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BREAKING WAVE LOADS ON A SLENDER PILE IN SHALLOW WATER

KAI IRSCHIK
kai@irschik.de, Heeßeler Kirchweg 5
31303 Burgdorf, Germany

UWE SPARBOOM
Coastal Research Center (FZK), Merkurstr. 11
30419 Hannover, Germany

HOCINE OUMERACI
Leichtweiß-Institute for Hydraulic Engineering, Beethovenstr. 51a
38106 Braunschweig, Germany

The load of breaking waves distinguishes from the impact of non - breaking waves in the superposition of an additional, transient force of short duration. A simple method is presented to decompose the quasi –static force, the periodic part of the total measured force, and the dynamic component, which is the response of the cylinder due to the additional impact. The method is verified with large-scale model tests. The tests were carried out in the Large Wave Channel (GWK) with a slender, vertical and inclined cylindrical pile located at the end of a 1:10 slope. Finally the impact and the curling factor λ, an empirical coefficient to calculate the height of the impact area, is determined and compared to published data from laboratory deep water experiments.

1. Introduction

In the presence of breaking waves the total force on a slender cylinder is a superposition of a slowly varying force, proportional to the change of the water surface elevation, and an additional impulsive force of short duration due to the impact of the breaker front and / or the breaker tongue. In this case the description of the wave force using only the well known Morison equation will fail. The impact force has to be calculated separately:

$$F_{total} = F_{Morison} + F_{impact} = \left(F_M + F_D \right) + F_I \tag{1}$$

with the impact force F_I

$$F_I(t) = f_I(t) \cdot \lambda \cdot \eta_b = \rho \cdot R \cdot V^2 \cdot C_S(t) \cdot \lambda \cdot \eta_b \tag{2}$$

where F_I = impact force; f_I = impact line force; ρ = density of the water; R = radius of the pile; C_b = wave celerity at breaking point; C_S = slamming factor; λ = curling factor; η_b = maximum water surface elevation at breaking point

The formulation of the line force f_l is based on the descriptions of von Karman (1932) and Wagner (1932), which basically differs in the slamming coefficient C_S. Wagner considered the pile-up effect and estimated C_S at the beginning of the impact as:

$$C_S\,(t=0) = 2\pi \quad (3)$$

which is twice compared to von Karman´s value with C_S (t=0) = π . The model is extended to 3 – D by introducing the height of the impact area. The height is related to the water surface elevation η_b through the curling factor λ. The fraction of the elevation η_b over which the impact acts, i.e. the curling factor λ, depends on the breaker type. In the case of plunging breakers Goda et al. (1966) estimated a value of $\lambda = 0.4$ for vertical piles. Wiegel (1982) recommends a more conservative value of $\lambda = 0.5$. These values are confirmed by the results of in a large scale model tests (Wienke 2001). The mean curling factor for the maximum loading case was $\lambda = 0.46$. Additionally Wienke (2001) investigated the influence of the inclination of the cylinder on the curling factor as shown in more detail in Figure 8.

In this paper the curling factor λ estimated for shallow water conditions and five inclinations of the test pile will be discussed. Since the estimation of λ is a result of several analysis steps and cannot be recorded directly, great care was taken on minimizing the associated uncertainties. First a simple method to decompose the measured total force into a quasi – static and a dynamic component is presented. The verification is performed by comparing the separated oscillation of the cylinder with an ideal damped oscillation. Using the dynamic component, the response of the cylinder due to the hit of the water mass, the impact force can be estimated. Wienke and Oumeraci (2005) developed a method based on the deconvolution of the signal using a given time history of the impact force. The curling factors are calculated and a distinction is made for different loading cases.

2. Experimental Set-Up and Procedure

The experimental tests were performed in the Large Wave Flume (GWK) of the Coastal Research Center in Hannover, Germany. The range of wave periods used was between 3.0 and 10.0 s with a water depth of about 4.0 m. The wave parameters of the regular waves are listed in Table 1. A 1:10 slope was built to produce depth limited wave breaking. The test cylinder was installed immediate behind of the slope on the berm, see Figure 1. The investigation covers in total five inclinations of the test cylinder.

Table 1. List of wave parameters tested.

α	[°]	-45°	-22.5°	0°	22.5°	45°
d	[m]	3.80-4.50	3.80-4.20	3.80-4.50	3.80-4.50	3.80-4.50
H	[m]	1.2-1.7	1.2-1.7	1.2-1.7	1.3-1.65	1.2-1.7
T	[s]	4-10	4-8	3-10	4-8	4-10
f_E	[Hz]	11.3-14.5	15.2-18.3	17.1-21.2-	15.2-18.3	11.3-14.5

α = inclination of the pile; d = water depth over flume bottom; H = wave height at wave generator ; T = wave period; f_E = natural frequency of the pile

The test pile is 5 m long in the vertical position ($\alpha = 0°$) and has a diameter of 0.7 m. In four additional set - ups the test cylinder was inclined against the wave propagation ($\alpha = -22.5$ & $-45°$) and in the direction of wave propagation ($\alpha = +22.5$ & $+45°$), see Figure 1. The structure was mounted on a steel beam 2.30 m above the flume bottom. At the top of the flume the pile was fixed at a traverse structure. The total horizontal wave force was measured with strain gauges in the two bearings at the top and the bottom of the pile. The calibration of the strain gauges was performed with static towing tests.

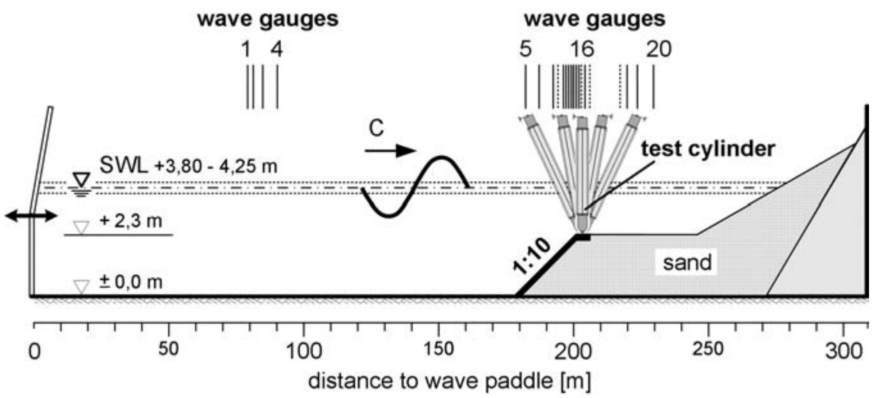

Figure 1. Experimental set-up in the Large Wave Flume (GWK).

The water surface elevation far in front of the slope is measured with four wave gauges. 12 gauges were distributed over the foreshore and four are installed behind the test pile on the berm. Additionally, 4 wave gauges were fixed at the cylinder. The locations of pressure cells and current meters have been reported in Irschik et al. (2002).

All data were recorded synchronously with a sampling rate of 200 Hz. This relatively low sampling rate was selected, because the spatial resolution of the pressure cells does not allow obtaining accurately the impact force, even for sampling rates in the order of 10 kHz. In fact, Wienke (2001) showed that the integration of the measured impact pressures to obtain the impact force is not justified in the area of impact. With the force transducers in the bearings the response of the pile is recorded. Therefore for the analysis of the impact force by using the force measurements, the natural frequency of the test pile has to be taken into account (Table 1) and the sampling rate has been selected according to the pile response.

3. Separation of Dynamic and Quasi - Static Force

3.1. *Separation procedure*

The measured total wave force is obtained from the superposition of the forces measured in the two bearings (Figure 2). From the physical point of view it is a superposition of two forces with different time – dependent variations and therefore influenced by different parameters, the quasi – static and the dynamic force. Before starting the analysis of these two parts of the wave force the total wave force has to be separated into a quasi – static and a dynamic component. Next, the investigation of possible correlations and the verification of existing practical formulas for each of the two force components can be done.

Figure 2. Scheme of force separation.

The different nature of the time histories can be seen in Figure 3. In the first quarter of the shown time interval the measured total force is equal to the quasi – static force and varies in the same way the water surface elevation changes. When the impact force takes place, the total force shows a high increase of the load, followed by an oscillation that is governed by the dynamic characteristics of the system. This means, the measured total force represents a periodic time series that is superimposed by a transient data series.

Consequently, a reliable separation of the quasi – static and dynamic force is inevitable for an investigation of the breaking wave force as uncertainties of the force separation will be directly transmitted to the following steps. In the present study, a combination of a FFT low – pass filter and the Empirical Mode Decomposition (EMD) is used. Finally a verification of the separation procedure is performed.

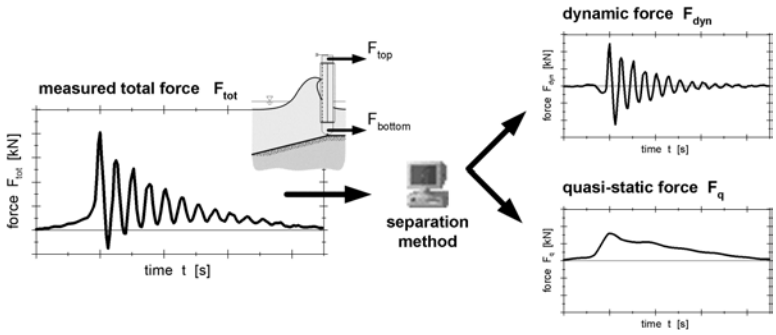

Figure 3. Example of measured total force and of separated force time series.

3.2. *Used Method to Estimate the Quasi – Static Force*

The method used for the estimation of the quasi – static force is a combination of a FFT low-pass-filter and the EMD. The dynamic force is then defined as the difference of the total and the quasi – static force. The method can be applied on time series of different loading cases (e.g. Chang et al. 1995, Wienke 2001) and all inclination of the cylinder. Uncertainties due to the arbitrary selection of parameters like the cut - off frequency or the standard deviation (SD) as a criterion for stoppage in the EMD are avoided as these parameters are either not necessary or determined from the measured wave force itself.

First, the wave force is filtered by a FFT low-pass-filter as shown in Figure 4. The natural frequency f_E of the test cylinder is chosen as the cut-off frequency f_{cut}. The natural frequency varies for the test conditions when the length of the pile and the water depth are changed, but differs only slightly from the peak frequency of the dynamic part, if the damping is small (Hapel 1990). With this definition the cut-off frequency can be estimated from the force measurement itself. In the present study, the quasi – static part is not influenced by the low-pass-filter since the cut-off frequency is far away from the wave frequency. The lowest natural pile frequency ($\alpha = \pm 45°$) exceeds the lowest wave frequency by a factor of about 6.

As can be seen in Figure 4 the highest amplitudes are lowered in the filtered time series. Additionally, local extremes are generated for the time period before the impact is taking place and only the quasi – static force is acting on the pile. Both effects improve the result of the next step when using the EMD.

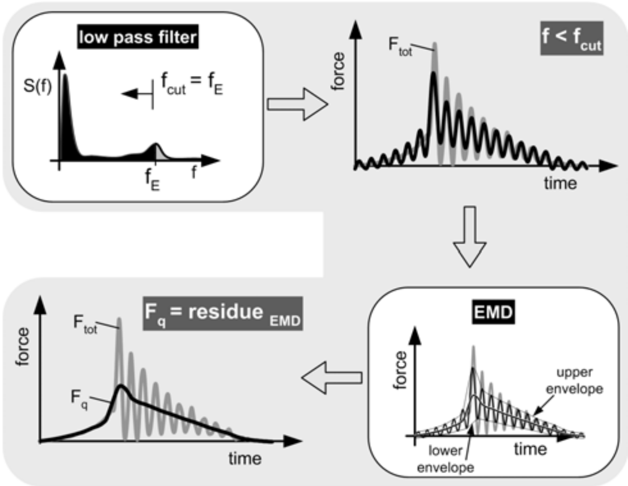

Figure 4. Force separation procedure.

Without any preprocessing of the time series the total forces shows at the instant of the impact a sudden rise with a high amplitude compared to periodic maxima, which will lead to an overestimation of the quasi – static force in the region of the maximum forces. The overestimation is minimized due to the introduced local extremes, since the latter are uniformly distributed around the total force when no response of the structure is measured. As a result the mean of the upper and lower envelope is more or less equal to total measured force in this region.

After filtering the total force, the quasi – static force is estimated with the Empirical Mode Decomposition (EMD) developed by Huang et al. (1999) in only one shifting step (Figure 4). The time series is decomposed into one Instrinsic Mode Function (IMF) and a residue. The residue is equal to the quasi – static part of the measured force.

The common artificial oscillations at both ends which are caused by FFT - filters and the different end conditions for the EMD (Dätig and Schlurmann (2004) are ignored in this procedure, since all records start several wave periods before the first wave and end the same period of time after the last wave. When analyzing the breaking waves, the artefacts due to the separation are outside the region of interest. Therefore, the first and last data point of every time series is set equal to zero and defined as local extremes of the upper and lower envelope. Other boundary conditions as mentioned in Dätig and Schlurmann (2004) are not considered.

3.3. *Verification*

For the verification of the separation of the quasi – static and the dynamic force, the definition of both parts of the load is used. The dynamic part is defined as a damped oscillation:

$$F_{ref}(t) = F_{max} \cdot e^{-\xi\omega_E t} \cdot \cos(\omega_E t) \tag{4}$$

The natural frequency ω_E is equal to the natural frequency of the test cylinder. The damping parameter ξ is calculated with a modified least square error fit for every single wave by only considering the local maximum and minimum values of the oscillation. In this way small variations of the oscillation frequency of the test cylinder during one impact incident have no influence on the error fit and the damping parameter. The difference of the reference force and the separated dynamic force is calculated:

$$\Delta F = F_{ref} - F_{meas} \tag{5}$$

In Figure 5 the difference of the force ΔF can be seen for the vertical cylinder position, when the first oscillation (Max 1, Min 1) is neglected for the determination of the damping parameter. The analysis showed that this procedure highlights the characteristic and behavior of the used method of separation best. The breaking waves considered for the verification have to fulfill two criteria. First, the measured total force has to exceed the threshold of 15 kN. Second the relation of the maxima of the dynamic force and the total force has to exceed 40 %. This will ensure that all waves of interest, i.e. waves of the maximum loading case and corresponding waves generating highest loadings, are considered. On the other hand, the assumption is best fulfilled when the response of the structure to the impact force is similar to a damped oscillation.

Besides the mean values for every single local extreme, the standard deviations can also be seen in Figure 5. A significant systematic error for the first four extremes can be seen. For the following extremes the mean value is only slightly different from zero and the difference of the measured and calculated force ΔF is assumed to be a statistical error.

Due to the definition of ΔF, the plotted line in Figure 5 also shows the overestimation of the quasi – static force in the region of the maximum load. This systematic error is related to the still high increase of the amplitude when the impact takes place, even after the total force time series is filtered (Figure 4).

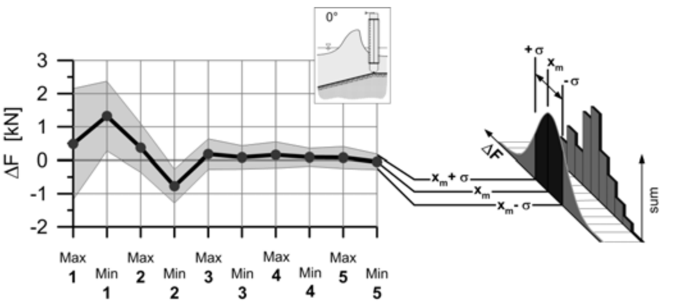

Figure 5. Result for vertical pile ($\alpha = 0°$).

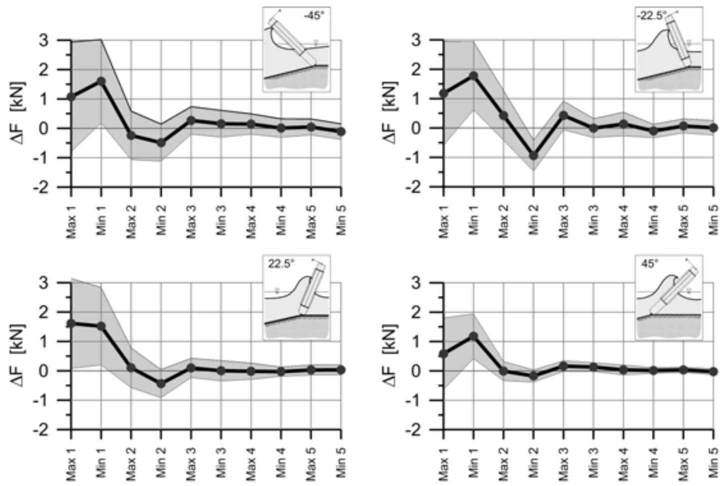

Figure 6. Results for inclined piles ($\alpha = \pm 22.5°$ and $\pm 45°$).

The force differences ΔF are plotted for the inclined test cylinders in Figure 6. The standard deviation decreases with the inclination of the cylinder, since the increase rate of the total measured force is slower when the pile is inclined in the direction of wave propagation. But in general the plots show the same pattern, irrespective of the yaw angle of the cylinder. An overestimation of the quasi – static force at Max 1 and Min 1 is also observed.

By definition the quasi – static force will not cause a dynamic response of the structure. As the verification shows an overestimation of the quasi – static force in a small time period when the maximum load is measured, the response of the structure due to slowly varying force is also calculated. It was found that the maximum of the calculated response, when related to the maximum of the input, i.e. the quasi – static component, differs only slightly with the yaw angle of the pile. The relation of the maxima of the response and of the quasi – static maxima is about 6 % on average for all inclinations of the cylinder. Although this means that the observed overestimation of the quasi – static component would cause an oscillation of the structure, this response is only small in magnitude. The definition of the quasi – static force is therefore regarded to be fulfilled.

4. Impact Force and Curling Factor λ

4.1. *Estimation of the Impact Force*

The impact force has to be estimated from the dynamic force, since only the response of the test cylinder is measured in the bearings instead of the direct load of the breaking wave. This is due to the very short duration of the impact, in the order of several milliseconds, compared to the natural frequency of the test pile (f_E (α, d) = 11 – 20 Hz). Therefore, the impact force is not recorded directly, but has to be determined from the dynamic force.

The numerical solution of the equation of motion in order to calculate the impact force will cause some problems. Wienke (2001) examined the formation of noise with high amplitude as stated before from Hanssen and Tørum (1999). He avoided the use of any filter and used instead a theoretical model to estimate the impact for which the time history of the impact has to be specified before. Wienke verified the time history by pressure measurements over the circumference of the pile. A detailed description of the development and verification of the basic approach is given in Wienke and Oumeraci (2005). The following algorithm summarizes the estimation of the intensity of the impact force briefly. At the same time the curling factor λ is experimentally determined:

1. Estimation of the dynamic component of the measured total force F_{dyn} and the normalized cylinder oscillation governed by the eigenfrequency ω_E and damping coefficient ξ
2. Calculation of the impact line force with the measured wave celerity C_b using the theoretical approach of Wienke and Oumeraci (2005)
3. a) Convolution of the impact force and the cylinder oscillation to calculate the theoretical response of the cylinder
   b) Comparison of theoretical response with "measured" dynamic force
   c) If theoretical and measured response is in good agreement stop, else variation of the intensity of the impact force and go to a)

The variation of the intensity of the impact force in 3c) is equal to the adjustment of the curling factor λ. Introducing the slamming coefficient $C_S(t)$, the 3 – D model in Wienke and Oumeraci (2005)may be simplified to:

$$F_I(t) = f_I(t) \cdot \lambda \cdot \eta_b = \rho \cdot R \cdot C_b{}^2 \cdot \cos^2 \alpha \cdot C_S(t) \cdot \lambda \cdot \eta_b \tag{6}$$

In the analysis of the impact force the wave and cylinder properties are set to be constant for every single event (ρ, C_b, η_b, R, α) and have to be known beforehand. The time history of the slamming coefficient is calculated using the wave celerity and radius of the cylinder. The only variable is the curling factor l which is included in the theoretical description. This means, when the magnitude of the impact force is adjusted to the measured response until best agreement is obtained, the curling factor is empirical determined.

In using the afore mentioned algorithm, the time history is set constant but only the magnitude of the impact is varied until there is good agreement between the theoretical and the measured response of the cylinder. Wienke and Oumeraci (2005) calculate the difference of the calculated and measured curves by comparing the maximum values (Max 1). In the present study, this is the time region associated with the highest uncertainties in the estimation of the dynamic force as shown in the verification of the separation method before. Here the difference between the local extremes neglecting the first oscillation (Max 2-5, Min 2-5) is used to compare the time series.

4.2. *Curling Factor λ*

The tests performed at the GWK and listed in Table 1 cover all types of loading cases including non-breaking waves, wave breaking far in front of the cylinder, at and behind the cylinder. Wienke (2001) found the highest force peaks and best agreement with the developed 3-D description of the impact, when the wave breaks immediately in front of the cylinder according to loading case 3. The tests were subdivided into five loading cases by visual analysis of the breaking and splash processes.

Due to the high amount of recorded waves in the present study, the visual observation is not practicable. Instead of the visual analysis, first the waves are subdivided into different characteristic time series of the total measured force. They are subdivided into events with double or more peaks, with single peaks and with no or no significant peak in the presence of non – breaking waves. If the time history of the total force shows another peak before the maximum value, the wave is assumed to break in front of the cylinder and represent loading case 1 or 2 (Wienke 2001). In the case where no peak is detected, the waves are defined as non – breaking and equal to loading case 5. The waves causing the highest loading and single peak events belong to loading case 3. The impact starts at one point and spreads over the circumference and the height of the cylinder. The single peak events also include the wave breaking behind the frontline of the cylinder, loading case 4, and double peak events which could not be recorded as such due to the slow response of the test cylinder (loading case 2).

In order to estimate the curling factors λ according to the highest intensities of loading case 3, in the second step only the mean value of the 10 % highest curling factors of the single peak events are considered. In Figure 7 these values for all inclinations of the test cylinder can be seen, including the $\lambda_{1/10}$ values, i.e. the mean of the 10 % highest factors. Figure 7 shows the expected dependency of the inclination of the cylinder. The highest value is obtained for the yaw angle of α = -45° against the direction of wave propagation. It decreases when the pile is inclined in the direction of wave propagation.

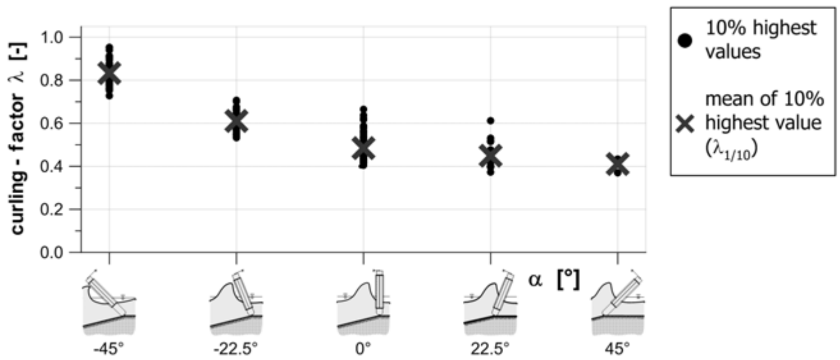

Figure 7. Curling factor $\lambda_{1/10}$ versus inclination of the cylinder.

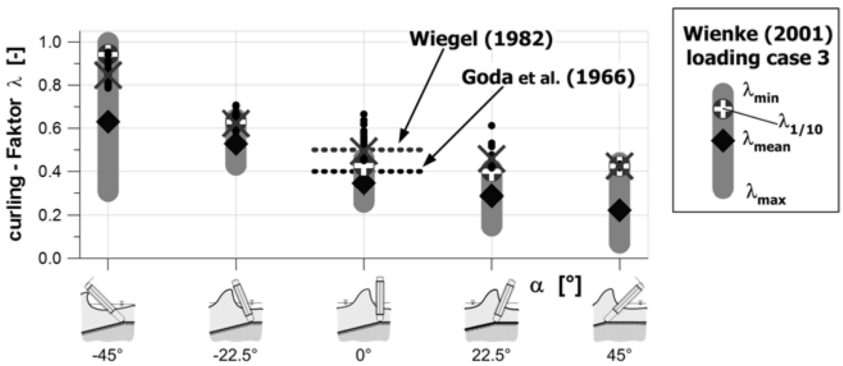

Figure 8. Curling factor λ in comparison with previous results.

The comparison of the curling factors with values published by other authors is shown in Figure 8. For the vertical pile position the $\lambda_{1/10}$ value agrees very well with the recommendations of Wiegel (1982), Goda et al. (1966) and the highest values of Wienke (2001). The λ - values related to the inclined piles represent a good approximation of the highest curling factors proposed by Wienke (2001) for loading case 3. Calculating the $\lambda_{1/10}$ values for waves of loading case 3 and all single peaks events estimated by Wienke (2001), the curling factors of the present study are confirmed. As in Wienke (2001) breaking waves were generated on a horizontal bottom using transient wave packets, in the present study no considerable influence of the breaking wave generation on the highest curling factors are detectable.

5. Summary and Concluding Remarks

The separation of the quasi – static and dynamic force is conducted by using a combination of a FFT low – pass filter and the Empirical Mode Decomposition (EMD). The cut – off frequency of the filter is equal to natural frequency f_E of the test cylinder. The filtered time series is then decomposed into an Instrinsic Mode Function (IMF) and a residue. The latter represents the quasi – static component of the measured force. The parameters needed for the force separation, e.g. the cut – off frequency, can be determined from the measurement itself. The result is unique and independent of any subjective choice. The method overestimates the quasi – static force in the region of the maximum impact. Only a statistical error for the following oscillations of the cylinder is observed. This behavior has to be considered in the further analysis of the impact force.

The analytical 3 – D model of Wienke and Oumeraci (2005) was used to determine the impact force and the experimental estimation of the curling factor λ. The estimated curling factors λ for the waves with the highest loading are in good agreement with values published by Wienke (2001), irrespective of the inclination of the cylinder. At this stage, no influence of breaker type on the curling factor can be clearly identified. Nonetheless, the visual agreement of the coefficients has to be confirmed in a statistical comparison to prove the validity of the $\lambda_{1/10}$ value in representing the highest values of loading case 3 (Wienke and Oumeraci 2005).

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