DOWNFLOW BAFFLE BREAKWATERS
LATEST DEVELOPMENTS AND LESSONS LEARNED

Marianne Frese[1], Matthias Bleck[1] and Michael Schöner[1]

Downflow baffle breakwaters or floating breakwaters are not as common as "full-depth" breakwaters. As a consequence the scientific work on hydraulic performance and loading is limited and most work dates back to the 1960s and 1970s. Several baffle breakwaters were planned and constructed in Germany in the last decades. Their advantages are reduced costs due to less material required and less impact on sediment transport and water quality. Experiences from different case studies and first results of a desk study on hydraulic performance and hydraulic loading will be described.

Keywords: Scum Board; Semi Permeable; Baffle Breakwater; Hydraulic Function; Hydraulic Loads; Skirt breakwater

INTRODUCTION

In urban and river hydraulics scum boards are often used to prevent floating objects (e.g. debris) from entering cooling water lines or water treatment plants. This application is well known. The application as a breakwater in harbour and coastal engineering is only occasionally. In course these structures are only treated limited in the standard rules and guidelines.

Scum boards as breakwaters (baffle breakwaters) are a point wise measure which bloc the upper part of the water column. Instead of debris they prevent wave energy in the upper part from entering the protected region.

If waves reach a baffle breakwater, they are partially reflected and transmitted. Also a certain part of the wave energy will be dissipated by the flow resistance of the structure and vortices generated at the structure's edges.

In breakwater design processes mostly no total blockage of wave energy is required nor desired. In this case baffle breakwaters may be a technical and economic alternative for full-depth rubble mound or caisson breakwaters. Baffle breakwaters do not prevent all of the wave energy to enter the sheltered region, so negative impacts like accumulation and lee erosion are less compared to full-depth break water. Also the near bed sediment transport is less influenced. Thus negative impacts on the morphology are reduced. Also in terms of water quality this type of breakwater will have less impact as water exchange happens in the lower water column.

MOTIVATION

General

Downflow baffle and floating breakwaters are relatively seldom applied as a coastal protection measure in Germany. Nevertheless in deeper water they are advantageous e.g. for berths as they require less material than normal breakwaters.

KED has constructed and planned several baffle plate type and floating breakwaters in the last years. One challenge in the design process was that in the common rules and guidelines no information on the hydraulic performance and the hydraulic loading is given especially for plate type breakwaters. The German standard guideline for coastal engineering (EAK; 2005) states that semi permeable and permeable structures are of minor use in coastal protection and refers to Eggert and Kohlhase (1980) and Eggert (1983).

Also in the international standards, the Shore Protection Manual (SPM; 1984) and the Coastal Engineering Manual (CEM; 2006), no satisfactory information on the hydraulic performance of these structures is given. Regarding the example projects described below the common design methods for vertical breakwaters were applied using a reduced surface area to calculate the hydraulic loads. This approach is very conservative regarding the structure's stability but not satisfactory regarding an economic design.

Therefore based on Eggert (1983) and PIANC (1994) an extensive literature review and desk study has been conducted to get more insight in the function and behaviour of these structures.

Yacht Harbour Laboe

One starting point for the described research was the breakwater construction for the marina at Laboe at the German Baltic Sea coast (Figure 1). As a cost efficient solution a baffle breakwater was planned. The breakwater was designed to protect the marina of wind induced waves and still preserve

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[1] All: KED Consultants; Gasstrasse 18, Haus 4; D-22761 Hamburg; Germany; info @ked-ingenieure.de

the water circulation for ecological reasons. For the structural design the approach of Sainflou according to EAU (1990) (E135) was applied. Overtopping was considered and non-breaking waves without pressure beats were assumed.

After the construction of the breakwater waves went through the breakwater into the marina and disturbances occurred. This causes that the masts of the sailing yachts hit together and were partially damaged. Reasons for these disturbances were unconsidered vessel induced waves with a very long period which were identified within a subsequently conducted study. The unconsidered ship waves passed the baffle breakwater nearly non-reduced because of their long period in the relatively shallow water. Due to vertical quay walls and an unfavourable harbour geometry the waves were superimposed, resonance effects occurred and the disturbance increased.

As a consequence, a sheet pile wall was placed in front of the baffle breakwater resulting in a quasi-full depth breakwater.

This example clearly indicates the importance of investigating waves of different origins as the hydraulic function (wave transmission) of baffle breakwaters is very sensitive regarding wave periods and wave lengths respectively.

Figure 1. Breakwater Construction at Laboe, Baltic Sea, Germany

Further Examples for Baffle Breakwaters

A further successful example for using the advantages of a baffle breakwater is the ferry berth at Glückstadt in the Elbe estuary in Germany which was constructed in the 1970s. In order not to disturb the natural sediment transport in the river and thus preventing harbour siltation this type of breakwater was chosen. Beside the function as a ferry berth the breakwater was designed to protect the ferries against wind induced waves. Ship induced waves were not critical as the berth is located in a tributary to the main river which is the approach channel to Hamburg.

A spatiality of the ferry berth is the inclined seaward front which is supposed to reduce the ice loads (Haas et al.;1981). In this context KED was approached to comment on a research proposal on the impact of the seaward front inclination on the hydraulic performance and the hydraulic loads on the baffle breakwater.

Floating Breakwaters

Regarding the hydraulic function and loading floating breakwaters are comparable to baffle breakwaters as both structures block the upper part of the water column. The difference is that floating breakwaters always block a constant part of the water column. In tidal waters this part varies for baffle breakwaters as they are fixed in a certain height.

For the hydraulic function of floating breakwaters the extent in wave direction has to be considered which is mostly larger than for baffle breakwaters. Also the dynamic response of the structure has to be considered. Details on the design of floating breakwaters can be found in PIANC (1994). Beside the publications of Eggers and Kohlhase (1980) and Eggers (1983) this publication was a starting point for the described study as the behaviour of baffle and floating breakwaters is comparable.

Examples for floating breakwaters are landings for smaller boats in yacht harbours. This often used application is advantageous due to their flexibility e.g. for temporary harbours for touristic use.

LATEST DEVELOPMENTS

Hydraulic Function

When waves reach a baffle breakwater a part of the incident wave is reflected, a part transmitted and a certain part of the wave energy is dissipated. Usually this is expressed in terms of energy coefficients:

C_t = transmission coefficient = $H_t/H_i = (E_t/E_i)^{1/2}$ [-];
C_r = reflection coefficient = $H_r/H_i = (E_r/E_i)^{1/2}$ [-];
C_d = dissipation coefficient = $H_d/H_i = (E_d/E_i)^{1/2}$ [-];

Where E stands for the wave energy and H for the correlating wave height. The dissipated wave height has to be seen as a virtual value. The indices indicate incident (i), reflected (r), transmitted (t) and dissipated part of the according values.

Figure 2 sketches the hydraulic system at a baffle breakwater. The distribution of energy is indicated by their distribution within the water column. The dissipated wave energy is symbolized by a vortex at the lower edge of the breakwater as large-scale vortices and pressure-resistance of the plate at the breakwater are in general responsible for the energy losses.

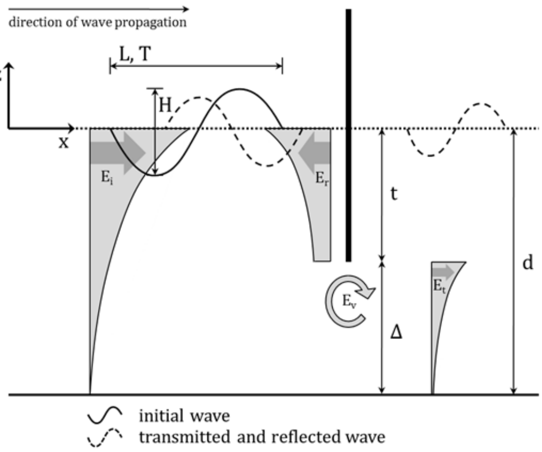

Figure 2. Hydraulic System

Figure 2 also displays the relevant parameters influencing the hydraulic performance of a baffle breakwater. These are, beside the parameters of the incoming wave (height H, period T), the water depth d and the penetration depth t. The wave length L is a non-independent value being a function of wave period T and water depth d. Dimensional analysis yields the following dimensionless parameters (wave parameters and structural parameters respectively):

- Wave steepness: H/L
- Relative water depth: d/L
- Relative wave height: H/d
- Relative submergence: t/L
- Relative blockage: t/d

In the past various design concepts were developed to estimate the hydraulic function of plate type breakwater. The first scientific works were written by mathematicians as the wave motion at an infinite thin, semi-submerged plate can be described by solving the underlying Laplace equation considering the boundary conditions as applied in Linear Wave Theory. The solution is comparable to the Sommerfeld solution for diffraction at semi-infinite breakwaters (Sommerfeld; 1896). The according equations can be found in Ursell (1946):

$$C_{t,URSELL} = \frac{K_1(kt)}{\sqrt{\pi^2 I_1^2(kt)+K_1^2(kt)}} \tag{1}$$

With k being the wave number (k = (2 · π)/L) and $I_1(kt)$ and $K_1(kt)$ being modified Bessel functions of the first and second kind, first order.

The most common and used method to estimate the transmitted and reflected part of the incident wave energy at baffle breakwater is the power transmission theory by Wiegel (1960). Wiegel's approach is based on the energy distribution in the water column following linear wave theory as indicated in Figure 2. The respective parts of the energy in the upper part of the water column which are blocked by the breakwater respectively are considered to be reflected while the other part is transmitted. Based on the Linear Wave Theory, Wiegel calculates the integral of the pressure distribution in one wave period and the respective part of the water column:

$$P_\Delta = \frac{1}{T}\int_0^T \int_{-d}^t p\, u\, dt\, dz \tag{2}$$

Relating the different values and neglecting any energy losses the transmission coefficient is derived to:

$$C_{t,WIEGEL} = \sqrt{\frac{2k\,(d-t)+\sinh(2k\,(d-t))}{2kd+\sinh(2kd)}} \tag{3}$$

The most renowned work in Germany on semi-impermeable breakwaters is by Eggert (1983). It is based on a desk study supplemented by own model test results and meta data. In the end the derived design formula is an adaption of the formula of Hoffmann (1967):

$$C_{t,HOFFMANN} = \frac{1}{\sqrt{1+\left(\frac{(l_e/d)\cdot kd\cdot \sinh(kd)}{2\cdot \sinh(k(d-t))}\right)^2}} \tag{4}$$

(limits: 0.10 < d/L < 0.80 and t/d > 0.15; Eggert (1983)).

Unlike Ursell (1947) or Wiegel (1965) Hoffmann (1967) applied Stokes 2nd Order Theory in the derivation of his design concept. He introduced a virtual length (l_e/d) for the relative blockage (t/d) which was adapted by Eggert (1983) (see Figure 3). The virtual length thereby considers energy losses and has been derived by physical model tests and analysing meta data.

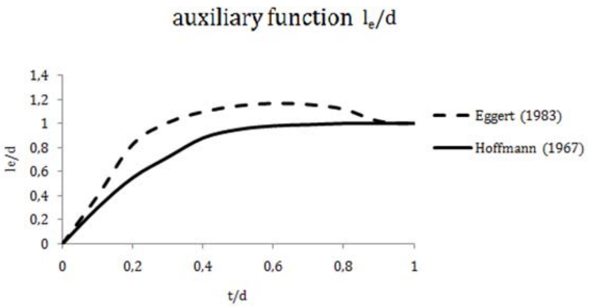

Figure 3. Virtual length (l_e/d) for the relative blockage (t/d) according to Eggert (1983)

The comparative new design formula by Bollmann (1996) is a refinement of the classic Wiegel power transmission theory (Wiegel; 1960). As for Eggert (1983) the work of Bollmann (1996) is based on a desk study, meta data and additional own model tests. Beside undisturbed wave fields on both sides of the plate type breakwater Bollmann (1996) considers the influence of the reflected wave on the incident wave train. The horizontal orbital velocities of the reflected wave are superimposed to those of the incident wave and partially neutralize them. As a consequence the dynamic pressure is reduced and the pressure integral of Wiegel (1960) as in Eq. 2 yields in:

$$P_\Delta = \frac{1}{T}\int_0^T \int_{-d}^{-t} (p_i + p_r)(u_i - u_r)dz\,dt \tag{5}$$

The according equation for the transmission coefficient is:

$$c_{t,BOLLMANN} = 2\left[1 + \frac{2kd + \sinh 2kd}{2k(d-t) + \sinh 2k(d-t)}\right]^{-1} \tag{6}$$

A given advantage of this approach by Bollmann (1996) compared to Ursell (1946) and other methods is that the equations can be solved directly.

A further more theoretical method is the eigenfunction expansion method as described by Losada et al. (1992). In the end this method proved to be less reliable than the modified power transmission theory (Kriebel and Bollmann; 1996).

Frese (2011) draw up a comparison of these and additional design methods for baffle breakwater and conducted a sensitivity analysis regarding the governing hydraulic and structural parameters. A plausibility check revealed comparable results for deep water waves (Fig. 4). This can be explained by the fact that most of the design methods are based on the Linear Wave Theory which is developed for deep water waves.

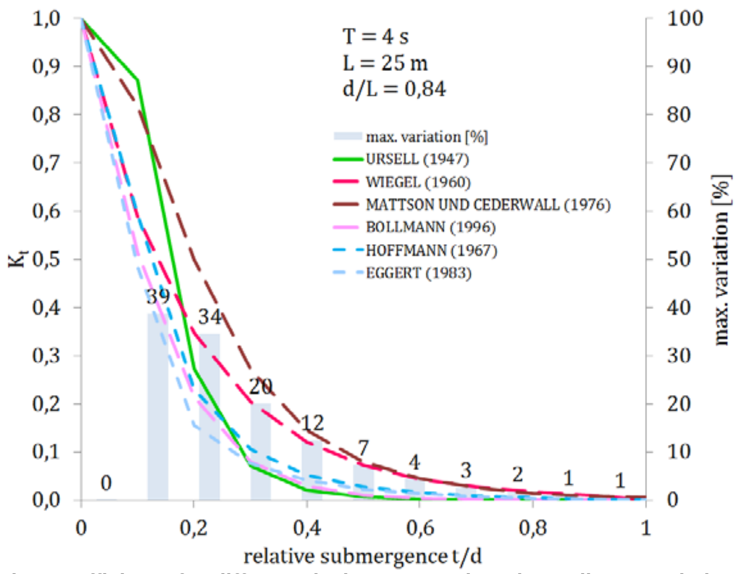

Figure 4. Transmission coefficients for different design approaches depending on relative submergence t/d for deep-water conditions

For shallow water waves the analysed methods differ in their results (Fig. 5). Especially the design formula by Ursell (1947) and Mattson and Cederwall (1976) show unrealistic results as for a total blockage of the water column a transmission of more than 90 % of the incident wave energy is calculated.

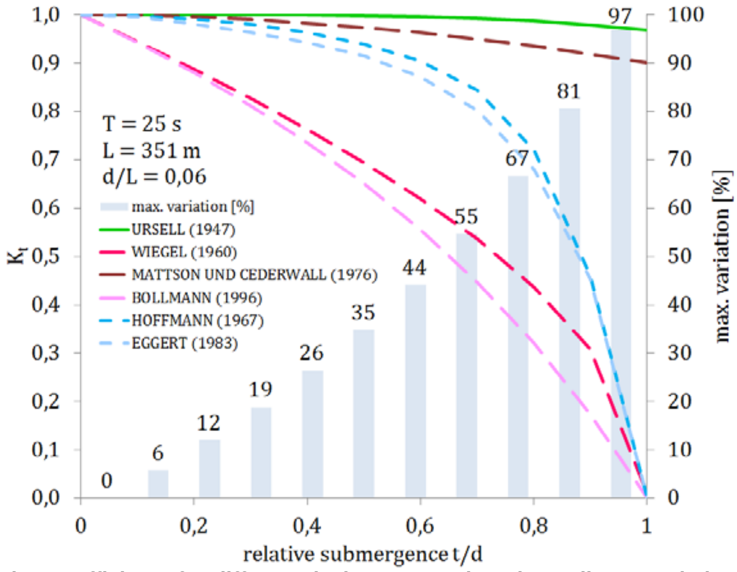

Figure 5. Transmission coefficients for different design approaches depending on relative submergence t/d for shallow water conditions

The results of the design methods of Hoffmann (1976) and Eggert (1983) are comparable as Eggert's approach is a refined version of Hoffmann. The same applies for the two design formulae by Wiegel (1965) and Bollmann (1996) the second being the one which finally proved to be best reliable (Frese; 2011).

Hydraulic Loads

Beside the hydraulic function the hydraulic loading is an important aspect in the design of a breakwater. Based on difficulties in the design of the Laboe breakwater and a floating breakwater an extensive desk study on this topic was conducted (Frese; 2011) as the classic design formulae for vertical breakwaters tend to overestimate the wave forces which leads to a non-economic but safe design.

The classic design approach for vertical breakwaters is the method of Sainflou (1928) which was refined by Miche-Rundgren (Miche; 1944). The method is based on total reflection and a standing wave in front of the breakwater. Thereby the asymmetry of the wave is considered by an increase h_0 of the still water level which is calculated to:

$$h_0 = \frac{\pi \cdot H^2}{L} \cdot coth\left(2 \cdot \pi \cdot \frac{d}{L}\right) \qquad (7)$$

The dynamic wave pressure is than calculated using linear wave theory (e.g. SPM; 1984).

For breaking and broken waves the classical Goda formula (Goda; 1985) is recommended (EAK; 2005). In case pressure beats are expected Oumeraci et al. (2001) recommend the PROVERBS method for preliminary design and to conduct project specific physical model tests.

As a baffle breakwater does not block the whole water column the reflection and the wave run-up on the plate are reduced which in course also reduces the wave force on the breakwater. As for his approach for wave transmission where he adapted the Wiegel power transmission theory for the hydraulic loading, Bollmann (1996) modified the approach of Sainflou were he considered the less wave run-up and reflection of the wall.

The resulting pressure on the baffle is calculated by the addition and subtraction of the dynamic pressure of the incoming, reflected and transmitted wave. Integrated over the height of the wall the pressure force is calculated to:

$$\mathrm{P_{dyn}} = \int_{-t}^{0} (\mathrm{p_i} + \mathrm{p_r} - \mathrm{p_t})\, \mathrm{dz} \qquad (8)$$

By considering the phase shift of 90 °between the front and rear of the baffle and further transformations Bollmann developed a formula for calculating the dynamic load due to waves, which depends on the wave height H, wave length L, depth d and penetration depth t of the baffle.

$$\frac{p_{dyn}}{\rho g} = \left[\frac{\sqrt{2}H_i}{k}\sqrt{2-2K_t+K_t^2}\,\frac{[\sinh kd-\sinh k(d-t)]}{\cosh kd} + \frac{H_i^2(2-K_t)}{8}\right]\cdot\frac{1}{t} \qquad (9)$$

A comparison with model test data Bollmann (1996) proved the reliability of his approach (Fig. 6).

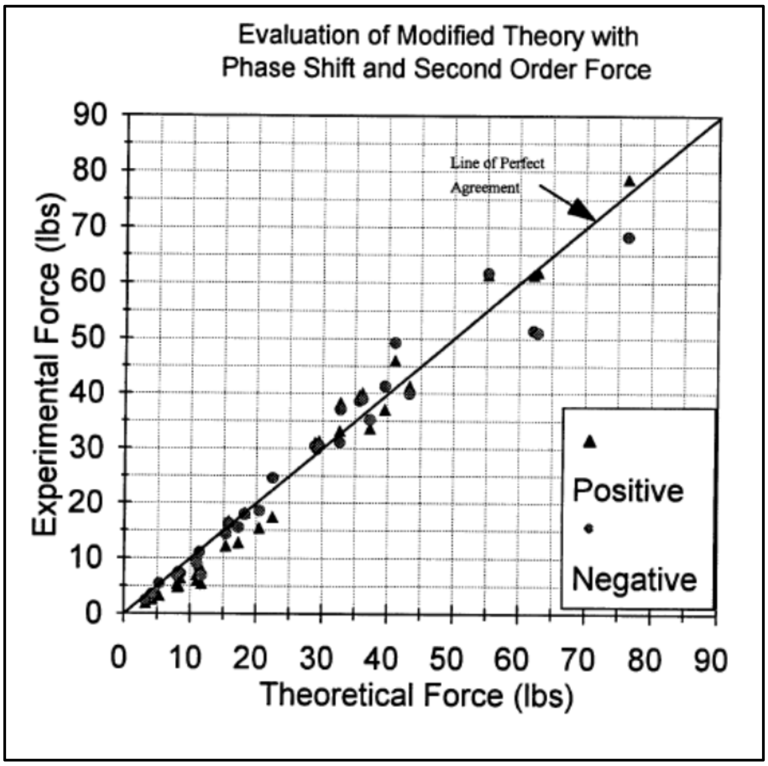

Figure 6. Comparison of Experimental Data to Design Values according to Bollmann (1996)

As for the wave transmission Kriebel et al. (1998) investigated the eigenfunction expansion method to calculate the hydraulic loads on a baffle breakwater. Opposite to the wave transmission the eigenfunction expansion method proved to be reliable but still tends to overestimate the hydraulic loads. The overestimation thereby is not as large as for the wave transmission which is explained that energy dissipation is not as crucial as for the wave transmission.

The front inclination of the baffle will not be relevant for the loading as the slope has to be reduced that much to alter the breaking conditions that the material needs are increased too much (Frese; 2011).

Concerning the influence of the inclination of the breakwater front Frese (2011) showed that for inclinations of more than 65 ° only surging breaker occur (shaded area in Fig. 7). In course for usual inclinations no influence on hydraulic function and loads are anticipated. To reduce the loads significantly the front inclination of the baffle has to be increased that much to alter the breaking conditions that the material needs are increased too much.

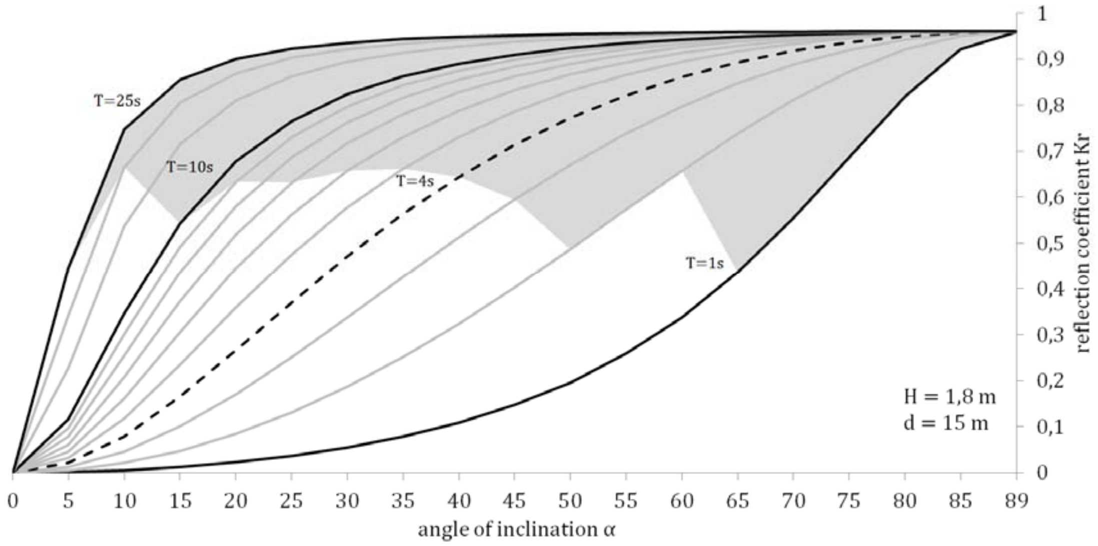

Figure 7. Influence of Front Inclination on Reflection Coefficient (Frese; 2011)

As for the Glücksburg breakwater the situation for ice loads is different. With increased inclination the load mechanism will switch from shear to bending. The loads are reduced by about 30 %. As in Glücksburg the tidal range is about 3 m the whole front is inclined. In the Baltic Sea where the tidal range is less than 50 cm locally inclined skirts are used, e.g. the so called ice cones for monopile foundations of offshore wind turbines.

SUMMARY AND RECOMMENDATIONS

Concerning the application of baffle breakwaters the following conclusions can be drawn:

Especially long waves (e.g. ship induced waves, tsunamis) have to be considered in the design of a baffle breakwater as they are not damped as good as shorter, wind induced waves. Thus near shipping lanes special care has to be taken in the design before choosing a baffle breakwater. Experiences (e.g. from Laboe) are that beside of the wave transmission at the breakwater itself the harbour geometry and the form of the quay walls are important. Further on the water depth and the soil conditions have to be taken into account.

For a high tidal range the application of baffle breakwaters has to be scrutinized as the effective application range is limited to a small band of penetration depth t/d. As the water level is out of this range the wave damping effect may decrease significantly. Floating breakwaters may be considered as an alternative because the floating object will follow the water level variations.

Finally it has to be pointed out that baffle breakwaters may be a reasonable coastal and shore protection method as well as a harbour construction element. Nevertheless in tidal rivers and navigational areas the application of baffle breakwaters have to designed very carefully and other measures may be preferred.

REFERENCES

Bollmann, C (1996): Wave interactions with vertical wave barriers, *United States Naval Academy, Annapolis*, USNA Trident Scholar report; no.237.

CEM (2006): Coastal Engineering Manual, U.S. Army Corps of Engineers (Online-Ressource)

EAK 2002 (2007): Empfehlungen für die Ausführung von Küstenschutzbauwerken – Korrigierte Ausgabe 2007. (Recommendations for Coastal Protection Works – Ammended Edition 2007) Herausgeber (Editor): „Kuratorium für Forschung im Küsteningenieurwesen“. *Die Küste*, Heft 65

Eggert, W.-D. und Kohlhase, S. (1980) Wave Transmission and Diffraction at Permeable Breakwaters. *Proceedings International Conference on Water Resources Development*, Taipei.

Eggert, W.-D. (1983): Diffraktion und Wellentransmission an Tauchwänden endlicher Länge. Ein Beitrag zur Bestimmung der Wellendämpfung teildurchlässiger Wellenbrecher (Diffraction and Wave Transmission at Baffle Breakwaters of Finite Length. Note on the Estimation of Wave Damping at Semi-Permeable Breakwaters). *Mitteilungen des Franzius-Instituts für Wasserbau und Küsteningenieurwesen*, Heft 56, Universität Hannover

Frese, M. (2011) Wirksamkeit von Tauchwänden auf die Dämpfung von Wind- und Schiffswellen unter Berücksichtigung ihrer Neigung. (Hydraulic Function of Scum Bords regarding the Damping of Ship and Wind Waves Considering their Inclination). Master Thesis in Civil Engineering, *Karlsruhe Institute of Technology*.

Goda, Y. (1985) Random seas and design of Maritime Structures. University of Tokyo Press.

Haas, H.-L.; Lenke, C. and Wünsche, B. (1981) Fähranleger Glückstadt - Wellenschutzwand aus großformatigen Betonelementen. (Ferry Berth Glückstadt – A Breakwater made of Large Concrete Elements) Beton 4/81

Kriebel, David L and Bollmann C. A. (1996) Wave Transmission past Vertical Wave Barriers. Proceedings of 25th Int. Conf. on Coastal Engineering, Orlando Florida

Kriebel, D.; Sollitt, C.; Gerken, W. (1998) Wave Forces on a Vertical Wave Barrier. Proceedings of 26th Int. Conf. on Coastal Engineering, Copenhagen Denmark

Miche, R. (1944) Mouvements ondulatoires de la mer en profundeur croissante ou decroissante. Annales des Ponts et Chaussées.

Oumeraci, H,; Kortenhaus, A.; Allsop, N.W.H.; De Groot, M.B.; Crouch, R.S.; Vrijling, J.K. and Voortman, H.G. (2001) Probabilistic Design Tools for Vertical Breakwaters. Balkema.

PIANC (1994): Floating Breakwaters – A Practical Guide for Design and Construction. *Report of Working Group no. 13 of the Permanent Technical Committee II*

Sainflou, G. (1928) Essai sur les digues maritimes verticales. Annales des Ponts et Chaussées, Vol. 98, No. 4.

Sommerfeld, A. (1896) Mathematische Theorie der Diffraktion. (Mathematical theory of Diffraction) *Mathematische Annalen*, Bd. 47.

SPM (1984): Shore Protection Manual. Vol. I + II. U.S. Army Coastal Engineering Research Center, US Army Corps of Engineers, Vicksburg.

Ursell, F (1946): The effect of a fixed vertical barrier on surface waves in deep water, *Mathematical Proceedings of the Cambridge Philosophical Society*, 43: pp. 374-382

Wiegel, R. L. (1960) Transmission of Waves Past a Rigid Vertical Thin Barrier. Journal of the Waterways and Harbors Division, Vol. 86, No. 1, pp. 1-