WAVES FORCES ON OFFSHORE PIPELINES

by

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INTRODUCTION

Transportation of offshore oil and gas is mostly carried out by means of offshore pipelines. Depending on the ocean environment these pipelines are either buried or made to rest on the ocean bed or placed on excavated trenches. In cases where the sea bed is mostly of rock, pipelines can be laid on the bed and anchored to the ocean floor by suitable supports. In certain instances pipelines are also placed on saddles leaving a clearance between pipe and the sea floor. The design of these pipelines requires an accurate assessment of wave induced loads acting on them.

The objective of this paper is to present the experimental results of wave forces exerted on a model pipeline, of diameter 5 cms at different clearances from the bed of the flume. Hydrodynamic coefficients namely Drag and Inertia are computed from the measured forces and their correlation with the non-dimensional parameters, Reynold's Number, Keulegan-Carpenter Number and relative clearance from the bed are presented.

LITERATURE REVIEW

The relationship between the hydrodynamic coefficients C_D, C_M, C_L and the environmental forces which can be represented in terms of non-dimensional flow parameters is essential for the prediction of wave forces acting on pipelines. Several investigations (Brater, E.F., and Wallace, R. (1972), Johansson, B. (1968), Keulegan, G.H., and Carpenter, L.H. (1958), Sarapkaya, T. (1976), Nath, J.H. and Yamamoto, T. (1974), Grace, R.A. and Nicinski, S.A. (1976), Wright, J.C., and Yamamoto, T. (1979), have been carried out regarding this aspect and there is a

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considerable variation in their results in respect of the coefficients.

Beckmann, H. and Thibodeaux, M.H. (1962) recommended values of $C_D = 0.5$, $C_L = 0.5$ for the case of rough pipes resting on the bed and $C_D = 0.5$ and $C_L = 0$ for a freely suspended pipe. Johansson, B. (1968) performed experiments with 3 inches (7.5 cms) diameter pipeline with Reynold's Number varying from 3×10^3 to 2×10^4 and observed that for a constant clearance varying 0 to 1.0 D. C_M varied from 4.0 to 2.8 and C_L from 6.0 to 1.8. As the clearance increased it was found that values of C_D, C_M and C_L decreased. Grace, R.A. (1971) reanalysed Wallingford wave force data (1961) on a 1-1/2 inches model pipeline just clear of the bed and concluded that C_D roughly decreases with increase in the Reynold's Number from about 3.8 at $Re = 9 \times 10^3$ to 1.8×10^4. The value of C_L was found to decrease with increase in Reynold's Number from 3.1 at $Re = 7 \times 10^3$ to 0.8 for $Re = 1.8 \times 10^4$. The inertia coefficient varied from 2.4 to 8.5 with an average value of 4.7.

Grace, R.A. (1971) conducted experiments on a 3 inch dia aluminium pipe and obtained the horizontal force coefficients for $Re = 2.5 \times 10^4$ as given in table 1.

Table 1 : Horizontal Force Coefficients
Grace R.A. (1971)

e/D	C_M	C_D
0.042	3.50	2.53
0.083	3.54	2.73
0.167	1.81	3.61
0.292	1.17	3.17

The values of the coefficients were obtained using the data of peak horizontal force and the phase of the peak force.

Several studies on submarine pipelines are reported in literature wherein the viscous effects are negligible and the forces are predominantly inertial (Ref: Nath, J.H. and Yamamoto, T., (1974)). Recently Wright, J.C. and Yamamoto, T. (1979) have reported the results of their study on wave forces on a horizontal cylinder 12 inches dia subjected to regular waves. The variation of force coefficients of inertia, drag and lift with respect to relative clearance (e/D) have been presented.

EXPERIMENTAL SET UP - PRESENT STUDY

Experiments were conducted in a 29 m long x 0.9 m deep x 0.9 m wide wave flume to determine the wave forces acting on a 5 cm dia plexiglass pipe positioned at different clearances from the simulated ocean floor. The pipe was subjected to regular waves produced by a plunger type wave generator with a parabolic section. The wave period ranged from 1.0 to 2.0 secs and the wave height from 5.0 cms to 16.0 cm in a water depth of 40 cm. Force transducers working on strain gauge principle were encased in the model pipeline on cantilever beams which were supported at the sides of the flume on roller bearings. Proper care was taken to water proof the ends of the pipe. The cantilever beam and the associated strain gauge bridge was used to measure the horizontal and vertical forces. The test module used is similar to the one used by Garrison et al (1975). Suitable arrangements were made for positioning the pipeline at different clearances from the bed of the flume.

The outputs from the two force transducers are fed into a 3 channel carrier frequency amplifier the outputs of which are fed to two channels of Kempf and Remmers three-channel strip chart recorder. A resistance type wave probe is mounted in alignment with the central line of the model to record the time histories of the water surface elevation. The leads from the wave probe are connected to a wheatstone bridge the output of which is fed into the third channel of the recorder.

The model pipeline was kept at spacings of 3 cms, 5 cms and 7.5 cms from the bed of the flume and subjected to the action of regular waves. Fig. 1 shows the definition sketch of the model pipeline subjected to regular waves. The pipeline was immersed atleast five cylinder diameters below the free surface to avoid any free surface effect on the measured forces.

ANALYSIS

Consider a horizontal pipeline of diameter D at a spacing of e from the sea floor subjected to the action of a regular progressive wave train of wave height H in water of depth d as shown in Fig. 1. The

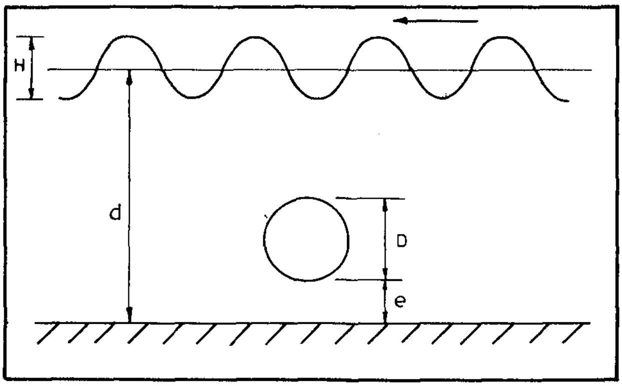

FIG. 1 DEFINITION SKETCH

maximum horizontal or vertical component of force per unit length acting on the pipeline can be expressed as a function of the following physical parameters.

$$\frac{F_{x(max)}}{\ell} \text{ or } \frac{F_{y(max)}}{\ell} = f\,(\nu, g, D, u_{max}, e, b, T \text{ or } L) \qquad (1)$$

in which F_{max} = maximum force, ℓ = length of cylinder, D = cylinder diameter, g = acceleration due to gravity, T = wave period, L = wave length, e = clearance of bottom of pipe from sea floor, b = depth of submergence of the pipe centre line below the still water level, and ν = fluid viscosity.

Expressing Eq. (1) in non-dimensional form one gets, in the horizontal direction

$$\frac{F_{x(max)}}{\frac{\rho}{2}\, D\ell\, u_{max}^2} = f(e/D,\ D/L,\ u_{max}T/D,\ u_{max}D/\nu,\ \frac{u_{max}}{\sqrt{g(d-b)}}) \qquad (2)$$

as drag form or

$$\frac{F_{x(max)}}{\rho(\frac{\pi D^2 \ell}{4})\ 2\pi\frac{u_{max}}{T}} = f(e/D,\ D/L,\ u_{max}T/D,\ u_{max}D/\nu,\ \frac{u_{max}}{\sqrt{g(d-b)}}) \qquad (3)$$

as an inertia form.

For a cylinder far away from the free surface as is the case studied here, the effect of free surface can be neglected, in which case the Froude Number $u_{max}/\sqrt{g(d-b)}$ can be ignored in the equations (2) and (3). For $D/L > 0.2$ the diffraction effects become dominant (Ref: Hogben et al (1977) and for $D/L < 0.2$ Morison Equation is applicable. In the case considered here D/L is less than 0.2 and the influence of D/L in this range may be neglected. With these reasonings equation 2 and 3 can simply be written as

$$\frac{F_{x(max)}}{\frac{\rho}{2}\, u_{max}^2 (D\ell)} \text{ or } \frac{F_{x(max)}}{\rho(\frac{\pi D^2 \ell}{4})2\pi\frac{u_{max}}{T}} = f(e/D,\ u_{max}T/D,\ u_{max}D/\nu) \qquad (4)$$

DETERMINATION OF HYDRODYNAMIC COEFFICIENTS C_D and C_M

The analysis of the experimental data is based on the wave force trace and wave profile trace obtained at the central line of the pipe for different clearances of the pipeline from the simulated sea floor. The drag and the horizontal inertia coefficient are obtained from the horizontal force trace while the lift and vertical inertia coefficients are computed using the vertical force profile. The coefficients are assumed to be constant over a wave period. The coefficients C_D and C_M

are obtained based on the peak force and the phase at which the peak force occurs. If F_T is the total force per unit length of the pipeline, then using Morison's formula

$$F_T = F_D + F_I$$

in which

$$F_D = \tfrac{1}{2} C_D \, \rho D \, u|u| \qquad (5)$$

and

$$F_I = C_M \, \rho \frac{\pi}{4} \, D^2 \dot{u} \qquad (6)$$

in which D = pipe diameter, ρ = mass density of water; u = horizontal particle velocity at the centraline of the pipe; and $\dot{u}$ = corresponding horizontal water particle acceleration. Using Airy's theory it can be shown that the maximum total force on the pipe is

$$\frac{F_{max}}{\frac{\rho}{2} u_{max}^2 \, (D\ell)} = C_D \left(1 + \frac{C_M}{C_D} \frac{\pi^2}{2} \frac{1}{K^2}\right) \qquad (7)$$

where K = Keulegan-Carpenter number = $u_{max}T/D$. The phase at which the maximum force occurs is given by

$$\text{Sin } \theta = \frac{C_M}{C_D} \frac{\pi^2}{2} \frac{1}{K} \qquad (8)$$

Using measured values of F_{max} and θ from the force trace, C_D and C_M can be computed using Equations 7 and 8.

RESULTS

Experimental runs yielded Reynolds Number in the range 5 x 10^3 to 1.7 x 10^4 and Keulegan-Carpenter number in the range 1 to 9.

Typical plots showing the variation of C_D and C_M with the wave Reynold's Number $u_{max}D/\nu$ are shown in Figs. 2 and 3, for a relative clearance of e/D = 1.0. The least square fit of the data is also shown in the figures. Similar plots were obtained for relative clearances 0.60 and 1.50. The lines of least square fit for the three clearances tested are shown in Figs. 4 and 5, for C_D and C_M respectively. The results indicate that within the Reynold's number range of data, C_D tends to decrease with increasing Reynold's number. Similar results were obtained by Brater et al (1972) and Grace, R.A. (1971) on analysing Wallingford's (1962) data. It is also seen that for a given Reynold's number the value of C_D decreases with increasing clearance. C_D varies from 4.3 to 0.8 for e/D varying from 0.6 to 1.5.

The variation of C_D with Keulegan-Carpenter Number is shown in Fig. 6 for the e/D ratios tested. Only the lines of the best fit are shown in this figure to simplify the presentation of the data. Within the range of Keulegan-Carpenter Numbers tested (2 to 9) it is observed that C_D decreases with increase in Keulegen-Carpenter Number. Similar results were reported by Grace and Nicinski (1976), who plotted the

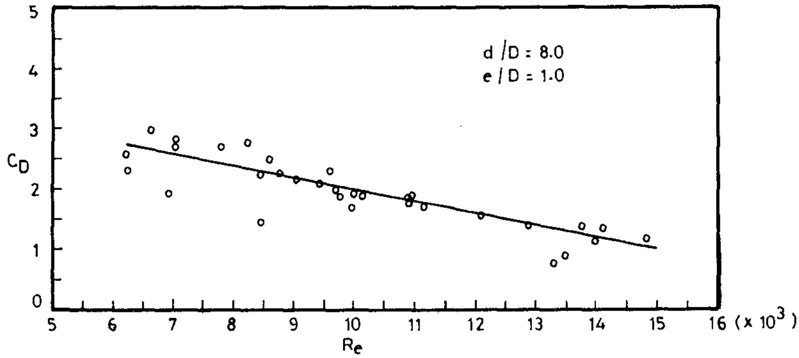

FIG. 2 VARIATION OF C_D WITH REYNOLD'S NUMBER

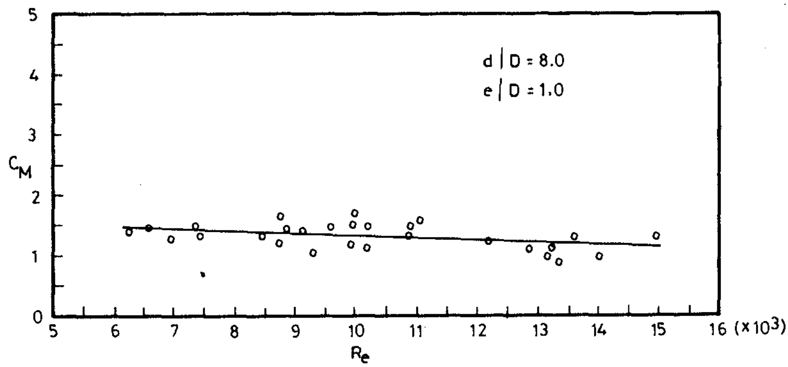

FIG. 3 VARIATION OF C_M WITH REYNOLD'S NUMBER

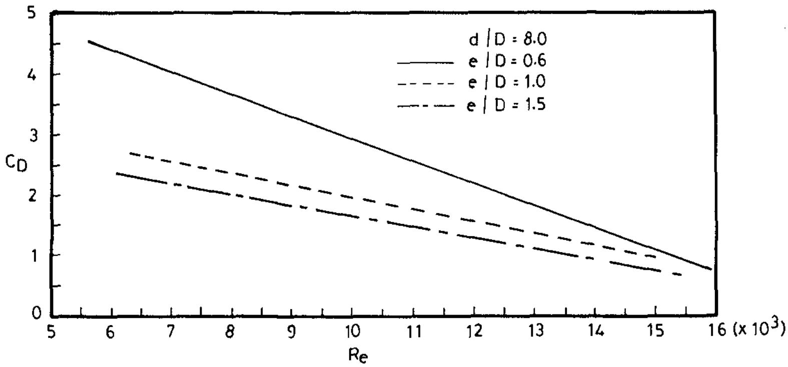

FIG. 4 DRAG COEFFICIENT Vs REYNOLD'S NUMBER FOR VARIOUS CLEARANCES

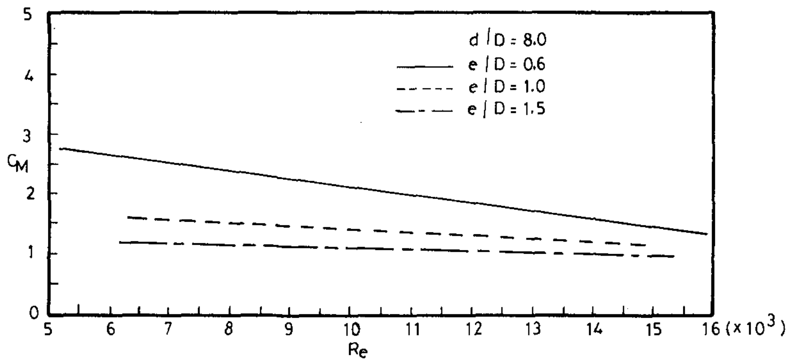

FIG. 5 INERTIA COEFFICIENT Vs REYNOLD'S NUMBER FOR VARIOUS CLEARANCES

values of C_D against relative distance of water particle travel. This trend may be due to the interaction between two boundaries (plane bottom boundary and cylinder itself) and the generation and behaviour of eddies. High Drag Coefficients of the order of 3.75 are obtained at Keulegan-Carpenter Number around 3.0 for e/D = 0.6. For e/D > 1.0 the variation in the value of C_D with e/D tends to become small. This is to be expected since far away from the boundary the effect of boundary will diminish and the C_D values would approach those found for e/D = ∞ as pointed out by Sarapkaya, T. (1976).

For a relative clearance of e/D = 0.6, C_M is found to decrease from 2.7 at Re = 5 x 10^3 to 1.5 at Re = 1.6 x 10^4. For the other two increasing clearances C_M values are not very sensitive to variation in Reynold's number. It is also inferred that C_M decreases with increase in clearance for the range of Reynold's number tested.

The variation of Inertia Coefficient with Keulegan-Carpenter number is shown in Fig. 7 for the three clearances. It is clearly seen from these plots that the inertia coefficient decreases with increase in the clearance. Within the Keulegan-Carpenter number range of 2 to 9 the variation of C_M is insignificant. For e/D > 1.0 the variation of C_M with e/D becomes small. It is also inferred that C_M is dominant at smaller Keulegan-Carpenter number values when the relative clearance is less.

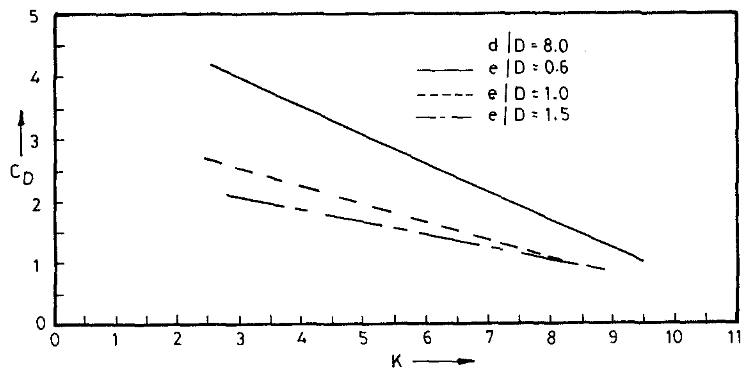

FIG. 6 DRAG COEFFICIENT Vs KEULEGAN-CARPENTER NUMBER FOR VARIOUS CLEARANCES

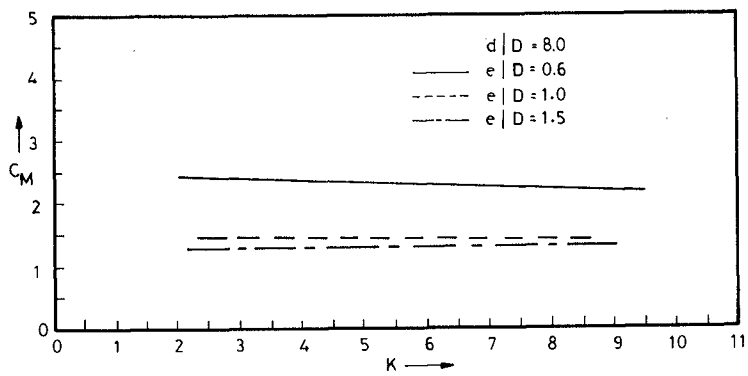

FIG. 7 INERTIA COEFFICIENT Vs KEULEGAN-CARPENTER NUMBER FOR VARIOUS CLEARANCES

CONCLUSIONS

The analysis of wave forces on pipelines at different clearances from the simulated ocean floor has shown that the hydrodynamic coefficients C_D and C_M computed from measurement of horizontal force are functions of relative clearance, Reynold's number and Keulegan-Carpenter number. The drag coefficient is found to decrease with the Reynold's number while the inertia coefficient is fairly constant over the Reynold's Number range (5×10^3 to 1.7×10^4).

As the Keulegan-Carpenter number increases it is found that the C_D value decreases. However, the variation of C_M with the Keulegan-Carpenter number is insignificant in the range tested. The values of both C_D and C_M are found to decrease with increase in clearance. The analysis of vertical force coefficients namely C_{MV} and C_L will be reported in a future paper.

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REFERENCES

1. Anonymous (1961), "Model Investigation of the Wave Forces on Submarine Pipelines", Hydraulic Research Station, Wallingford, England, Report Ex 158, July.
2. Beckmann, H. and M.H. Thibodeuax (1962), "Wave Force Coefficients for Offshore Pipelines", Journal of Waterways, Harbours and Coastal Division, ASCE, Vol. 88, No. WW2, Part 1, May.
3. Brater, E.F. and R. Wallace (1972), "Wave Forces on Submerged Pipelines", Thirteenth Coastal Engg. Conf., Vancouver, B.C., Canada, July 10-14, Vol. III, pp 1703-1721.
4. Garrison, C.J., M. ASCE, F.H. Gehram and B.T. Perkinson (1975), "Wave Forces on Bottom Mounted Large Diameter Cylinder", Journal of Waterways, Harbours and Coastal Engg. Div., ASCE, Vol. 101, No. WW4, Nov. pp 343-356.
5. Grace, R.A., (1971), "The Effects of Clearance and Orientation on Wave Induced Forces on Pipelines: Results of Lab Experiments", Univ. of Hawaii, Look Lab of Oceanographic Engineering, Technical Report No. 15, April.
6. Grace, R.A. and S.A. Nicinski (1976), "Wave Force Coefficients from Pipelines Research in the Ocean", Offshore Technology Conf., Vol. III, May 3-6, Houston, Texas, paper No. OTC 2676.
7. Hogben, N., B.L. Miller, J.W. Searle and J. Ward (1977), "Estimation of Fluid Loading on Offshore Structures", Proc. Inst. Civ. Engrs., Part 2, 63 Sept., 515-562.
8. Johansson, B., (1968), "Wave Forces on a Pipe at the Bottom of the Sea", Royal Institute of Tech., Stockholm, Sweden, Division of Hydraulics, Bulletin, No. 71.
9. Keulegan, G.H. and L.H. Carpenter (1958), "Forces on Cylinders and Plates in an oscillating Fluid", Journal of Research of the National Bureau of Standards, Vol. 69, No. 5, May, pp 423-40.
10. Nath, J.H. and T. Yamamoto (1974), "Forces from Fluid Flow Around Objects", Proc. Fourteenth ASCE Conf. on Coastal Engg., Copenhagen, Denmark, pp 1808-27.
11. Sarapkaya, T. (1976), "Forces on Cylinders near a Plane Boundary in a Sinusoidally oscillating Fluid", Journal of Fluid Engg., Trans. ASME, Vol. 98, No. 3, pp. 499-505.
12. Wright, J.C., A.M. ASCE and T. Yamamota (1979), "Wave Forces on Cylinders near Plane Boundary", Journal of the Waterway, Port, Coastal and Ocean Division, ASCE, Vol. 101, No. WW1, Feb., pp 1-13.