f_m but for predicted force and N is the number of waves of above average height. These parameters provide a basis for comparing force coefficients obtained by the different analysis methods discussed earlier. They are also used to compare measured wave particle velocity and those predicted by wave theories from surface wave height and period.

The parameters above can be unduly influenced when f_m is small and the absolute error is large so it is desirable not to consider small waves and their corresponding forces when predicting the measured time series. For jacket type offshore structures, the ultimate wave loading involves very high KC and most of the fatigue damage occurs in waves of at least moderate KC (typically above about 7-10). Therefore, it was decided to see how well the measured force due to waves of above average height could be predicted.

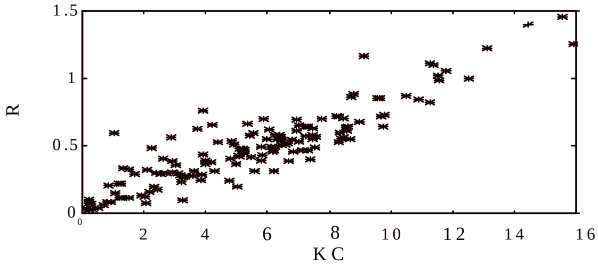

Figure 6. Variation of reliability ratio with KC for fixed large pile.

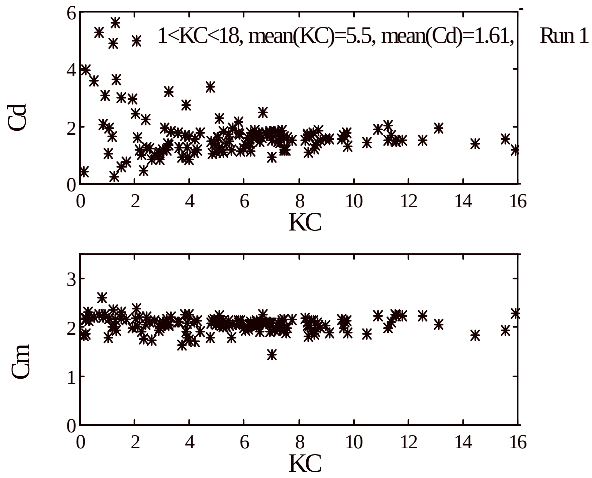

Figure 7. Variation of Cd and Cm with KC in the random waves for a fixed large pile (using wave by wave least square method (WWLSM).

Variation of Cd and Cm and Predictive Accuracy with Analysis Method Tables 1

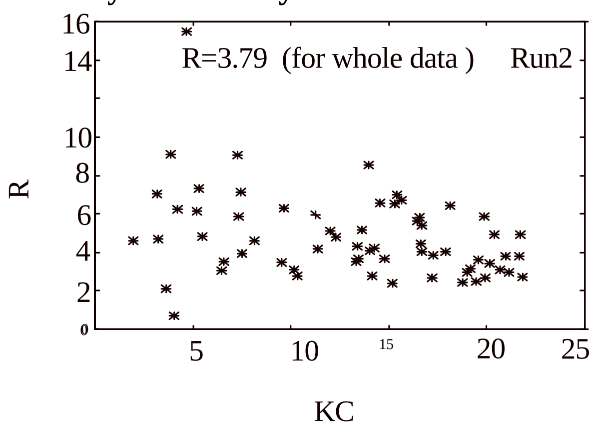

Figure 8. Variation of reliability ratio with KC for mobile large pile.

curacy with Analysis Method Tables 1 and 2 show the mean values of Cd and Cm obtained using the various analysis methods described in Section 3. For those methods, which use a wave-by-wave analysis, a pair of force coefficients is obtained for each wave cycle and in these cases the standard deviations are quoted. Also shown in these tables are the corresponding mean bias and standard error when these coefficients are used for predicting the second, unanalyzed, part of the measured force time series.

Looking at the wave by wave analysis methods in these tables it is noticeable that the standard deviation of the Cd values reduce significantly in all cases with the addition of current but for the Cm values the reverse is true. When it comes to predictive accuracy few clear trends occur. The rmse tends to reduce somewhat in most cases when current is added but the bias shows no particular trend. As far as the analysis methods are concerned the performance are quite similar as would be expected in light of the similarity among these methods shown in Section 3. For these data sets the least squares method comes out slightly ahead overall of the existing methods for wave-by-wave analysis but not consistently so. The weighted least squares (particularly with a weight index of 2) is seen to be generally superior to the existing methods.

The method of moments applied to the whole time history of each run gives results with generally low bias, less than 8%, and rmse values of 9.5 to 15 %.

The least squares method applied to the whole time history has a bias of less than 9% for all the runs an average of less than 4%. The corresponding rmse varies between 7.5 and 16% and the method seems to give force coefficients broadly consistent with other methods. The author has tried a weighted least squares approach as described in section 3.6 and by Equations 17 and 18, which gives additional emphasis to the fitting at large values of the modules of the measured force. The results show some improvement when this is done and the bias is always less than 6.3% with an average of 2.03% for a power factor of n=2 but the rmse still varies from 7.36 to 14.79%.

Table 3 shows the averages from all the methods discussed above used for each run together with the overall averages for all six runs. Overall the mean value of Cd is 1.47 and Cm is 1.83 with an overall average rmse of 13.34% and mean modules of bias of 6.18.

CONCLUSIONS

It is clear that the method used to analyze experiment

TABLE 1. Values of C_m and C_d from the Analysis Methods in the Random Waves for a Fixed Large Pile (* :The Result is not Included in the Mean Value).

Methods of	analysis	Cd(mean)	σ_{cd}	Cm(mean)	σ_{cm}	MNE%	rmse%
Wave by *Wave* *Analysis*	**Least Squares Method**	1.88	1.54	2.08	0.15	1.32	11.41
	Bearman Method	1.55	1.01	2.04	0.17	5.28	11.57
	Klopman Method	1.38	1.11	2.04	0.17	6.78	12.31
Moments method		1.73	__	2.06	__	2.78	11.08
Least squares		1.57	__	2.04	__	5.08	11.51
Weighted Least Squares Method	n=0 *	1.57	__	2.04	__	5.08	11.51
	n=1 *	1.54	__	2.14	__	1.23	10.82
	n=2	1.52	__	2.22	__	-1.64	11.28
	n=3 *	1.50	__	2.28	__	-4.18	12.24
Mean	**value**	**1.61**		**2.08**		**3.27**	**11.53**

TABLE 2. Values of C_m and C_d from the Analysis Methods in the Random Waves for a Mobile Large Pile (* :The Result is not Included in the Mean Value).

Methods of Analysis		Cd(mean)	σ_{cd}	Cm(mean)	σ_{cm}	MNE %	rmse %
Wave by Wave Analysis	Least Squares Method	1.51	0.37	1.72	0.72	2.82	8.44
	Bearman Method	1.32	0.37	1.49	0.56	15.18	16.69
	Klopman Method	1.32	0.36	1.50	0.57	15.54	17.01
Moments Method		1.46	_ _	0.53	_ _	7.80	11.01
Least Squares		1.42	_ _	1.59	_ _	8.74	11.50
Weighted Least Squares Method	n = 0 *	1.42	_ _	1.59	_ _	8.74	11.50
	n = 1 *	1.44	_ _	1.82	_ _	7.29	10.49
	n = 2	1.44	_ _	1.98	_ _	6.26	9.85
	n = 3 *	1.45	_ _	2.13	_ _	5.36	9.35
Mean Value		**1.41**		**1.47**		**9.39**	**12.42**

TABLE 3. Values of C_m and C_d from the Analysis Methods in the Random Waves (Averaged in the Six Runs).

Methods of Analysis		%Bias	%RMSE	Cd(mean)	Cm(mean)
Time Domain (Wave by Wave Analysis)	**Least Squares Method**	5.56	12.83	1.42	1.80
	Bearman Method	10.19	15.76	1.49	1.65
	Klopman Method	9.09	14.91	1.44	1.66
	WLSM (2)	2.03	10.90	1.51	2.04
	Moments Method	6.57	14.19	1.51	2.05
	Least Squares	3.66	11.44	1.46	1.77
Mean Value		**6.18**	**13.34**	**1.47**	**1.83**

data in terms of Morison equation has a significant affect on both the force coefficients obtained and their predictive accuracy. It is found that no single method is consistently better under all circumstances but on average the wave by wave weighted least squares method gives both the lowest bias (2.03%) and root mean squares error (10.9%) as can be seen in Table 3.

The force coefficients obtained by the various methods varied significantly but there was a clear trend which showed that the addition of current significantly decreased the drag coefficient and to a lesser extent the inertia coefficient.

For KC values of above around 10, uses of single mean drag and inertia coefficients (about 1.7 and 2, respectively) for heavily marine roughened cylinders in waves without current, seems satisfactory. When current is present, both coefficients should be significantly less than the above values (see Figures 8 and 9 and Table 2).

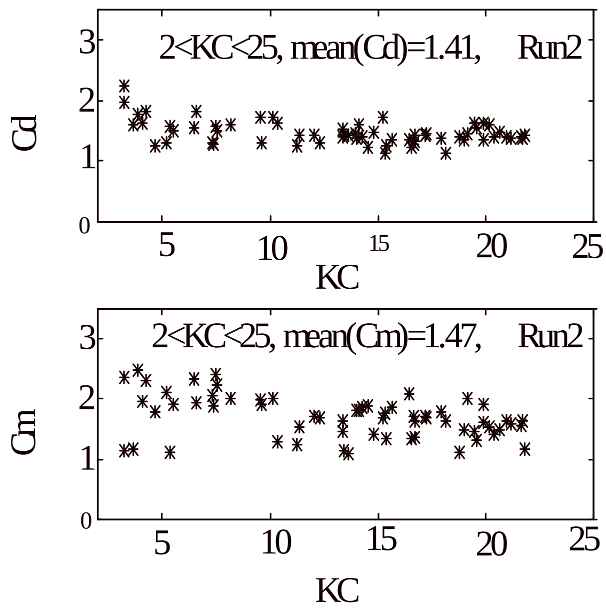

Figure 9. Variation of Cd & Cm with KC in the random waves for a mobile large pile (using wave by wave least square method WWLSM).

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