WAVE FORCES ON GROUPS OF SLENDER CYLINDERS IN COMPARISON TO AN ISOLATED CYLINDER DUE TO NON-BREAKING WAVES

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This paper presents results of large scale experiments with various cylinder groups in tandem and side by side configurations. The transverse and inline forces have been investigated in regard to the vortex shedding processes, and the influences of neighboring cylinders on the wave load of a single isolated cylinder are pointed out. Furthermore, the C_D and C_M coefficients as well as the drag force and added mass characteristics were investigated by the method of the least square fit for the cylinder groups with diverse center to center spacing.

INTRODUCTION AND MOTIVATION

Several offshore constructions are commonly built by cylinder structures in various ways. Predominantly the offshore oil industry uses structures with cylindrical shape for the design of platforms, storage systems, and transportation facilities. Furthermore, jacket constructions are used for the foundation of offshore wind power plants and piles are a basic element to build bridges, moles, and quaysides. Cylinders in different arrangements are used along quaysides to absorb wave energy within harbors and to reduce spray.

While slamming coefficients of breaking waves are decisive for the prediction of extreme loads, non-breaking wave loads are relevant for the design parameters required in fatigue limit state analysis, since wind power plants in the North Sea, for instance, are encountered by approximately 3.000.000 waves per year. Reliable wave data has to be considered for the design in order to prevent loss of human life and monetary losses in case of structure failure. In addition large areas of complex marine ecosystems depend on the stability of industrial structures to diminish contamination.

A commonly used method to calculate wave forces on a single isolated cylinder is given by the Morison-equation for non-breaking waves (Morison et al. 1950). In addition to the velocities and accelerations under the wave, two empirically estimated coefficients for the drag and inertia components are required. Several studies have focused on force measurements and the estimation

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of the Morison coefficients for single cylinders (Sarpkaya 1976 & 1986, Justesen 1989). In addition, the vortex dynamics and flow separation processes in the cylinder wake have been investigated for steady and oscillating flow (Schlichting 1982, Bearman 1986, Williamson 1996). Less extensive in comparison to single cylinders, groups of cylinders in different arrangements have been investigated in steady flow conditions as well as in oscillatory flow (Zdravkovich 1977, 1985, Sumner 2005). The same applies for the investigation of C_D and C_M values for cylinder arrangements, which were investigated by Chakrabarti (1978, 1979) and Smith and Haritos (1997). To investigate the interaction of adjacent cylinders, extensive and systematic large-scale model tests were performed in the Large Wave Flume (Sparboom et al. 2005).

Experimental Setup

All tests were conducted in the Large Wave Flume (GWK) of the Coastal Research Center (FZK) in Hanover. The channel is 310 m long, 5 m wide, 7 m deep, and the water level was kept constant 4.26 m for all tests. A slender cylinder with a diameter of 0.32 m was instrumented with strain gauges and installed like a cantilever pile (Fig. 1) on the same level with two current meters 105 m in front the wave maker. The wave kinematics and the surface elevations were recorded synchronously by nine wave gauges and two current meters as shown in the plan view in Fig. 1.

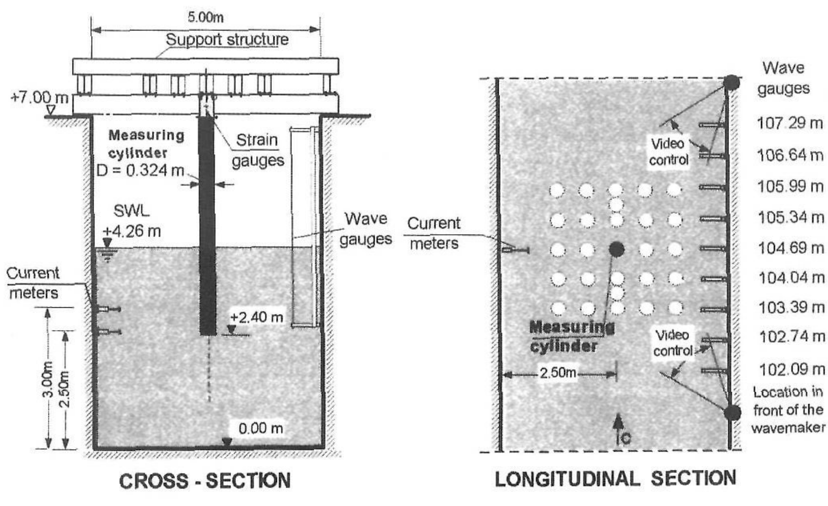

Figure 1. Cross-section and plan-view of the model set up in the Large Wave Flume (Sparboom et al. 2006)

The two current meters were installed 1.26 m and 1.76 m below the still water level and measure horizontal and vertical orbital velocity components in a vertical plane with the measuring cylinder.

Fig. 1 shows the supporting points for adjacent cylinders indicated by the white circles and the fixed position of the measuring cylinder in the middle. Next to the instrumented cylinder (Fig. 2, open circles) additional cylinders (filled circles) with the same diameter were installed at the support structure with a center to center spacing up to four times the cylinder diameter. The nine cylinder arrangements outlined in Fig. 2 were investigated out of fifteen arrangements in a total.

To investigate the influence of the neighboring cylinders, the single cylinder was first tested separately with regular waves of 4, 5, 6, 7, and 8 sec wave period and wave heights of 0.8, 1.10, and 1.4 meters. Due to the high reproducible waves in the Large Wave Flume, the same tests were conducted with tandem and side by side cylinder configurations as described above.

For further details of the experimental setup with additional cylinder arrangements and the whole wave program, please refer to Sparboom et al. (2006).

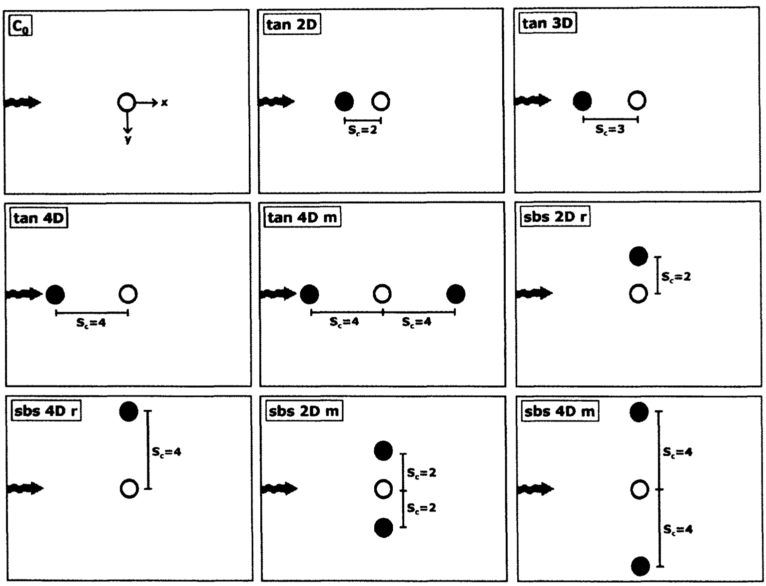

Figure 2. Single cylinder configuration (C_0), cylinder groups with tandem (tan) and side by side (sbs) arrangements and center to center spacing in cylinder diameters and position of the white indicated measuring cylinder (m=middle, r=right).

Physical processes

The following section describes observed hydrodynamic processes related to the changing wave loads of the instrumented cylinder in side by side arrangements. Fig. 3 shows the inline bending moment and the transverse moment of the reference case "single isolated cylinder" (C_0) by the dashed lines. For comparison the inline and transverse moments of two side by side cylinders with a center to center spacing of two cylinder diameters is shown by the solid lines. The time resolved subtraction of the inline wave loads of the group configuration and the single cylinder is given by the area plots. Furthermore, the water surface elevation for the wave period of 7sec is plotted.

The comparison of the inline bending moments reveals that the maximum wave load increases 25% for the group configuration. The main loading differences occur right under the wave crest during the decreasing bending moment and less intense during the back flow under the wave trough. When taking the transverse forces into account, a connection between the zero crossing of the lift force and the increased wave loads in wave direction is observed. The maximum differences of the inline bending moments occur at the zero crossing of the lift force, which is related to the vortex shedding and clearly present in all tested cylinder arrangements. However, the lift force of the two adjacent cylinders is doubled in comparison to the single cylinder, which is seen in Fig. 3 for t=2 sec under the wave crest and for t=4.5 sec.

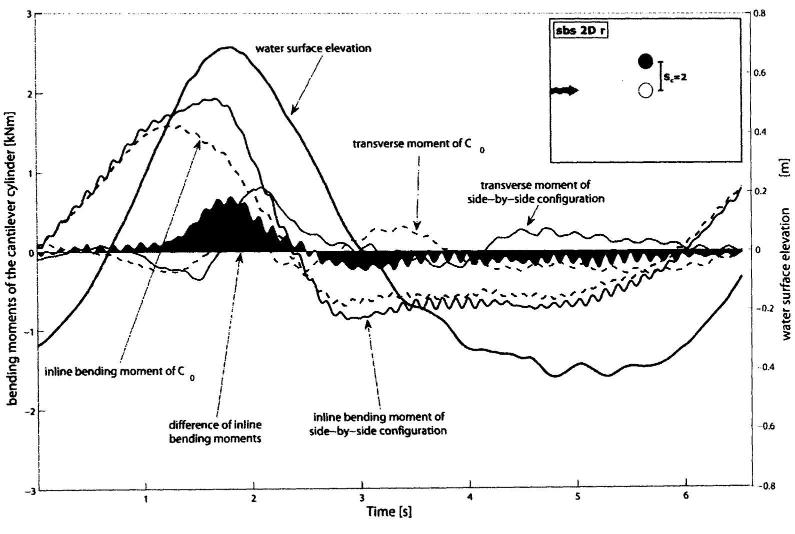

Figure 3. Comparison of inline and transverse bending moments of the single cylinder and two cylinders in a side by side arrangement with two diameters of center to center spacing for T=7 sec and H=1.10 m.

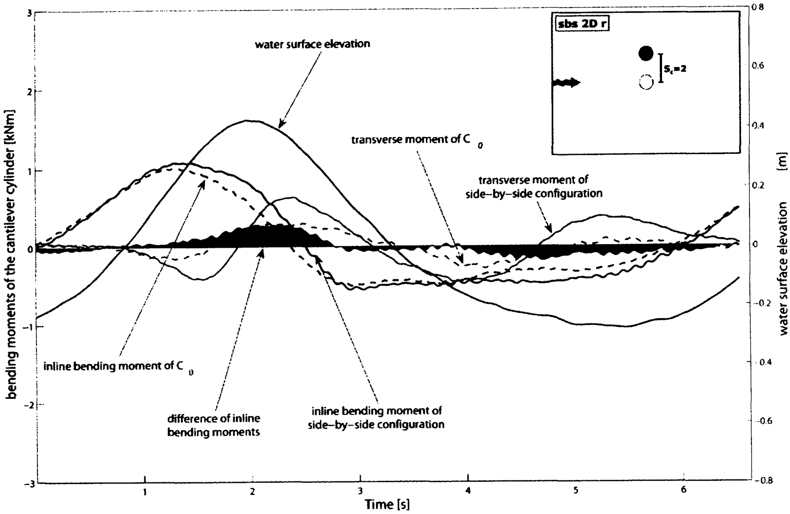

Figure 4. Comparison of inline and transverse bending moments of the single cylinder and two cylinders in a side by side arrangement with two diameters of center to center spacing for T=7 sec and H=0.80 m.

The higher lift forces result from greater velocities between the two cylinders, which enhance the development of the vortex pair, and thus its increased intensity.

In comparison to the wave height of 1.10 m shows Fig. 4, the corresponding plot for a wave height of 0.80 m and 7 sec wave period. As described above, the same interaction between the enforced vortex shedding, the lift forces, and the resulting inline bending moment is seen. However, the process has no significant effect on the maximum wave load. In this case the effect of the adjacent cylinder is rather small, due to the time shift of the maximum wave load and the vortex shedding, which is approximately 1s or 14% of the wave period after the peak value of the inline moment.

While the time shift of the 0.80 m high wave is about 1 sec the time shift of the maximum surface elevation and the maximum inline moment of the 1.10 m wave height is only 0.5 sec. The water surface and the horizontal velocity are in phase, and in both cases the vortex shedding takes place right under the wave crest. This is the point of time when the maximum horizontal velocity acts on the cylinders and shortly after induces the vortex shedding. This shows that the phase shift of the horizontal velocity and the bending moment has significant influence on the increased maximum wave loads of a cylinder arrangement. The phase shift is small for asymmetric waves or waves in the drag regime, while waves dominated by inertia forces have a larger phase shift. The first mentioned wave forms are more influenced by side by side arrangements with regard to the maximum wave loads. Beside the influence on the maximum inline moment, increased lift forces due to intensive vortex shedding and the corresponding enforcement of the inline moment was observed for all 15 tested wave forms.

No significant trends were observed for the tandem arrangements. The sheltering effects for the inline bending moments were less than 8%, in contrast to increased maximum wave loads up to 10%. However, within the standard deviation of the tests no obvious trends were estimated.

Drag and inertia coefficients

Wave forces on structures for engineering purposes are commonly calculated with the Morison equation. Due to the widely known method it is of practical interest to reproduce the observed changes of the wave loads for cylinders in group configurations with adequate Morison coefficients. The two coefficients for the drag (C_D) and inertia (C_M) components take the shape of the structure and the roughness of the surface into account as well as the modified hydrodynamic mass. Generally, phase-ignoring coefficients are estimated, which assume a constant behavior of the influence of the structure roughness on the separation points and a constant development of the hydrodynamic mass over the whole wave period. The hydrodynamic processes around a cylinder change with varying flow velocities and thus change with wave height (H) and period (T), which is often expressed by the Keulegan-Carpenter (KC) number.

$$KC = u\,T / D \tag{1}$$

with u(H,T) as maximum horizontal particle velocity within a wave period T and D as the cylinder's diameter. With increasing KC numbers the flow conditions develop from a non-separated state to different kinds and amounts of vortex shedding (Bearman 1985). The vortex shedding becomes more intensive with increasing turbulence. This process is induced in the wake of the cylinder, then reaches the shear layer near the separation point and finally develops along the boundary layer (Williamson 1996). With regard to this development the C_D coefficient changes significantly when reaching the critical flow regime.

These hydrodynamic processes become influenced by adjacent cylinders, which leads to modified vortex shedding and different wave forces on a cylinder within a cylinder group.

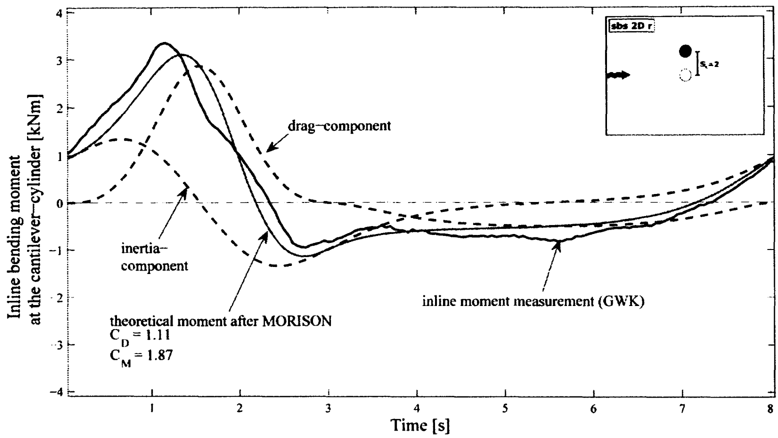

Figure 5. Theoretical inline bending moments based on Morison with C_D and C_M coefficients in comparison to the measurement for H=1.4 m and T=8 sec.

With the method of the least square fit the variation of the drag and inertia components was estimated, where N is the number of samples for a wave period:

$$\varepsilon^2 = \frac{1}{N}\sum_{t=1}^{N}(F_{Theory}(t, C_D, C_M) - F_{Experiment}(t))^2 \tag{2}$$

Higher wave theories from Stokes 5th to 9th Fenton stream function theory according to Chakrabarti (2005) were used to calculate the theoretical wave kinematics, which have been validated with the measured signals of the current meters in the wave channel. Fig. 5 shows the theoretical approximation in time and magnitude to the experimental recorded inline moment for a 1.4 m high wave with a period of 8 sec.

Figs. 6-9 show the results of the estimated C_D and C_M coefficients against KC for the 9 tested configurations. The estimated values for the reference case C_0 vary for KC < 20 from 0.7 up to 0.9, and are rather constant for KC > 20 with values around 0.9 (Fig. 6). While the C_D coefficients partially exceed the commonly used C_D value of 0.7, reveal the C_M coefficients reduced values from 1.6 up to 1.9 in contrast to the standard literature value of 2.0.

In comparison to the single cylinder, increased wave loads are clearly noticeable for the side by side arrangements with a center to center spacing of two diameters.

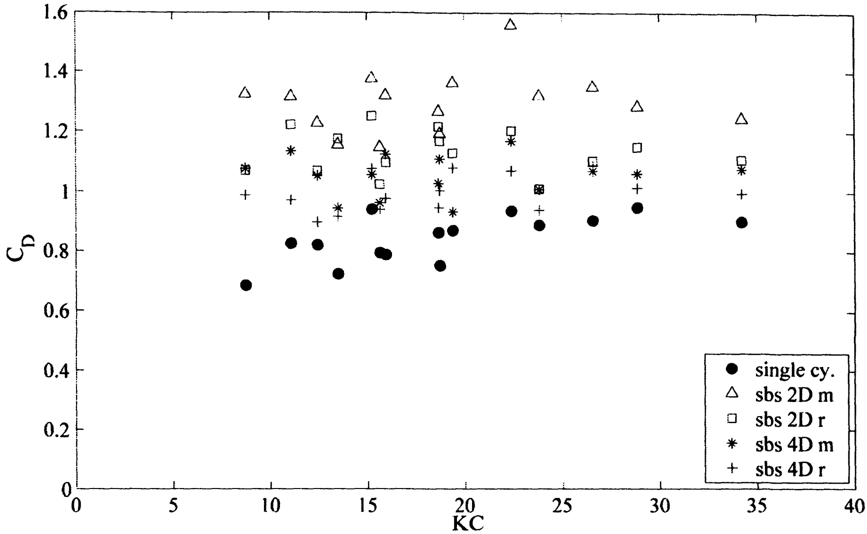

Figure 6. C_D coefficients for side-by-side (sbs) arrangements with 2 and 4 diameter center to center spacing

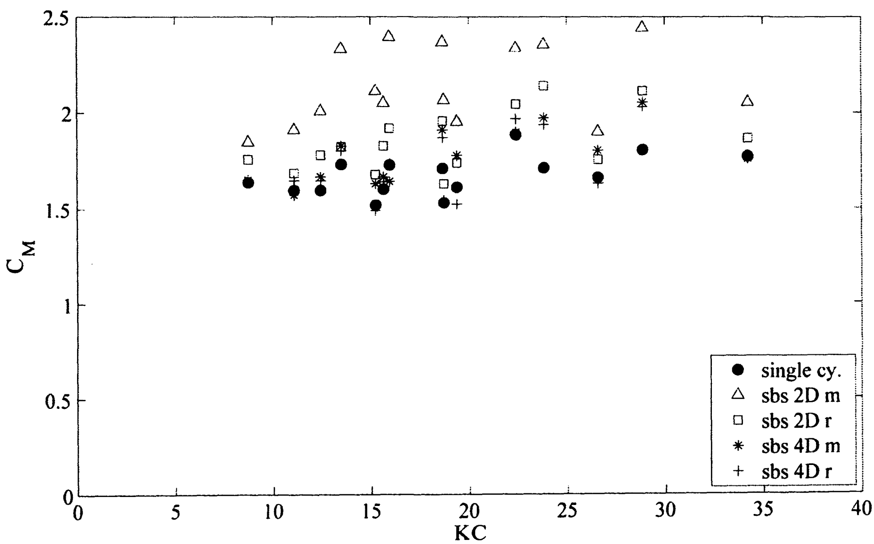

Figure 7. C_M coefficients for side-by-side (sbs) arrangements with 2 and 4 diameter center to center spacing

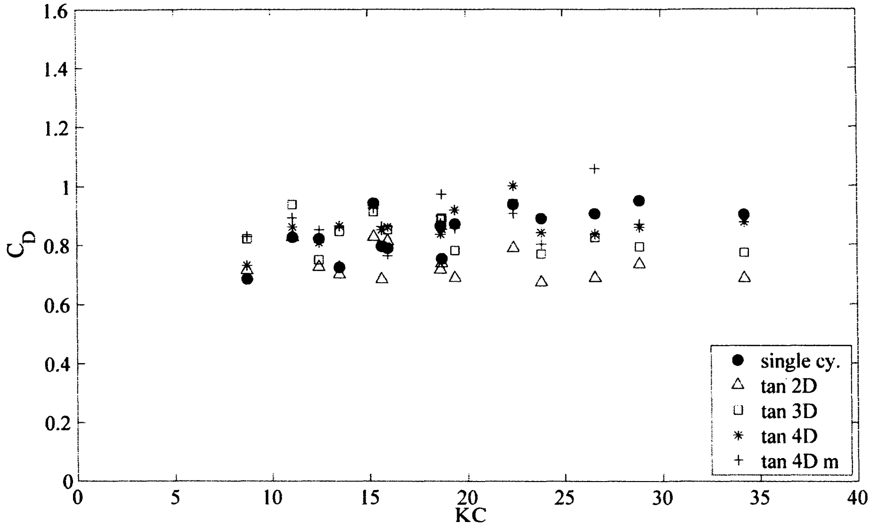

Figure 8. C_D coefficients for tandem (tan) arrangements with 2, 3 and 4 diameter center to center spacing

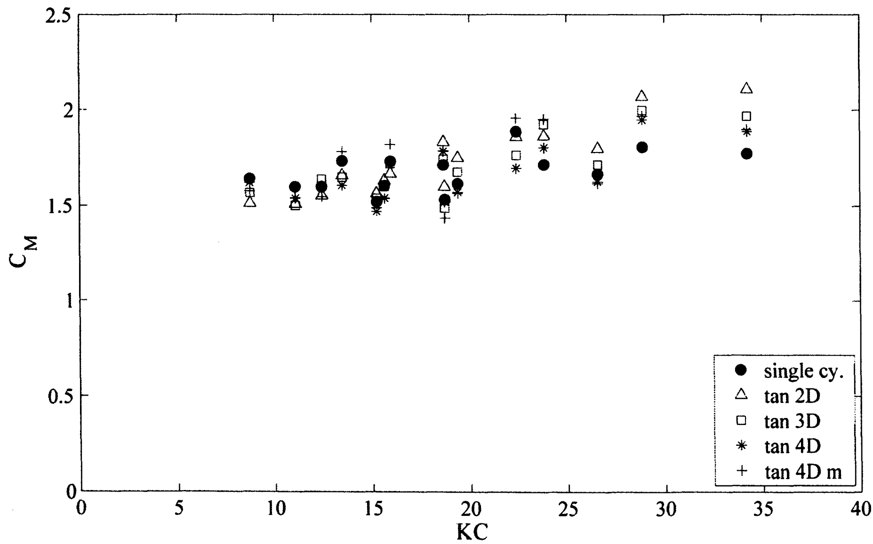

Figure 9. C_M coefficients for tandem (tan) arrangements with 2, 3 and 4 diameter center to center spacing

The C_D values for the "sbs 2D m" configuration (Figs. 2 and 6) range from 1.15 to 1.55 and exceed the average C_0 coefficient by 60% in average. Similar trends are visible for the C_M values, which exceed the C_0 coefficients roughly by 35-45% for $13 < KC < 25$.

Furthermore, a perceptible difference between the "sbs 2D m" and the "sbs 2D r" arrangement can be seen, which are based on the same cylinder spacing whereas the last mentioned configuration represents a cylinder at the end of a row with only one adjacent pile (Fig. 2). Likewise, the C_D values also exceed the C_0 coefficients. However, they are positioned under the values of the "sbs 2D m" configuration. The coefficients increase approximately 45% with respect to C_0 and the decrease of the C_D coefficient in regard to "sbs 2D m" varies from 0.1 to 0.2. In contrast to the C_D coefficients the C_M values for the "sbs 2D r" configuration reveal a rather small intensive magnification with 10% in average. However, all values are higher than the coefficients of the C_0 reference configuration (Fig. 2) and underline a small but distinctive influence by the neighboring cylinder.

For the cylinder arrangements with a center to center spacing of four diameters (Fig. 2, "sbs 4D m", "sbs 4D r") increased wave loads are still present. Even though the differences for those 2 arrangements are small, it can be seen that the values of the configuration with 2 neighboring cylinders are arranged above the values of the configuration with one neighboring cylinder. They exceed the C_D values of C_0 by 20-25% ("sbs 4D m") and by 10-15% ("sbs 4D r"). No significant trends were observed for the C_M coefficients in 4D spacing with regard to the scatter of the configurations (Fig. 7), which are close to the C_M values of the single isolated cylinder.

For the tandem arrangements only marginal trends can be seen. There is no definite tendency of the C_D and C_M values (Figs. 8 and 9) for the four investigated configurations (Fig. 2) in the range of $KC < 23$. The values show no sorted pattern in regard to the configurations like the C_D values for the side by side configurations did. However, for KC values larger than approximately 23 the C_D values for the tandem arrangements with 2D and 3D center to center spacing show a definite reduction of 25% and 10% in average, respectively.

CONCLUDING REMARKS AND OUTLOOK

The large scale experiments in the wave flume of the FZK provide facilities for investigations of hydrodynamic processes at relatively high Keulegan-Carpenter and Reynold numbers. With the analysis of synchronously recorded transverse and inline bending moments, horizontal and vertical wave kinematics, and the water surface elevation, side by side and tandem cylinder arrangements were investigated.

For side by side arrangements it was observed that the phase shift of the horizontal velocity, which is in phase with the surface elevation, and the bending moment has significant influence on the increased peak wave load. The phase shift is small for asymmetric waves or waves in the drag regime. This explains why the modified vortex shedding due to neighboring cylinders coincidence with the maximum bending moment. Inertia dominated waves have a larger phase shift and therefore the likewise modified vortex shedding doesn't coincide with the timeframe of the maximum loads. For tandem arrangements the sheltering effect for the inline bending moments were less than 8% in average and on the contrary partly up to 10% increased maximum wave loads were measured.

To reveal more information of the physical processes in regard to the characteristics of the drag and the added mass behavior, C_D and C_M values were estimated with the method of the least square fit. The C_D coefficients for the side by side arrangements reveal a clear correspondence to the different center to center cylinder spacing and to the number of neighboring cylinders (Fig. 6). This underlines the effect of neighboring cylinders on the increased flow velocities between two cylinders, and thus to the higher drag coefficients. The influence of nearby side by side cylinders on the hydrodynamic or added mass is partly seen in Fig. 7, where the added mass coefficients for two adjacent cylinders exceed the C_0 values. However, this trend is considerably reduced for arrangements with only one flanking cylinder and also for the center to center spacing of 4 diameters. For tandem arrangements and KC values < 23 no definite developments were observed with respect to the scattering. Only for KC greater 23 a sheltering effect for the drag coefficient becomes obvious.

Further analysis on the scattering of the C_D and C_M values in all 9 arrangements are currently in progress for the identification of clearer boundaries. This includes the analysis of more waves and the sensitivity of the least square fitting error, which varies with each wave and thus should have an influence on the C_D and C_M values. In addition, the estimated C_D and C_M values for regular waves will be compared with estimated coefficients from JONSWAP spectra tests, also performed in the Large Wave Flume (GWK).

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