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WILHELM DURSTHOFF, BOLESŁAW MAZURKIEWICZ, FRANK PRESER
Hannower, Gdańsk

Large-scale tests on smooth and rough cylinders placed horizontally on a plane bottom

1. Introduction

The reason for the current importance of research on submerged pipeline elements placed on the bottom with special regard to the wave-induced forces does not have to be outlined in this report, since it is already common knowledge. A large number of publications exist on this topic covering its general substance as well as detailed problems. Since the proximity of the seabed assumed as a plane boundary to the cylindrical body provides a considerable variety of influencing parameters, a reasonable and well-defined number of the most important factors affecting the pipelines has to be chosen on the basis of experience.

The Morison equation (MOJS) has become the most common method of estimating wave forces on pipelines; for many reasons this has, unfortunately, determined the direction of research in many respects, and still does so, but this will be changed when the realistic environmental conditions of a natural bottom are included in scientific work.

However, in order to prove the significance of the MOJS equation, only large-scale tests, i.e. tests with prototype sizes, are the appropriate tool for surveying the limited application of the equation. Results of large-scale tests of this kind made in the Large Wave Channel in Hannover are presented here and critically discussed. Further reference can be made on DURSTHOFF [4].

Nomenclature

C_D – drag coefficient
C_M – inertia coefficient
C_L – lift coefficient
D – cylinder diameter
d – water depth
e – clearance of the cylinder
F_D – drag force
F_M – inertia force
F_L – lift force
$F_{x,y}$ – resultant force

Dr Ing. W. DURSTHOFF, Dipl., Ing. F. PRESER, Franzius-Institut for Hydraulics and Coastal Engineering, Hannover University, Fed. Rep. of Germany; Prof. zw. dr hab. inż. B. MAZURKIEWICZ Technical University, Gdańsk, ul. Majakowskiego 11.

H – wave height
k – mean height of roughness element
k' – negative fraction of the lift force cycle
T – wave period
u, v – horizontal, vertical velocity component
$\dot{u}, \dot{v}$ – horizontal, vertical acceleration
ρ – mass density of fluid
Φ – phase shift of maximum lift forces with respect to wave cycle
θ – $2\pi t/T$

2. Test setup

All the experiments mentioned in this paper were carried out in the Large Wave Channel in Hannover, which is 320 m long, 5 m wide, and 7 m deep. More detail about this channel has been published by GRÜNE [5]. Measurements of the wave-induced forces and pressures were performed with a 5 m-long circular cylinder of 800 mm diameter placed horizontally near or on the bottom of the channel. At the cross-section in the middle of the cylinder, 36 pressure transducers were mounted around the cylinder, and were connected to the water at the cylinder surface by two small holes of 1.2 mm diameter bored into the hull for each sensor.

The cylinder was fixed at the lateral walls of the channel by means of an axis at each of the two sides with a squared diameter. The axis-part was protected by circular dummies during tests. Strain gauges were attached to these axes in order to measure the horizontal and vertical force component as well.

Tests were made with a smooth (polished) surface ($k/D=0$) and a hydraulically rough cylinder surface ($k/D=0.011$). The roughness of the bottom was $k=0.8$ mm and $k=60$ mm respectively; the relative clearance e/D actually varied between 0 and 0.25, but with gradations between 0 and 0.0875. All the analogous signals of the 55 channels for simultaneously recording pressure, force, and wave height were digitalized by a sampling rate of 20 Hz.

3. Results and interpretation

3.1. Pressure distribution

Fig. 1 shows as example the wave-phase dependent pressure distribution around the cylinder and the resultant force vector with 10 variable wave-phases with equal time steps along a wave period. Measured pressure data inserted within the circly (cylinder surface) represent negative values and, conversely, outside the circly they correspond to positive values. The resultant forces were calculated by integrating the pressure area which was deduced from the measured instantaneous pressure values.

The remarkable pressure distribution at the bottom of the cylinder indicates a high velocity of flow between channel bottom and cylinder – increasing with decreasing gap width, but highly dependent on the relative gab. Due to horizontal water mass transport, a water particle jam develops in front of the cylinder when the orbital velocity exceeds a certain value that is also dependent on the gap, i.e. governed by viscosity and turbulence.

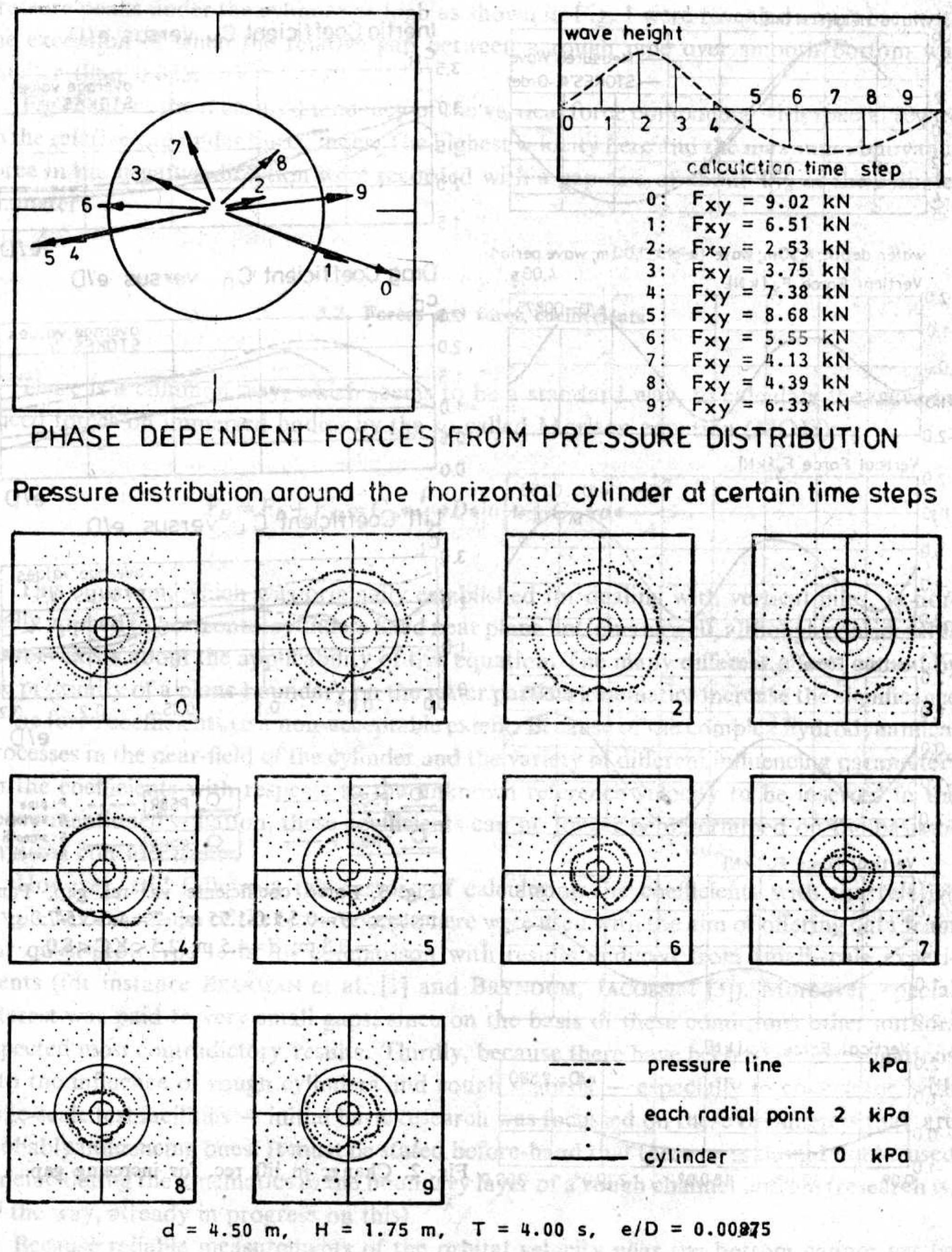
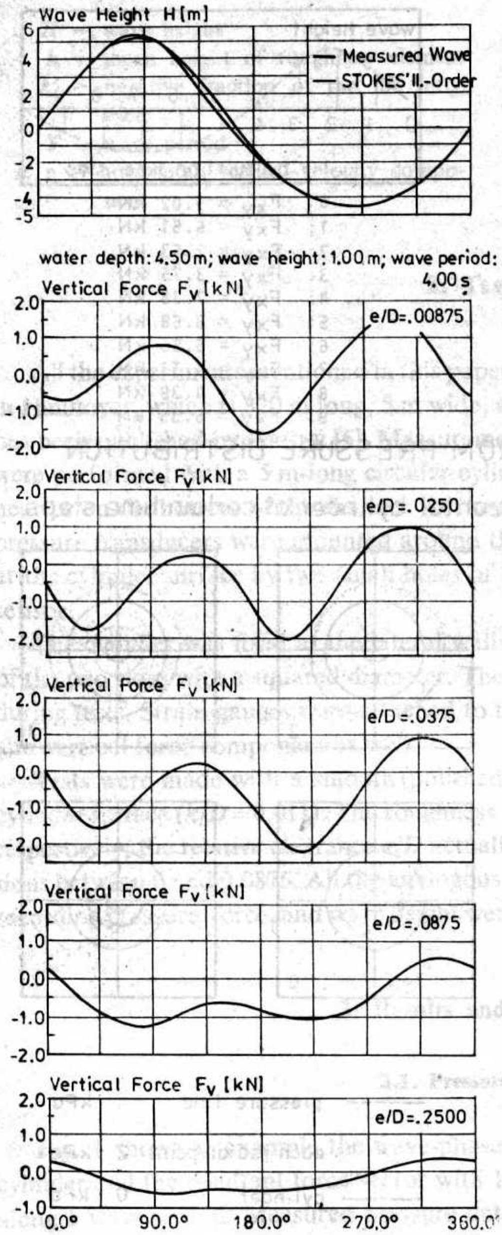


Fig. 1. Wave-phase dependent pressure distribution around the cylinder and resultant force vectors $d=4.50$ m, $H=1.75$ m, $T=4.00$ s, $e/D=0.00875$



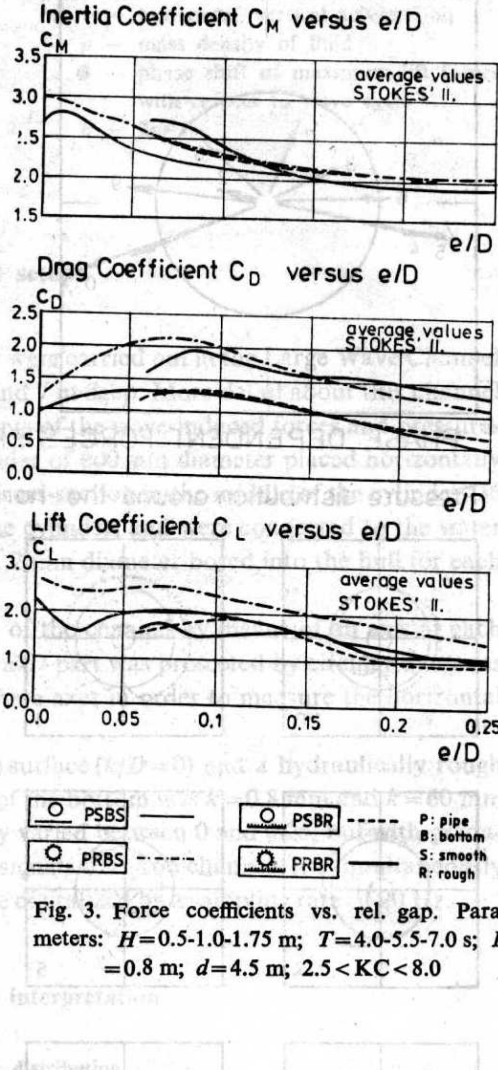


Fig. 3. Force coefficients vs. rel. gap. Parameters: $H=0.5\text{-}1.0\text{-}1.75$ m; $T=4.0\text{-}5.5\text{-}7.0$ s; $D=0.8$ m; $d=4.5$ m; $2.5<KC<8.0$

Fig. 2. Change in lift rec. for incresing gap.

This choking effect then, for a short time, causes a higher velocity at the top of the testing body, resulting in a positive buoyancy force. The pressure distribution at the top increases again in association with decreasing velocities and this leads to negative buoyancy forces at some time or other.

The roughness of the cylinder and the roughness at the bottom reduce the pressure gradient between the top and the bottom of the cylinder, as tests proved. Consequently, no pressure peaks under the cylinder as high as shown in Fig. 1 were revealed any more, with the exception of when the relative gap between a rough pipe over smooth bottom was smaller than 0.025.

Fig. 2 shows the measured tendency of the vertical force component with special regard to the relative gap under the cylinder. The highest velocity here and the maximum buoyancy force in the negative direction were recorded with a gap size of about 4% of the cylinder diameter.

3.2. Forces and force coeffiecients

There is a common way, which seems to be a standard way, to calculate the wave-induced forces on immersed bodies by the so-called Morison equation (MOJS):

$$F_H = F_D + F_M = C_D * \frac{\rho}{2} * D * |u| \, u + C_M * \rho * \frac{\pi D^2}{4} * \dot{u} . \quad (1)$$

This equation, which was originally established for dealing with vertical piles, is normally applied to horizontal cylinders fixed near plane bottoms as well, although considerable doubts exists about the applicability of this equation. The many different effects caused by the proximity of a plane boundary on the water particle kinematics increase the significance of the force coefficients to a non-acceptable extent. Because of the complex hydrodynamical processes in the near-field of the cylinder and the variety of different influencing parameters on the coefficients with respects to the unknown reference velocity to be inserted in the above-mentioned equation, these coefficients can no longer be determined on the basis of physical considerations.

However, still following the custom of calculating the coefficients with the relative simple MOJS, results of the tests reported here were used with the aim of offering data from our quasi-prototype tests for comparison with results deduced from small-scale experiments (for instance Bearman et al. [1] and Bryndum, Jacobsen [3]). Moreover, special interest was paid to very small gaps, since on the basis of these conditions other authors expected most contradictory results. Thirdly, because there have been fewer investigations into the influence of rough cylinders and rough seabeds — especially in connection with large-scale test facilities — initial basic research was focussed on these parameters that are probably influencing ones. It must be stated before-hand that these tests should not be used for elucidating the kinematics in the boundary layer of a rough channel bottom (research is, by the way, already in progress on this).

Because reliable measurements of the orbital velocity near the bottom cannot yet be made in large-scale testing facilities, the velocity and the acceleration were calculated with the help of the linear wave theory and Stokes' 2nd and 3rd order theories. After thorough estimation of the results, one can apply the 2nd order theory of Stokes. In this way, C_D and C_M were estimated by using the measured force components deduced from strain gauge measurements and pressure recording according to the FFT-method.

Only the horizontal orbital velocity was taken into account when calculating the vertical force component:

$$F_L = C_L * \frac{\rho}{2} * D * u^2. \quad (2)$$

Fig. 3 shows averaged C_D, C_M, and C_L in relation to the relative gap width. The roughness heights have been considered.

Inertia coefficients. A general decrease in the coefficients with an increasing gap can be seen when the gap is less than about 15% of the diameter of the cylinder. C_M is then 2.0. Contrary to the statements of some authors, the inertia coefficients do not rise to high values for the smallest gaps, and they are rather lower if the cylinder touches the bottom.

Drag coefficients. From the maximum C_D-values at about $e/D = 0.075$ (e = gap of 7.5% of the diameter) the clearance-dependent drag coefficient decreases for $e/D < 0.075$ and $e/D > 0.075$. The difference in the C_D-values of 0.5 to 1.0 for a smooth cylinder on the one hand, and for a rough cylinder on the other hand (without any influence of the roughness of the seabed), is unexpected. It will therefore be investigated in detail in the future.

Lift coefficients. The lift coefficients reach their highest values when the cylinder is extremely near the bottom or at it. An increasing gap results in a slight reduction of C_L to about 1.0. In order to determine the C_L-values according to Equation (2), only the positive force components measured were taken into account (see next paragraph).

4. Modifed Morison-equation

As Fig. 4 demonstrates, Equation (2) can hardly be used to determine the time-dependent vertical forces; the maximum force component was recorded with a phase shift up to 0.25*T in relation to the theoretical horizontal velocity component of the regular wave, which corresponds to the second peak of the spectral density distribution containing the highest energy. These results generally conform to those of other researchers (for instance BEARMAN et al. [1]). However, diverging data were obtained from the correlation of maximum vertical force components and the absolute values of the horizontal orbital velocities. The

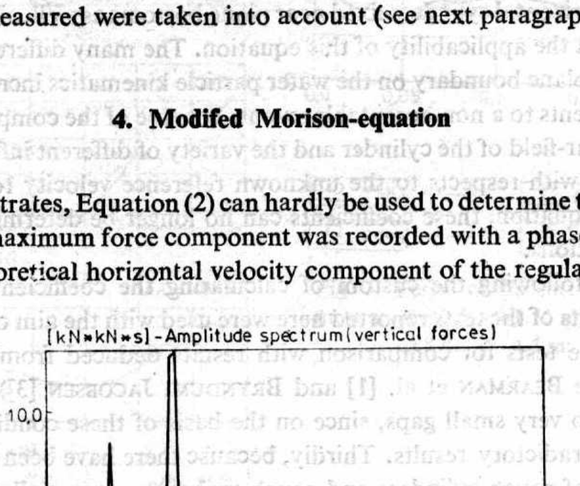


Fig. 4. Spectrum of lift force

tests in the Large Wave Channel also provided force peaks when the horizontal velocity components were not equal to zero. A modified MOJS-equation has therefore to pay attention to negative and positive vertical force components as well as to the measured phase shift. The following equation meets these requirements as follows:

$$F_V = F_{D_v} + F_{M_v} + F_L = C_{D_v} * \frac{\rho}{2} * D * |v| \, v + C_{M_v} * \rho * \frac{\pi D^2}{4} * \dot{v} + C_L * \frac{\rho}{2} * D * u_{max}^2 \left[\cos^2(\Theta - \Phi) - k'\right]. \quad (3)$$

Good agreement over a wide range of tested parameters is demonstrated by Fig. 5 as an example. Appending a trigonometric term to the simple MOJS-equation has also been tried by BOWIE [2] and KAO [6] with more or less success; the above equation has, however, a less complicated form, and is applicable for all large scale tests performed under smooth and rough conditions in the Large Wave Channel.

5. Final remarks

All tests results can, of course, be represented by a modified MOJS-equation with determined force coefficients after formal mathematical processing of the data. But this method of calculating the wave-induced forces on horizontal cylinders is rather unsatisfsfactory. This is, because the coefficients are dependent on a variety of uncoupled processes

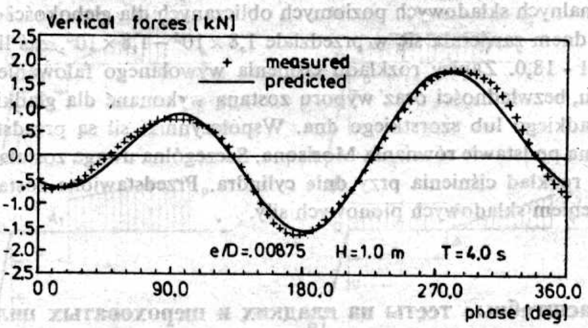


Fig. 5. Lift force acc. to Eq. (3)

and many influencing factors. One more shortcoming of this equation is, in fact, the necessary application of wave theories. This leads to uncertainties and, in many cases, doubtful results.

In order to improve the MOJS-equation, further research should, therefore, be focussed on measuring the real velocity components under quasi-prototype conditions without disturbing the flow field.

The question of whether the MOJS-equation provides the best method for dimensioning purposes with respect to pipelines was not a subject under discussion here. This problem will arise when more influencing parameters, such as erodible bottom, vibration of the pipeline etc. have to be taken into account.

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Badania w dużej skali gładkich i szorstkich cylindrów umieszczonych poziomo na płaskim dnie

Streszczenie

Przedstawiony artykuł dotyczy niemal wzorcowych badań przeprowadzonych w Franzius-Institut for Hydraulics and Coastal Engineering oraz w Wielkim Kanale Falowym w Hannowerze. Liczby Reynoldsa dla maksymalnych składowych poziomych obliczanych dla głębokości wody będącej połową średnicy cylindra nad dnem zawierała się w przedziale $1{,}8\times10^5-1{,}8\times10^6$, zaś liczba Keulegana-Carpentera w zakresie 1,1 - 18,0. Zapisy rozkładu ciśnienia wywołanego falowaniem oraz oszacowania współczynników oporu, bezwładności oraz wyporu zostaną wykonane dla gładkiego oraz szorstkiego cylindra w pobliżu gładkiego lub szorstkiego dna. Współczynniki sił są przedstawione jako funkcja względnego prześwitu na podstawie równania Morisona. Szczególna uwaga została zwrócona na składową pionową siły oraz rozkład ciśnienia przy dnie cylindra. Przedstawione zostało również równanie Morisona z uwzględnieniem składowych pionowych siły.

Крупномасштабные тесты на гладких и шероховатых цилиндрах, расположенных горизонтально на плоском дне

Содержание

Работа посвящена почти эталонным тестам, проведенным в Институте Франциуса гидравлики и береговых сооружений, а также в Большом волновом канале в Ганновере. Число Рейнольдса для максимальных горизонтальных составляющих, рассчитанных при глубине воды, равной половине диаметра цилиндра над дном, находилось в пределах $1{,}8\times10^5\div1{,}8\times10^6$, а число Кейлегана-Карпентера в пределах $1{,}1\div18{,}0$. Записи распределения давления вызванного волнением, а также оценка коэффициентов сопротивления, инерции и подпора будут производиться для гладкого и шероховатого цилиндра вблизи гладкого или шероховатого дна. Коэффициенты сил представлены как функция относительного просвета на основе уравнения Морисона. Особое внимание уделено вертикальной составляющей силы и распределению давления у дна цилиндра. Представлено также уравнение Морисона с учетом вертикальных составляющих силы.