FLOWDIKE
INVESTIGATING THE EFFECT OF WIND AND CURRENT ON WAVE RUN-UP AND WAVE OVERTOPPING

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Abstract: This study describes the experimental work and preliminary results of investigations made on the effects of wind and currents on wave run-up and wave overtopping. The tests were carried out in the shallow water wave basin at the DHI (Hørsholm / Denmark). A detailed description of the set-up and measurements will be given followed by a parametric and a regression analysis which aims at the development of reduction factors for wind, current and obliquity. This is done with respect to the existent design formulae in the Eurotop-Manual (2007) and the results are discussed with regard to former investigations.

INTRODUCTION

In the past, a variety of structures was built to protect the hinterland during high water levels from coastal flooding or river flooding. Common use in practice is the application of smooth sloped dikes as well as steep or vertical walls. Today the knowledge of the design water level, wind surge, wave run- up and/or wave

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overtopping is used to determine the crest height of these structures. Due to the choice of the return interval of the design water level, the uncertainties in applied formulae for wave run-up or wave overtopping as well as the incoming wave parameters, wave overtopping can not be avoided.

Relevant for the freeboard design in wide rivers, estuaries and at the coast are the incoming wave parameters at the toe of the structure. These are influenced by local wind fields and strong currents - occurring at high water levels mostly parallel to the structure. Earlier investigations did not consider the combined effects of wind and current on wave run-up and wave overtopping. Only few papers, dealing either with wind effects or current influence, are published.

In 2006 Gonzalez-Escriva mentioned that strong winds may have multiple effects on wave run-up and wave overtopping (deformation of incoming wave field, generation and transport of spray, direct influence on wave run-up and wave overtopping). Especially for small overtopping rates and vertical structures the effect of wind might be significant (de Waal et al., 1996). On the other hand, the influence of wind can be neglected for high overtopping rates and/or low wind velocities (Ward et al., 1996). But it has to be stated that the information on wind influence is still scarce.

By now, no systematic investigations are available on the effect of currents on wave run-up and wave overtopping. Jensen and Frigaard (2000) performed a small number of model tests as a part of the EU-Opticrest project to investigate the influence of introducing an along shore current on wave run-up for a model of the Zeebrugge breakwater site. The results indicate an increase of the wave run-up height of about 20% by introducing a current of 1m/s in the model.

To achieve an improved design of structures the effects of wind and currents should not be neglected, otherwise the lack of knowledge results in too high and expensive structures, or in an under design of the flood protection structure which increases the risk of flooding. Therefore the objective of the EU-Hydralab-FlowDike-Project is to investigate the effects of wind and current within experimental tests. Data from former investigations like the KFKI[10] projects "Oblique wave attack at sea dikes", "Loading of the inner slope of sea dikes by wave overtopping" and the CLASH-database are used to compare and integrate the test results in already existent design approaches.

EXPERIMENTAL SETUP

Configuration

The model tests were conducted in the shallow water wave basin of the DHI in Hørsholm (Denmark). The basin has a length of 35 m, a width of 25 m and can be flooded to a maximum water depth of 0.9 m. Along the east side (35 m in length) the basin is equipped with a multidirectional wave maker composed of 36-segments. The 0.5 m wide and 1.2 m high segments can be programmed to generate, multidirectional, long or short crested waves. Dynamic wave absorption for reflected waves is integrated in the wave generation with the DHI software by an automatic control system called Active Wave Absorption Control System (AWACS). For further absorption of reflection and diffraction effects gravel and metallic wave absorbers are placed on the edges of the dike.

The wave field containing incident and reflected waves as well as a directional spreading is determined by two arrays of 5 wave gauges (with a length of 60 cm) and an

10 KFKI – German Coastal Engineering Research Council (GCERC)

Acoustic Doppler Velocity Meter (ADV) respectively Minilab SD-12. An overview given in Fig. 1 demonstrates that each of them is orthogonally aligned between the wave maker and the overtopping unit per dike crest. The surface elevation is determined by wave gauges as a change of conductivity between two electronic wires. They should be calibrated for a constant water temperature at least once a day. Hereby a calibration factor of 10 cm/1 Volt is used.

To provide aligned streamlines within the channel three rows of beverage crates are used to straighten the inflow. For constant water depth of 0.5 m within the channel a stabilised current of approx. 0.3 m/s is achieved with a maximum pump capacity of 1.2 m³/s. The second investigated current of 0.15 m/s is adjusted by reducing the pump capacity to approx. 0.6 m³/s and raising the weir position from 32.16 cm to 38.66 cm above the ground.

The wind is generated by six wind generators placed on metal stands (80 cm high) in front of the wave generator. Therefore two different frequencies are set to produce a homogenous wind field with a maximum velocity of 10 m/s (49 Hz) and a lower one of 5 m/s (25 Hz).

Data collection is simplified by using the DHI Wave Synthesizer with an acquisition frequency of 25 Hz. All acquired data are stored in dfs0- and daf-files and calibration is easily set for most instrumentation in the user interface.

This study focuses on a dike structure with a slope of 1:3. The toe of the structure is situated in a distance of 6.5 m from the wave machine. It has an over all length of 26.5 m which is necessary to generate a homogeneous wave field in front of the dike for all investigated parameter combinations. The backside and crest of the dike are brick-built with a width of 0.3 m and its core is out of compacted gravel covered with 50 mm concrete. In order to acquire wave overtopping data for freeboard heights of 0.1 m and 0.2 m the dike is divided in two sections. The first 15 m upstream the weir, the dike has a crest height of 60 cm and 11.5 m further up the crest level is 70 cm from the basin floor. A variable crest extends the 70 cm crest 7 m further downstream. This additional part made of plywood is used to change the set-up configuration during the test programme.

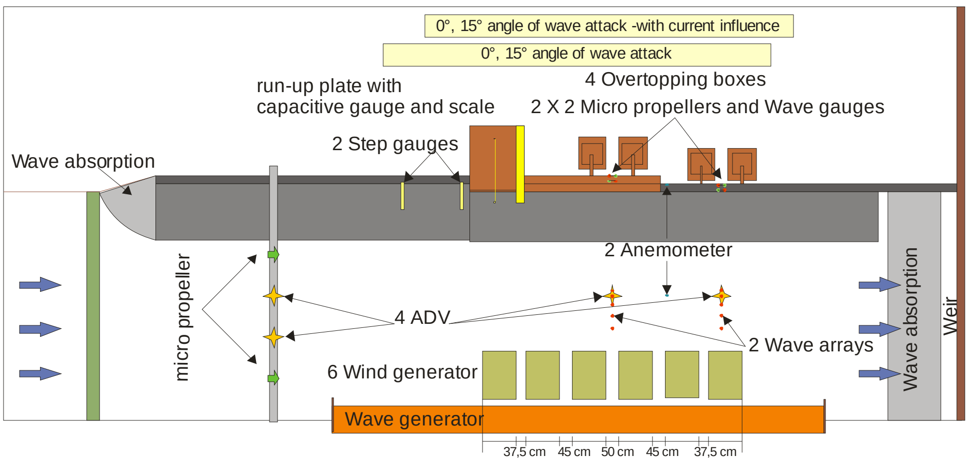

Fig. 1. Overview of the model with instruments and flow direction

A “run-up plate” of plywood (2 m x 2.5 m) is mounted on the concrete crest for the wave run-up measurement by a capacity gauge and video analysis. To prevent different roughness coefficients on the variable crest, the run-up plate and in the gap between concrete and plywood, a polish with sand is used.

The cross section for the wave overtopping unit is given in Fig. 2. For sampling of the overtopping volume a plywood channel is mounted at the landward edge of the crest and leads the incoming water directly into one of the four overtopping tanks. Two tanks are installed per section (60 cm and 70 cm crest) and the amount of water is measured by load cells and wave gauges. Dry boxes are constructed to prevent the tanks and load cells from uplift when the basin is flooded.

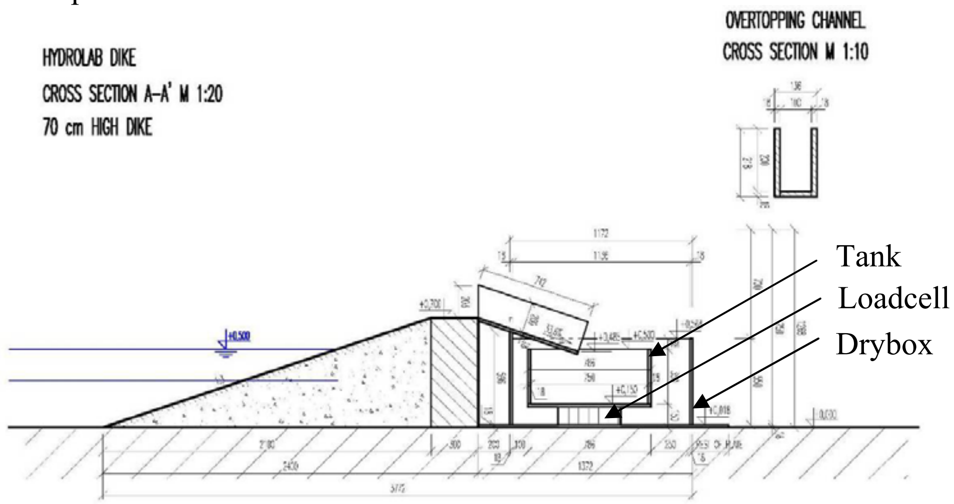

Fig. 2. Cross section of overtopping unit for the 70cm crest

Procedure

The test programme covers model tests on wave set-up, wave run-up and wave overtopping, with and without currents and with and without wind for different wave conditions. Short crested waves were generated for normal or oblique wave attack, respectively. Acquired raw data conduce to determine the degree of dependence of wave run-up and wave overtopping on wind, currents and incoming wave parameters.

A JONSWAP spectrum ($\gamma = 3.3$) is generated and controlled by using the Wave Synthesizer where a file for all six wave spectra could be stored. One test series was foreseen to contain all six wave spectra, differing from each other in significant wave height H_s, peak period T_p and Steepness s_0 as illustrated in Table 1.

Table 1. Jonswap Wave spectra – Parameters

Wave spectra	**H_s** [m]	**T_p** [s]	**Steepness s_0** [-]	**Duration** [min]	**No. of Waves**
1	0.07	1.474	0.025	23	1021
2	0.07	1.045	0.05	16	1002
3	0.1	1.76	0.025	27	1004
4	0.1	1.243	0.05	19	1001
5	0.15	2.156	0.025	33	1002
6	0.15	1.529	0.05	24	1027

The testing time was optimised by dividing the dike in three separate parts to perform wave run- up and wave overtopping at the same time. Furthermore the domain of fully developed sea state is limited by the length of the wave maker. Thus with the influence of current and angle of wave attack the section for a reliable measurement of run-up and overtopping on the dike is restricted. Three different set-up configurations are installed to cover the effective measurement range for all angles of wave attack issued within the test programme. The change of set-up is not avoidable and the test programme has to be optimised for the parameters of interest. A detailed overview of the final test programme is given in Table 2.

Table 2. Final Test Programme

Testseries	**Wave direction** [°]	**Current** [m/s]	**Wind speed** [m/s]	**Wave spectra** (ref. to Table 1)
Set-up 1				
T3	0	0.3	0	1 to 6
T8	0	0.3	10	1, 3, 5
T19	-15	0.3	0	1 to 6
T16	15	0.3	0	1 to 6
T8b	0	0.3	5	1, 3, 5
T1	0	0	0	1 to 6
T6b	0	0	5	1, 3, 5
T6	0	0	10	1, 3, 5
T12	-15	0	0	1 to 6
T11 = T3b	0	0.15	0	1 to 6
T13	-15	0.15	0	1 to 6
T15	15	0.15	0	1 to 6
Set-up 2				
T2	-30	0	0	1 to 6
T7b	-30	0	5	1, 3, 5
T7	-30	0	10	1, 3, 5
T20	-30	0.15	0	1 to 6
T4	-30	0.3	0	1 to 6
T9b	-30	0.3	5	1, 3, 5
T9	-30	0.3	10	1, 3, 5
Set-up 3				
T18	45	0	0	1 to 6
T5	30	0.3	0	1 to 6
T14	45	0.3	0	1 to 6
T21	30	0.15	0	1 to 6
T17	45	0.15	0	1 to 6

EVALUATION OF MEASURED DATA

An evaluation of the measured raw data of the wave field, overtopping and run-up is done to analyse and present the results in order to develop or modify the existent design formulae. As described previously the raw data are available from a digitalisation with $\Delta t = 0.04$ sec ($f_s = 25$Hz). In order to reduce their extent to characteristic parameters, analyses driven by time domain or by frequency domain are used. In the following only the analysis of the wave field and wave overtopping will be discussed, since detailed run-up analysis will be done in the near future.

Determining the wave field in time domain, a zero-down crossing is applied, whereby single wave events are defined. From the certain quantity (No. of waves) of the wave height H, related average values for the maximum wave height H_{max} (peak to peak decomposition) and the mean wave period $T_{p,mean}$ (event duration), can be calculated. These values are the average of all wave gauges contributing to one of the wave arrays. Other characteristic wave height parameters in time domain, such as $H_{1/3}$, have not been analysed yet.

In frequency domain the wave parameters are analysed using a reflection analysis, wherein the reflection coefficient Cr is determined at the same time. The time-series of water level elevation is transformed and analysed by a FOURIER-transformation giving the spectral energy density S(f) for incident and reflected wave and their average. Based on the moments m_n of the spectral densities, characteristic wave parameters such as $H_{m0} = 4\,(m_0)^{1/2}$ or T_p can be calculated. Since $T_{-1,0}$ could not be calculated with the applied software, the clear relation between spectral and peak period $T_p = 1.1 * T_{-1,0}$ is used (Eurotop-Manual, 2007).

The overtopping is calculated by adding the lost pump volumes (recalculation from known capacity and working period) to the collected amount within the tank. By dividing the overtopping amount by the channel width of 0.118 m and the testing duration an average overtopping rate q in [l/s m] is determined.

For data analysis the following parameters were distinguished to be analysed in a first step:

- Evaluation from wave measurements:
  - Frequency domain: H_{m0}; T_p, $T_{0,1}$; $T_{0,2}$; T_p; Cr, $T_{-1,0}$
  - Time domain: H_{max}, $T_{p,mean}$, No. of waves
  - Plots: time series, energy density, reflection function
- Analysis from wave overtopping:
  - Time domain: overtopping waves for 0.1 m/0.2 m freeboard, q
  - Plots: time series, exceedance curves

PRELIMINARY RESULTS

Remarks

The tests were carried out with short crested waves using a JONSWAP spectrum. According to the test set up in Fig. 1 wave run-up and wave overtopping were measured in separate sections in the middle of the dike to avoid the influence of edge effects. As described in the previous chapter wave field analysis are implemented in time and frequency domain. Existent approaches and theoretical investigations are used to verify and compare the data.

Wave field

To validate the application of a homogenous JONSWAP spectrum, the results from reflection and crossing analysis are evaluated. From the reflection analysis which is performed in frequency domain, the plotted distribution of energy density in Fig. 3 corresponds to the theoretical assumption for a JONSWAP spectrum to be single peaked.

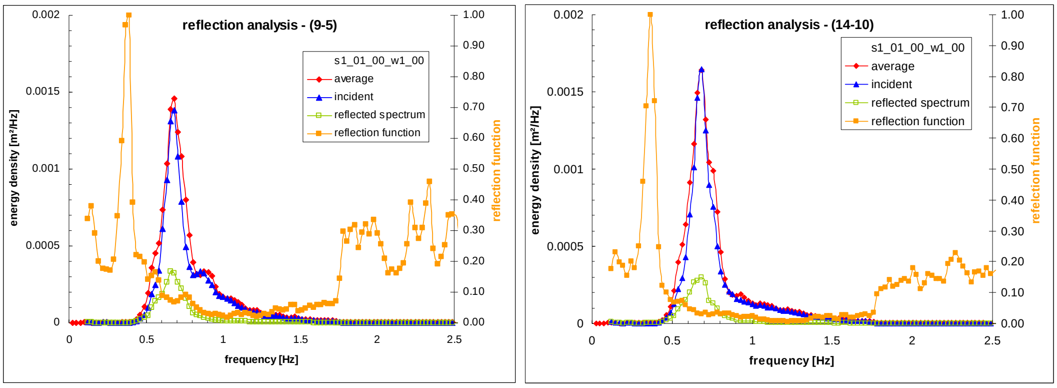

Fig. 3. Results for spectral energy density (frequency domain) for wave array 9-5 (left) and wave array 14-10 (right)

Fig. 4 depicts the Raleigh distribution of wave heights for both wave arrays, as it is common for JONSWAP spectra. The abscissa is fitted to a Raleigh scale; this is the reason why a linear distribution is noticeable. The similarity of their shape indicates the homogeneous arrangement for both crest heights.

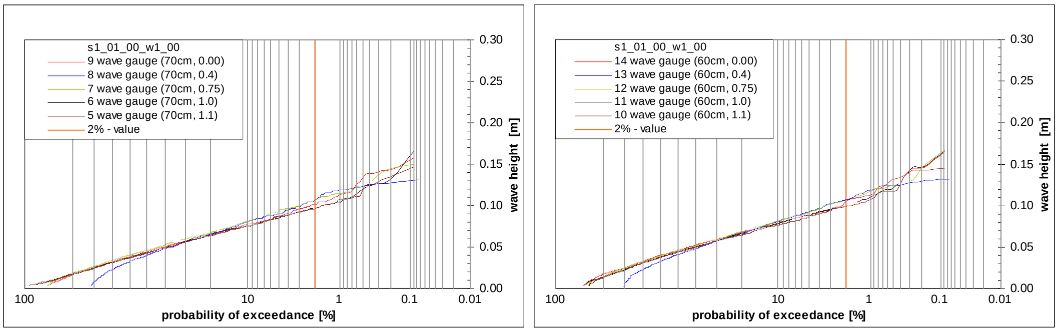

Fig. 4. Linear distribution of wave height H_{m0} over a Raleigh scale for a Jonswap spectrum for wave array 9-5 (left) and wave array 14-10 (right)

Homogeneity of wind field

To prove a homogeneous distributed wind field along the dike, the wind velocity for two different frequencies are measured with a propeller within defined distances. Reflection effects induced by the water surface and parallel flow from adjacent generators are observed by an increase of the velocity range.

In Fig. 5 and Fig. 6 the results for 49 Hz and 25 Hz are plotted along the dike. The wind velocity is assumed to be 10 m/s respectively 5 m/s in the following analyses.

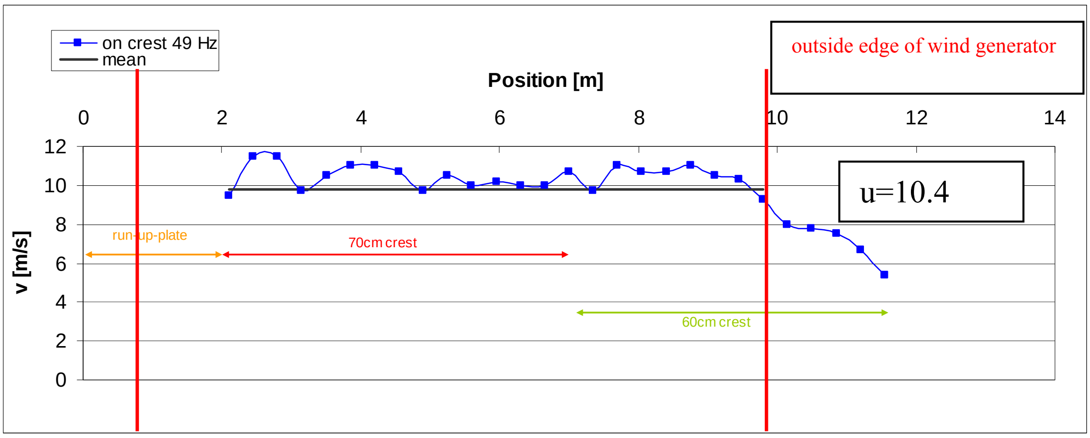

Fig. 5. Wind velocity distribution for a frequency of 49 Hz

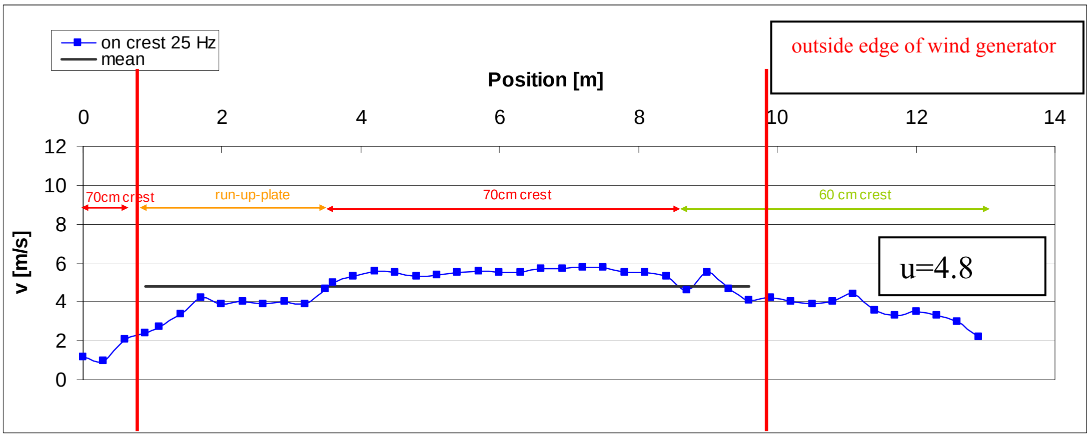

Fig. 6. Wind velocity distribution for a frequency of 25 Hz

Wave overtopping tests

The objective of the wave overtopping tests is to study the influence of currents and wind on the average wave overtopping rate q. Furthermore, the influence of oblique wave attack is identified and compared to former investigations by Oumeraci et al. (2001). Wave overtopping tests were performed corresponding to the test programme listed in Table 2. Using dimensionless factors for the average wave overtopping rate and a dimensionless freeboard height, presented in the Eurotop-Manual (2007), all four overtopping tanks for both crest heights could be included in the analysis. The dimensionless factors correspond to an exponential relationship used for the design formula of the average overtopping rate.

$$Q_* = Q_0 \cdot \exp(-b \cdot R_*) \qquad (1)$$

with: Q_0, b = dimensionless factors

Formulas for breaking ($\xi_{m\,1,0} < 2$; (2)) and non-breaking ($\xi_{m-1,0} \geq 2$; (3)) conditions determine the dimensionless parameters Q_* and R_* :

$$Q_* = \frac{q}{\sqrt{g \cdot H_{m0}^{\ 3}}} \cdot \sqrt{\frac{s_{m-1,0}}{\tan\alpha}}\ ;\ R_* = \frac{R_C}{H_{m0}} \cdot \frac{\sqrt{s_{m-1,0}}}{\tan\alpha} \tag{2}$$

with: $\frac{1}{\xi_{m-1,0}} = \frac{\sqrt{s_{m-1,0}}}{\tan\alpha}$

$$Q_* = \frac{q}{\sqrt{g \cdot H_{m0}^{\ 3}}}\ ;\ R_* = \frac{R_C}{H_{m0}} \tag{3}$$

where: Q_* = dimensionless overtopping rate; R_* = dimensionless freeboard; H_{m0} = significant wave height; $s_{m-1,0}$ = steepness; $\xi_{m-1,0}$ = Iribarren number (surf similarity parameter); α = angle of slope

Reduction factors for obliqueness and current (γ_θ; γ_C) and in case of the wind influence an increasing factor (γ_W) can be investigated by comparison of the different exponential coefficients b (see formula (4)). The coefficient b is obtained using a regression analysis for the test series of the decisive parameter, e.g. in Fig. 7 and Fig. 8 the corresponding graphs for current influence are shown. Therefore the distinction is made between breaking and non breaking waves.

$$\gamma_{\Theta,C,W} = \frac{b(\theta,C,W)}{b(\theta,C,W=0)} \tag{4}$$

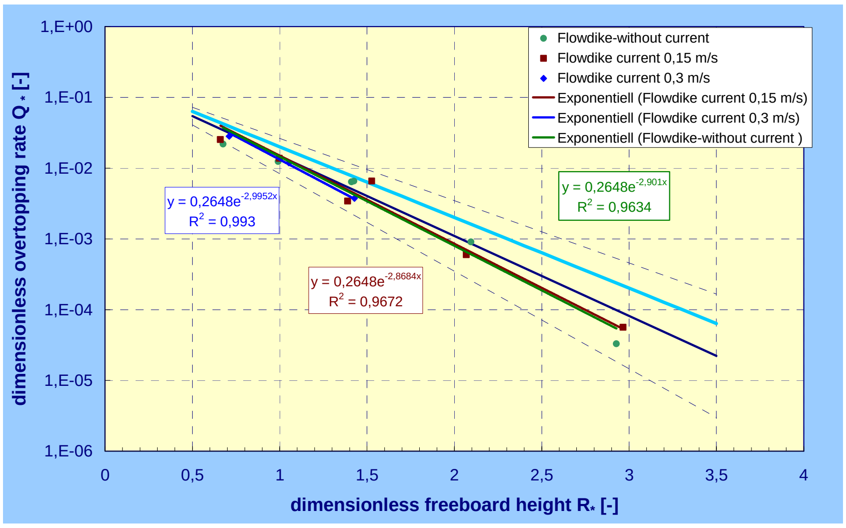

Fig. 7. Wave overtopping data influenced by current (non-breaking)

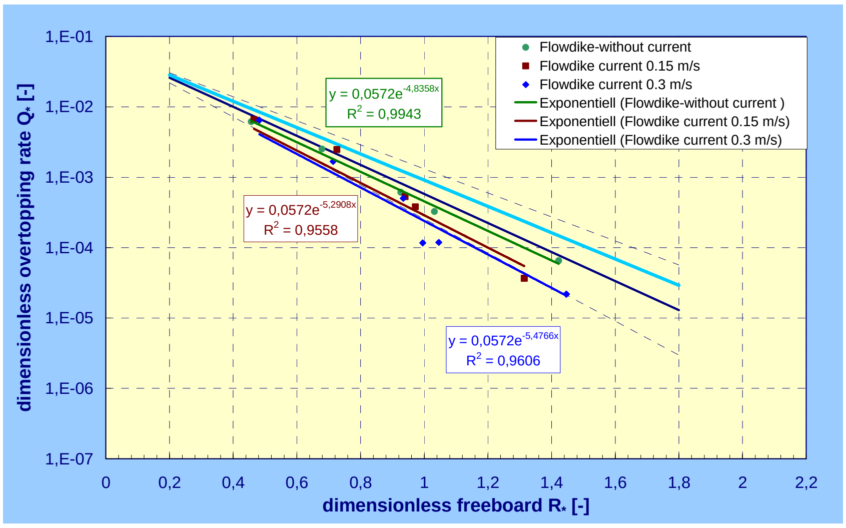

Fig. 8.Wave overtopping data influenced by current (breaking waves)

In Table 3 the calculated factors for all influencing parameters are summarised. It has to be mentioned, that all parameters included in the analyses are average values along the dike (average overtopping rate of two tanks per crest and characteristic wave parameters for each crest determined by the corresponding wave array). Furthermore, these results are preliminary and more detailed analyses will follow.

Validating the setup for oblique waves, the resulting reduction factors are compared with results from former investigations by Oumeraci et al. (2001) in Fig. 9.

Table 3. Factors for obliquity, current and wind influence

Breaking Waves			**Non-breaking Waves**		
θ	**b**	**γ_θ**	**θ**	**b**	**γ_θ**
0°	-4.8358	1.000	0°	-2.901	1.000
-15°	-5.1857	0.933	-15°	-3.016	0.962
-30°	-6.2685	0.771	-30°	-3.419	0.848
45°	-8.03	0.602	45°	No data	no data
Current	**b**	**γ_C**	**Current**	**B**	**γ_C**
0m/S	-4.8358	1.000	0m/S	-2.901	1.000
0.15m/s	-5.291	0.914	0.15m/s	-2.868	1.011
0.3m/S	-5.477	0.883	0.3m/S	-2.995	0.969
Wind	**b**	**γ_W**	**Wind**	**B**	**γ_W**
0m/S	-4.8358	1.000	0m/S	-2.901	1.000
5m/s	no data	no data	5m/s	-2.757	1.052
10m/S	no data	no data	10m/S	-2.730	1.063

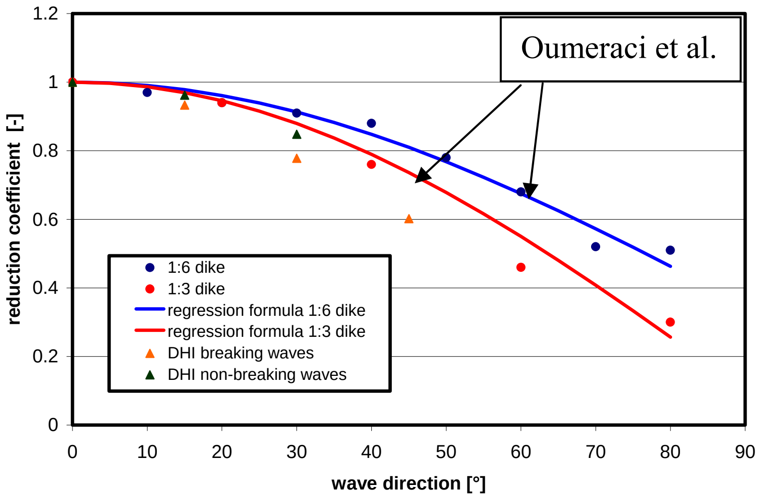

Fig. 9. Comparison of reduction coefficients

CONCLUSIONS

In the past a large variety of investigations concerning wave run-up and wave overtopping has been performed. Given by the diversity of influencing factors, uncertainties will still remain which have to be considered in the design of dikes in estuarine and coastal areas. Therefore, model tests are conducted in order to indicate these parameters. Parallel current and wind are two of the missing effects in freeboard design; hence model tests were performed in a shallow water wave basin at DHI (Denmark). The investigations carried out on a 1:3 sloped dike, used a JONSWAP spectrum with short crested waves.

As main objective of these tests can be declared:

- the influence of dike parallel currents on wave run-up and wave overtopping
- the influence of wind on wave run-up and wave overtopping, due to the direct influence by friction

First analysis covering the distribution of the wave field and the wind approved the sea state to be a JONSWAP spectrum and that the applied wind field is homogeneous. The model tests on wave overtopping confirmed the stated assumptions by Gonzalez-Escriva and de Waal concerning the significant wind impact on overtopping. Furthermore, the influence of oblique waves on overtopping has been validated. Preliminary correction factors (γ_θ; γ_C; γ_W) were designated for each influencing parameter of this validation. It can be stated that increasing overtopping volumes were determined for wind application, as well as decreasing volumes for test series with currents or oblique waves.

Finally the combined effects for wind, current and obliquity is still a matter of further analysis, especially the adoption of the factors by formulas has to be investigated. In addition, more theoretical work is required to determine the effect of currents on wave evolution and the resulting wave run-up and wave overtopping processes.

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