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THE INFLUENCE OF CURRENT ON THE HEIGHT OF WIND WAVE RUN-UP
A comparison of experimental results with the Czech National Standard

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One of the basic questions related to the safety of dikes and river levees is the size of the freeboard. One of the important parameters for freeboard design is the height of waves and wave run-up on levee slopes. Routine and standardised calculations of wave run-up deal with the freeboards of dams where wind waves originate on the still water of the reservoir. In the case of running water in streams (thereinafter only "currents") the effect of wave and current interaction on wave run-up is usually not taken into account due to the lack of reliable knowledge regarding the phenomenon. In the Czech Republic this question is topical in the case of large rivers such as the Elbe, the Vltava and the Morava. Within the framework of the projects Hydralab III and NAZV QI 92A139, hydraulic research and further analysis focused on wave run-up as a result of the combination of current and wind wave parameters were performed. The laboratory research was carried out in a hydraulic flume with a wavemaker on the right bank and a levee with a slope of 1:3 installed on the left bank opposite the wavemaker. Waves were generated both perpendicular and oblique to the levee axis; the angle of oblique wave attack varied within the range of ± 30°. The aim of this paper is to compare the results of the mentioned research with recommendations mentioned in the Czech National Standard CSN 75 0255 *Calculation of wave effects on water structures* and to quantify the effect of current on the wave run-up height.

KEY WORDS: Levee, Dike, Wind Wave, Wave Height, Wave Run-up, Current, Freeboard Design.

Jaromír Říha, Miroslav Špano: VLIV PROUDĚNÍ NA VÝŠKU VÝBĚHU VĚTROVÝCH VLN, POROVNÁNÍ VÝSLEDKŮ EXPERIMENTU S ČESKOU STÁTNÍ NORMOU. J. Hydrol. Hydromech., *60*, 2012, 3; 19 lit., 11 obr., 3 tab.

Jednou ze základních otázek spojených s bezpečností hráze je návrh převýšení její koruny nad maximální hladinou vzdouvané vody. Důležitým parametrem ovlivňujícím návrh převýšení je výška vln vybíhajících po svahu hráze. Běžné postupy výpočtu výšky výběhu vlny na svah jsou realizovány za předpokladu, že vlny vznikají na stojatých vodách. Vliv proudění se obvykle vzhledem k nízké úrovni znalostí tohoto jevu na tekoucích vodách zanedbává. V podmínkách České Republiky je otázka vlivu proudění na výšku výběhu relevantní zejména na velkých tocích jako Labe, Vltava nebo Morava. V rámci projektů Hydralab III a NAZV QI 92A139 byl uskutečněn hydraulický výzkum a analýza dat se speciálním zaměřením na výšku výběhu větrových vln při započtení vlivu proudění. Výzkum byl realizován na modelu hráze se sklonem svahu 1 : 3, který byl umístěn ve zkušební nádrži osazené vlnoproduktorem vedeným rovnoběžně s modelem hráze. Vlny zde byly generovány jednak kolmo vzhledem k podélné ose hráze, jednak šikmo v rozsahu úhlů ± 30°. Výsledky výzkumu byly porovnány s doporučeními uvedenými v České státní normě ČSN 75 0255 *Výpočet účinků vln na stavby na vodních nádržích a zdržích*.

KLÍČOVÁ SLOVA: ochranná hráz, hrázka, větrová vlna, výška vlny, výběh vlny, proudění, návrh převýšení.

Introduction and aim of the study

One of the most important parameters for levee freeboard design is the height of the waves and namely wave run-up height on the upstream slope. At present the freeboard at levees is frequently designed omitting the effect of wind wave run-up. If calculated, the run-up is determined using the still water assumption due to the lack of knowledge about the wave run-up for running water. In the Czech Republic the calculation procedure for the determination of wind wave height and run-up height is described in the Czech National Standard CSN 75 0255 *Calculation of wave effects on water structures*.

The above standard was originally focused on wave run-up on the upstream slopes of embankment dams. In case of large rivers, e.g. the Elbe, Vltava or Morava rivers in the Czech Republic, improved knowledge about the effect of currents on wave run-up could aid in optimizing and improving the precision of freeboard design.

Within the framework of the international project Hydralab III hydraulic research was carried out with the aim of quantifying the effect of current on wave run-up. The research was carried out at the Laboratory of the Danish Hydraulic Institute (DHI) in Hørsholm, Denmark, in the first half of 2009. In total, 119 tests were performed in a flume with a left-bank levee with an upstream slope of 1 : 3 and a right-bank wave generator. Waves were generated both in the perpendicular direction and oblique to the dike within the range of $\pm 30^0$ against (–) and along (+) the direction of flow. In the case of 24 tests the wave run-up was generated including the effect of wind produced when wind blowers were operated. Only the 95 tests that did not include the additional wind effect fall within the scope of the current study.

The large amount of data obtained from Hydralab III was processed and analysed during the years 2009 and 2010 as a part of the national research project NAZV QI 92A139. The aim of this study is to assess the effect of current on the wave and run-up height on a levee slope of 1 : 3. Part of the analysis is a comparison between the experimentally obtained results from Hydralab III and the recommendations of the above-mentioned standard CSN 75 0255.

Literature review

Previous investigations of wave run-up on levee slopes started before 1935 and were carried out in the context of coastal structures such as dikes (*Wassing*, 1957; *Gibson*, 1930). Since that time many investigations have been carried out. These include laboratory and field experiments, numerical modelling, and theoretical works.

In the former Czechoslovakia comprehensive research on wave height and run-up was carried out by *Kratochvil* (1970). He reviewed the research results of several authors and proposed a relation between relative wave run-up, wave steepness and slope inclination. The results derived are valid for smooth impermeable slopes and wave parameters in what can be termed deep water. Later, the technique was completed by including periodic wave transformation during the transition from deep to shallow water (*Kratochvil*, 1976). Follow-up research by *Kratochvil*, (1980) resulted in the proposal of a complex method for the computation of wave effects on vertical and inclined slopes for still water conditions. These works formed the basic foundation for the proposal of the Czech National Standard (CSN 75 0255) in 1987.

Empirical formulas for wave run-up estimation are still widely used and recommended worldwide. The effect of oblique wave attack, berms, surface roughness, etc. is considered via simple correction factors in the formulas derived by various authors. The national standard CSN 75 0255 is recommended in the Czech Republic. A similar approach is described in *Van der Meer* et al. (1998) or *Eurotop-Manual* (2007), which provide a good overview of the present state of crest level design for coastal structures. Together with the run-up height the overtopping amount and its effect on the dike is often a studied topic (*Eurotop-Manual*, 2007; *Lorke* et al. 2010b). In case of overtopping the dike is usualy assumed as broad crested weir with rough surface (*Goodarzi* et al., 2012; *Parilkova* et al., 2012).

Some information on additional effects caused by high wind velocity (deformation of wave fields, generation and transport of spray, direct influences on wave run-up) is given by *Ward* et al. (1996) and *Gonzalez-Escriva* (2006). However, only a little research data can be found regarding the effects of these factors on wave height and run-up. The main problem for hydraulic models is the scale effect. According to *Yamashiro* et al. (2006) the scale factor for wind velocity should not be less than 1/3, while most experiments are scaled within the range of 1/10 to 1/45. In practice, the effect of strong wind should be taken into account during the design process. In CSN 75 0255 the additional wind effect is taken into account via heightened still water level in the reservoir at the dam toe.

Almost no systematic investigations regarding the influence of current (e.g. in wider rivers) on wave run-up are available. A small number of model tests are described in *Jensen* and *Frigaard* (2000). The results indicate an increase in the wave run-up height of about 20% after the introduction of a longshore current velocity of 1 m s^{-1} in the model. As CSN 75 0255 only deals with waves on reservoirs, no effect of current is dealt within this standard.

The first study on the interaction of waves and current was performed by *Lorke* et al. (2010a) and *Lorke* et al. (2010b). It is focused on wave – current interaction and it introduces two principal approaches. The first is focused on the wave run-up itself and determines the correction factor for current velocity. The second approach attempts to describe the influence of current on the wave parameters which are later used for the prediction of wave run-up. Based on the results of *Lorke* et al. (2010a) it is concluded that both approaches are practicable. Both approaches were applied with respect to standards used in Germany and the Netherlands which are summarized in *Eurotop-Manual* (2007). Since CSN 75 0255 uses a slightly different approach for the prediction of wave run-up compared with *Eurotop-Manual* (2007), the application of results reached by *Lorke* et al. (2010a) is not described in the present paper.

Theoretical background

Wave run-up height depends on a set of variables, namely on the wave parameters, the gravity, geometric and dynamic characteristics of the levee scheme, and the physical properties of the air and water. The wave parameters are wave height h, wave length L, wave period T, and the angle β of oblique wave attack. The scheme's characteristics are water depth H and mean current velocity v in the stream, and also geometrical properties such as levee slope α, slope friction and permeability, etc. The physical properties are water density ρ, surface tension, etc. A schematic diagram of wave run-up with the mentioned variables is shown in Fig. 1.

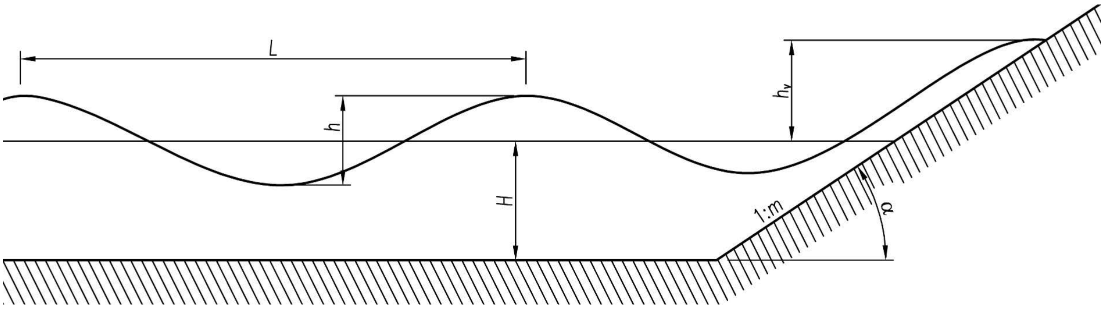

Fig. 1. Schematic diagram of wave run-up.

If the surface tension effect is neglected the run-up height can be expressed by the general functional relation (*Kratochvil*, 1970):

$$f(h_v, h, L, c, T, H, E, \beta, v, \rho, g, d, q, \alpha) = 0\,, \qquad (1)$$

where h_v is the run-up height [m], h – wave height [m], L – wave length [m], c – wave celerity [m s^{-1}], T – wave period [s], H – water depth [m], E – wave energy [J], β – the angle of oblique wave attack [rad, ^{0}], v – mean current velocity [m s^{-1}], ρ – water density [kg m^{-3}], g – gravity acceleration [m s^{-2}], d – the equivalent roughness size of the levee slope [m], q – the permeability of the slope [m s^{-1}], and α is the slope angle [rad, ^{0}].

Some variables are related via the theory of gravitational waves (Eqs. (2), (3) and (4)), see *Kratochvil*, (1969, 1970). The consideration of an impermeable slope implies in Eq. (5).

$$T = \frac{L}{c}\,, \qquad (2)$$

$$c = f(h, L, H)\,, \qquad (3)$$

$$E = f(\rho, g, h, L, H)\,, \qquad (4)$$

$$q = 0\,. \qquad (5)$$

Relation (1) is then simplified as follows:

$$f(h_v, h, L, H, \beta, v, \rho, g, d, \alpha) = 0. \qquad (6)$$

Dimensional analysis (*Apsley*, 2004; *Hanche-Olsen*, 2004) applied to (6) yields:

$$F\left(\frac{h_v}{h}, \frac{h}{L}, \frac{H}{L}, \alpha, \frac{d}{h}, \beta, \mathrm{Fr}_H = \frac{v}{\sqrt{gH}}\right) = 0\,. \qquad (7)$$

As it is not easy (in most cases it is even impossible) to express wave height and corresponding run-up height analytically, empirical formulas are used for this purpose (*Kratochvil*, 1970; *Eurotop-Manual*, 2007). The effect of individual wave parameters and other characteristics mentioned above is expressed via correction factors here. In our case the following correction factors are defined

$$k_p = f\left(\frac{h}{L}, \frac{H}{L}, \alpha\right), \quad (8)$$

$$k_d = f\left(\frac{d}{h}\right), \quad (9)$$

$$k_{\beta v} = f\left(\beta, \mathrm{Fr}_H\right), \quad (10)$$

where k_p is the correction factor for wave parameters (function of wave steepness, water depth and slope) [–], k_d – the factor for slope roughness [–], $k_{\beta v}$ – the correction factor for oblique wave attack combined with the mean current velocity [–], and Fr_H is the Froude number.

Since wave characteristics (height and length) are the result of more or less random processes, a statistical approach is introduced for the prediction of wave run-up height. For practical use a 2 % probability of run-up height exceedance is recommended in *Eurotop-Manual* (2007), which is the result of the observations and discussions of experts. CSN 75 0255 introduces the exceedance probability in dependence on given conditions. 13 % exceedance is usually recommended for e.g. loads, freeboard height design, etc.; 1 % is recommended for the design of the lining of the upstream dam face. For the run-up height calculation a 1 % exceedance probability is used according to CSN 75 0255 any other exceedance probability is taken into account via the correction factor k_n shown in Tab. 1.

T a b l e 1. Correction factor k_n according the CSN 75 0255.

Exceedance probability [%]	0.1	1	2	5	10	13	30	50
Correction factor k_n	1.1	1.0	0.96	0.91	0.86	0.85	0.76	0.68

The following dimensionless form of Eq. (7) taking into account formulas (8) to (10) and the exceedance probability correction factor k_n can be applied:

$$\frac{h_{vn}}{h_1} = k_p k_d k_n k_{\beta v}. \quad (11)$$

Note that under still water conditions ($\mathrm{Fr}_H = 0$) the correction factor $k_{\beta v}$ depends on the angle of oblique wave attack only. It therefore corresponds to the ordinary factor of oblique wave attack k_β known from the literature, i.e. CSN 75 0255 or *Eurotop-Manual* (2007).

In Eq. (11) h_{vn} is the run-up height exceeded by the n-% of incident waves [m], while h_1 is the wave height exceeded by 1 % of all wave heights [m].

As the analysis in this study is carried out for a levee slope of 1 : 3, the correction factor k_p for wave parameters is taken from CSN 75 0255, and expressed graphically in Fig. 2. The levee surface used in the model was smooth and impermeable, which resulted in the correction factor $k_d = 1.0$. The probability of exceedance was assumed to be $n = 1\%$ in this study. This implies a correction factor of $k_n = 1.0$ (see Tab. 1).

For the above-mentioned conditions the equation for run-up height prediction can be simplified as follows:

$$\frac{h_{v1}}{h_1} = k_p k_{\beta v}. \quad (12)$$

This formula was subject to an analysis with the purpose of deriving the value of correction factor $k_{\beta v}$.

Methodology

The overall steps involved in the methodology are as follows:

- experimental research consisting of:
  - generation of waves with specific parameters based on JONSWAP spectra,
  - measurement of the wave and run-up heights for individual tests,
- statistical processing of the measured data,
- comparison of measured values for still water conditions with the recommendations of CSN 75 0255,
- assessment of the effect of current velocity on wave run-up height.

In the Hydralab project, six types of irregular waves were generated based on JONSWAP spectra (*Hasselmann* et al., 1973). The basic parameters of the waves were set so as to simulate waves on large rivers and estuaries. The wave parameters used for wave generation correspond to approaches de-

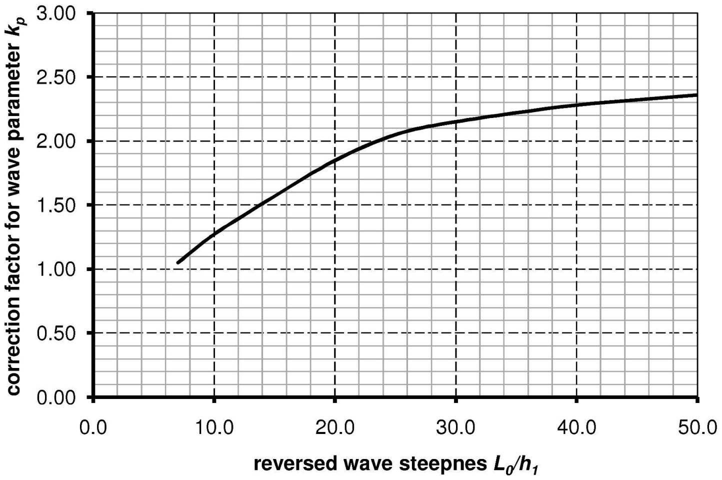

Fig. 2. Correction factor k_p of wave parameters for a slope of 1 : 3 according to CSN 75 0255.

scribed in *Eurotop-Manual* (2007), so the measured wave and run-up characteristics were used within this study when comparing results with CSN 75 0255.

For each of the 95 tests continuous measurement of wave and run-up heights was carried out using 10 probes for wave height and one probe for run-up height.

To achieve information on measured wave and run-up characteristics the data obtained were statistically processed. The first step involved data filtering to achieve a set of measured wave heights and periods. Here the wave height h is defined as the difference between peaks above and below the stable water level (Fig. 1). The same principle was used for filtering the run-up height data. Wave and run-up heights with an exceedance probability of 1 % were then computed as the 99th percentile from the measured data.

Knowing the values of correction factor k_p, correction factor $k_{\beta v}$ for oblique wave attack combined with the mean current velocity effect was computed by the least squares method:

$$\Sigma\left(\left(\frac{h_{v1}}{h_1}\right)_{\text{measured}} - k_p k_{\beta v}\right)^2 = \min . \qquad (13)$$

The correction factor for oblique attack was computed first for still water conditions in which $k_{\beta v} = k_\beta$. Then, the correction factor $k_{\beta v}$ covering the influence of current velocity was computed based on data measured under running water conditions.

The wave run-up heights obtained were compared with the recommended values in CSN 75 0255.

Hydraulic research

The extensive hydraulic research on wave run-up height as a result of wave and water current interaction was carried out within an international project, Hydralab III, involving the cooperation of international partners from Germany, Netherlands, the Czech Republic and Spain.

Description of the hydraulic model

The levee model used in the above-mentioned research was built in a shallow water basin at the DHI laboratory in Hørsholm, Denmark. The basin dimensions were 35 x 25 x 1.5 m. The basin was equipped with an 18 m long multidirectional wavemaker with 36 paddles. The basin was connected to a hydraulic circuit with a maximum capacity of approximately 3 m^3 s^{-1}. The wavemaker was controlled by a DHI software package called Wave Synthesizer.

The experimental investigations were performed on a simple 1 : 3 slope typical for river levees and estuarine dikes. The 25.5 m long levee was built parallel to the wavemaker at a distance of 6.5 m. The levee was divided into two parts with heights of 0.7 m (run-up plate) and 0.6 m (overtopping section) respectively. The relatively smooth levee surface was made of concrete. A gravel wave absorber was constructed at the upstream part of the levee.

Stilling arrangements were installed at the inflow part to ensure uniform flow. Metallic wave absorbers were installed at the outflow part of the flume upstream of the adjustable weir to stabilize the flow. The weir was used to set-up both the still water level and also the discharge. Wind generation was provided by six wind blowers. The ground plan layout of the model is shown in Fig. 3; a view of the model is shown in Fig. 4.

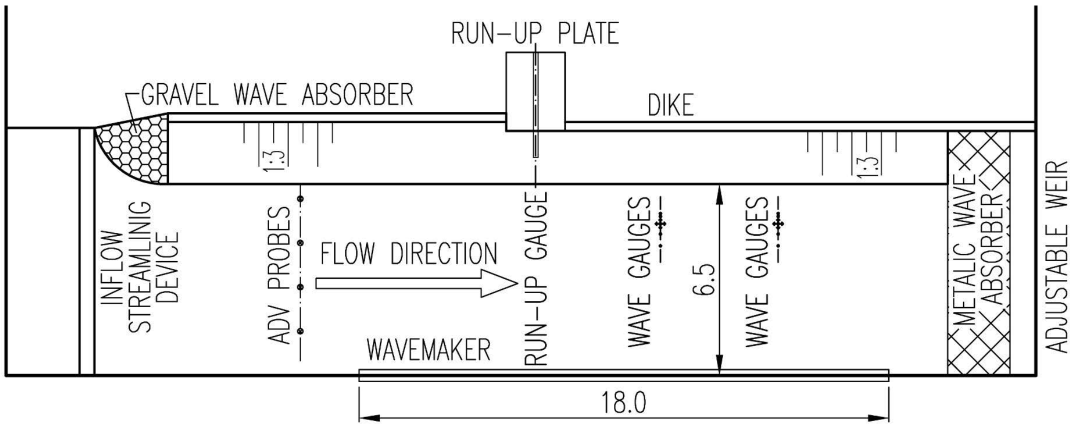

Fig. 3. Ground plan layout of the model, dimension in meters.

Fig. 4. View of the model (upper image: downstream view; lower images: upstream view).

Measuring instruments

Water depth was measured with wave gauges while wave run-up was measured with a capacitive gauge. Calibration of both types of gauges was carried out in stable water level conditions. Current velocity was measured with ADV (Acoustic Doppler Velocimeter) probes. These probes enable the measurement of all three velocity vector directions.

Measurement of water depth was performed by 10 gauges arranged along two lines (each equipped with five gauges). The capacitive gauge was installed on the run-up plate (Fig. 3, Fig. 4 lower right).

Uncertainty of measurements is given by combination of measuring device accuracy and other effects (like setup geometry, temperature, etc.). The accuracy of used capacitive gauges is up to 5 mm for wave height and 10 mm for wave run-up. The accuracy of ADV probe is 1 %. Depending on the range of measured wave and run-up heights and current velocities the total uncertainty of measurements should not exceed 6 %.

Experiments

Within the Hydralab III project 95 tests were processed and analysed. Each test represents a combination of basic wave properties (height and period), wave angle and mean current velocity only, with no additional wind effect.

Water depth was set to $H = 0.5$ m for all tests. Mean current velocity was set at $v = \{0.00; 0.15; 0.30\}$ m s^{-1}, which corresponds to the discharge $Q = \{0.0; 0.6; 1.2\}$ m^3 s^{-1} or to the Froude number related to water depth $Fr_H = \{0.00; 0.07; 0.14\}$. Waves were generated for a range of angles $\beta = \{-30; -15; 0; 15; 30\}$°. Here, zero degrees expresses waves perpendicular to the levee axis; a negative value means that waves are generated against the current.

Results and discussion

The main aim of the measurement analysis was to determine the influence of the current velocity on the wave run-up height via a correction factor. Within the analysis the effect of oblique wave attack was also observed and compared to recommendations published in CSN 75 0255.

Effect of oblique wave attack

The correction factor k_β of oblique attack for still water conditions derived from individual measured data, the corresponding values calculated from Eq. (13) using root mean square method (RMS) and the values taken from CSN 75 0255 are shown in Fig. 5 and Tab. 2.

T a b l e 2. Correction factor k_β for oblique wave attack at still water conditions.

β [°]	k_β	
	Measured RMS	CSN 75 0255
0	0.97	1.00
15	1.01	0.97
30	0.93	0.92

The results show there are some differences between the measured data and the data taken from CSN 75 0255. The evaluation of the correction factor k_β from Eq. (13) for angle $\beta = 0°$ indicates a minor measurement deviation when compared with the anticipated value $k_\beta = 1.0$ recommended by CSN 75 0255. This is particularly the result of the random nature of the waves generated and of the limited accuracy attained in the measurement of all related variables.

The main difference identified is seen in the case of the angle of oblique attack $\beta = 15°$, when the k_β value slightly exceeds the value of 1.0 (Fig. 5). However, a similar trend exhibited by correction factor k_β is described in *Schüttrumpf* et al. (2003), and is also summarized in *Eurotop-Manual* (2007). A more reliable and accurate understanding of this phenomenon will require additional research focused on a larger variety of angles of oblique attack.

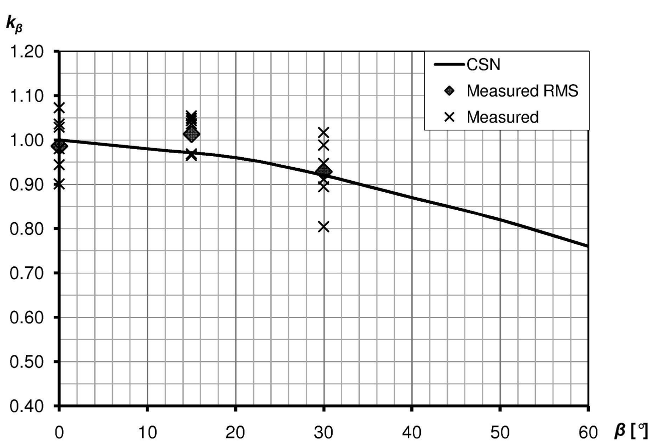

Fig. 5. Correction factor k_β for oblique wave attack under still water conditions.

The effect of current

The results of measurements shown as a function of relative run-up height on reverse steepness of wave for given angles of oblique attack can be seen in Fig. 6 to Fig. 10.

The results demonstrate that there is good agreement between the measured values and the CSN prediction for still water (mean current velocity $v = 0.0$ m s^{-1}), but also surprisingly even for slowly flowing water. The effect of current velocity on wave run-up does not exceed 10 % in most cases.

As shown in Fig. 6 and Fig. 7, the difference between the run-up height in the case of waves generated against the current and those generated under non-flowing conditions is practically negligible. Run-up height caused by waves generated along the direction of flow is slightly lower compared to that for non-flowing water up to the angle $\beta = 30°$; see Fig. 9 and Fig. 10. This effect is clear mainly at the angle $\beta = 30°$ (Fig. 10).

The correction factor for current velocity was computed including the effect of oblique wave attack. The factor values are shown in Fig. 11 and summarized in Tab. 3.

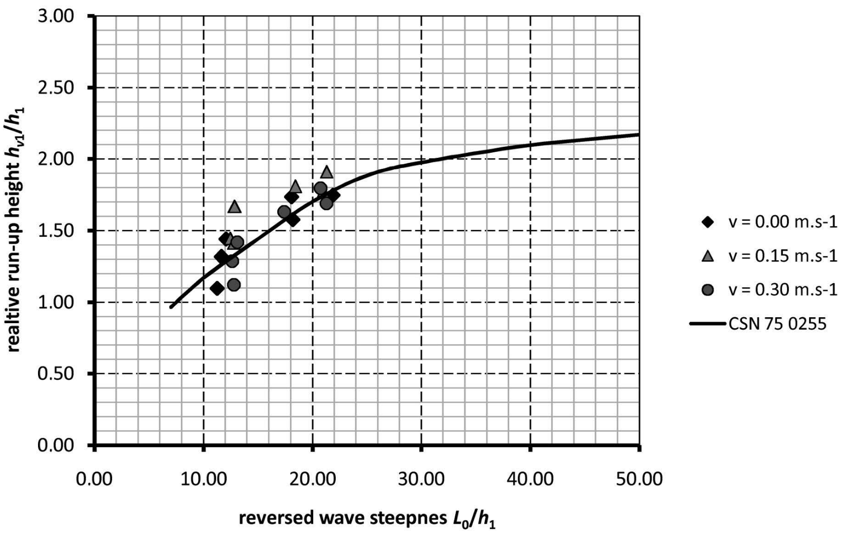

Fig. 6. Relative run-up in dependence on current velocity at the angle of attack $\beta = -30°$.

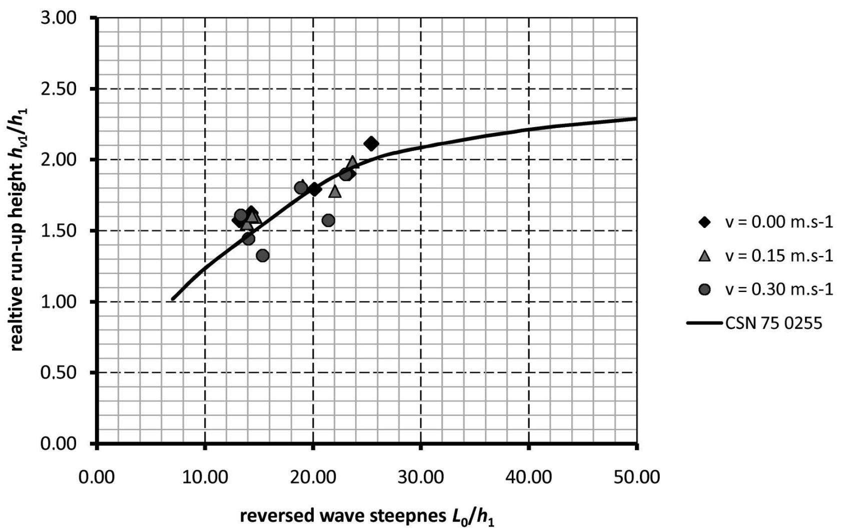

Fig. 7. Relative run-up in dependence on current velocity at the angle of attack $\beta = -15°$.

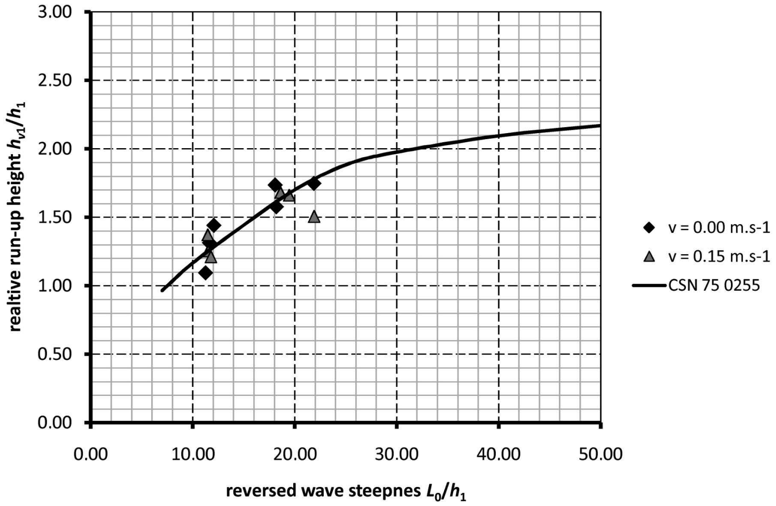

Fig. 8. Relative run-up in dependence on current velocity at the angle of attack $\beta = 0°$.

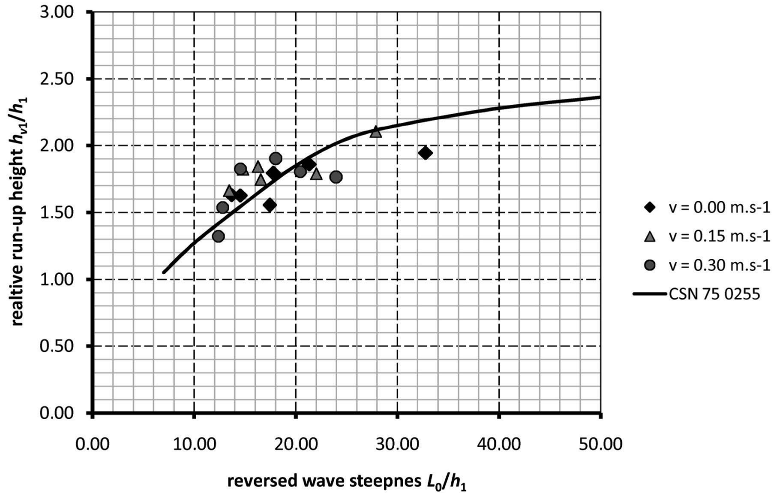

Fig. 9. Relative run-up in dependence on current velocity at the angle of attack $\beta = 15°$.

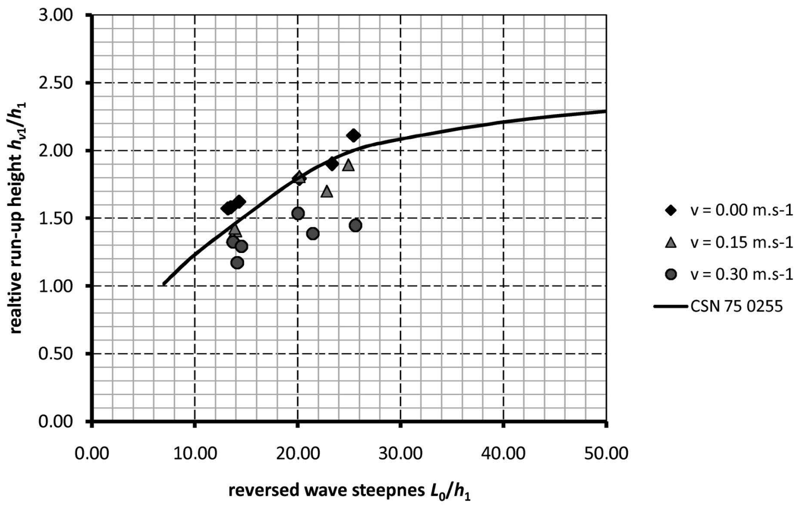

Fig. 10. Relative run-up in dependence on current velocity at the angle of attack $\beta = 30°$.

The results from Fig. 11 and Tab. 3 show that the wave run-up decreases with the current velocity despite the direction of wave propagation. Higher run-up was measured when generating waves against the current while lower run-up was measured when generating waves along the current. When generating waves perpendicularly to the current, the run-up is almost the same as that when the current was not present. The asymmetry in the values of the correction factor $k_{\beta v}$ with respect to β is probably caused by the change in the direction of wave propagation affected by the current. If a wave field is generated against the current, and the current velocity and the velocity of waves are assumed to be vectors, the obliqueness of the resultant vector of the wave field is less than that of the generated one. On the other hand, if waves are generated in the direction of current the obliqueness of the resultant vector of the wave field is higher than that of the generated one (*Lorke* et al., 2010b). Therefore, it is expected that the asymmetry in run-up height for flowing water is caused mainly by the difference in the obliqueness of the wave attack.

T a b l e 3. Correction factor for the flow velocity $k_{\beta v}$.

	v [m s^{-1}]	0.00	0.15	0.30
	Fr_H [–]	0.00	0.07	0.14
β [°]	–30	0.93	1.00	0.91
	–15	1.01	0.99	0.93
	0	0.97	1.04	1.00
	15	1.01	0.92	0.78
	30	0.93	0.89	0.78

However, if waves are generated against the current some additional losses can be seen for the current velocity $v = 0.3$ m s^{-1}. Additional research is therefore needed for further analysis.

The regressions shown in Fig. 11 were computed upon the assumption that the $k_{\beta v}$ factor is equal to 1.0 for perpendicular wave attack (β = 0°).

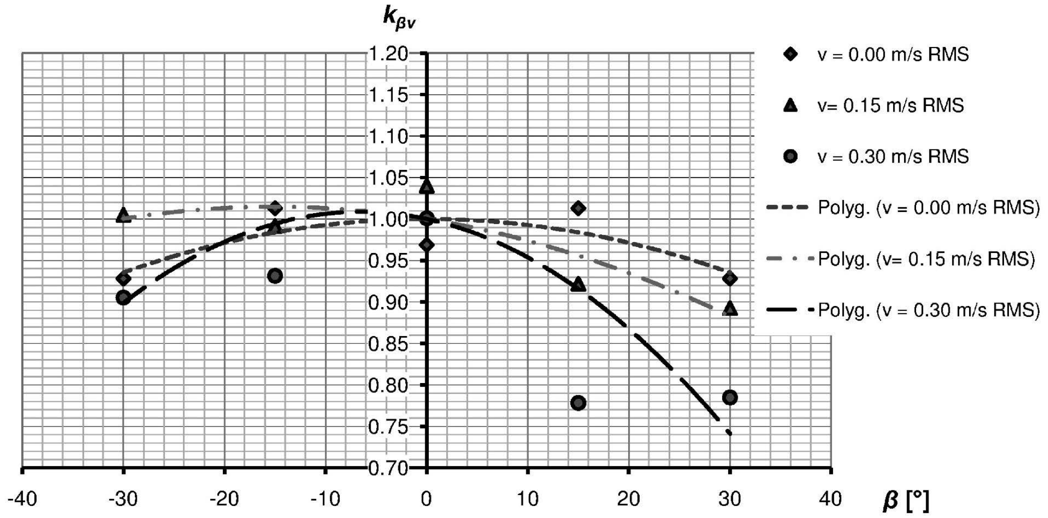

Fig. 11. Correction factor $k_{\beta v}$ for the current velocity.

Conclusions

Within the framework of the international project Hydralab III hydraulic research was performed with a focus on wave run-up and its interaction with current and wind. The present paper summarizes the results of this research in the context of Czech national standard CSN 75 0255. In our analysis wave run-up was related only to the wave parameters and current.

In general, it can be concluded that the CSN provides quite accurate predictions of wave run-up for still water conditions even if some differences in the correction factor for oblique wave attack were measured. Regarding the effect of the current, it was found that slow subcritical flow (Fr < 0.14) has only a small effect on wave run-up. A smaller run-up was measured for waves generated in the direction of flow.

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List of symbols

d – equivalent roughness size [m],
Fr_H – Froude number [–],
g – gravity acceleration [m s^{-2}],
H – still water depth [m],
h_s – significant wave height [m],
h_{vn} – run-up height exceeded by *n*-% of incident waves [m],
h_n – wave height exceeded by *n*-% of all wave heights [m],
k_p – coefficient of wave parameters (function of wave steepness, slope, and water depth) [–],
k_d – correction factor for roughness [–],
k_n – correction factor for probability of exceedance [–],
k_β – correction factor for oblique wave attack [–],
$k_{\beta v}$ – correction factor for oblique wave attack combined with current velocity [–],
L_0 – deep water wave length [m],
n – probability of exceedance [%],
Q – discharge [m^3 s^{-1}],
q – the permeability of the slope [m s^{-1}],
T – wave period [s],
v – mean current velocity [m s^{-1}],
α – slope angle [rad, °],
β – angle of oblique attack (if β = 0° waves attack the dike perpendicularly) [rad, °].

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