FEDERAL INSTITUE
OF HYDROLOGY
Koblenz

FEDERAL WATERWAYS
ENGINEERING AND
RESEARCH INSTITUTE
Karlsruhe

Examinations of Technical-Biological Bank Protections on Inland Waterways

Information Sheet:

Determination of Ship-Wave Heights at the Bank

R & D – Project
(BAW – BfG)

Effective: *November 2016*

Content

1. Calculation according to GBB

The publication *Principles for the Design of Bank and Bottom Protection for Inland Waterways* (GBB 2004) was initially published in May 2004 as the 87th edition of the *BAWMitteilungen* (BAW, 2004). A significantly revised and updated publication appeared as *GBB 2010* at the beginning of 2011 (BAW, 2011). This publication entails a comprehensive description of concepts, principles and dimensioning approaches for the purpose of slope and bottom protection dimensioning for inland waterways, especially for artificial waterways. Both GBB 2004 and GBB 2010 take account of the latest research results as well as international specialised literature. Comprehensive definitions of terminology and notions on security and dimensioning concepts are presented as an introduction. The determination of values of hydraulic charges from ship-induced waves and propulsion units as well as their usage for the establishment of rock-size and layer thickness of loose revetments constitute the first focal point of the GBB. Wind waves are solely presented in GBB 2004. A second focus is put on the geotechnical dimensioning of the revetment, considering the revetment structure and foot stability. Figure 1 shows a schematic overview of the main structure of the GBB for the dimensioning of loose revetments.

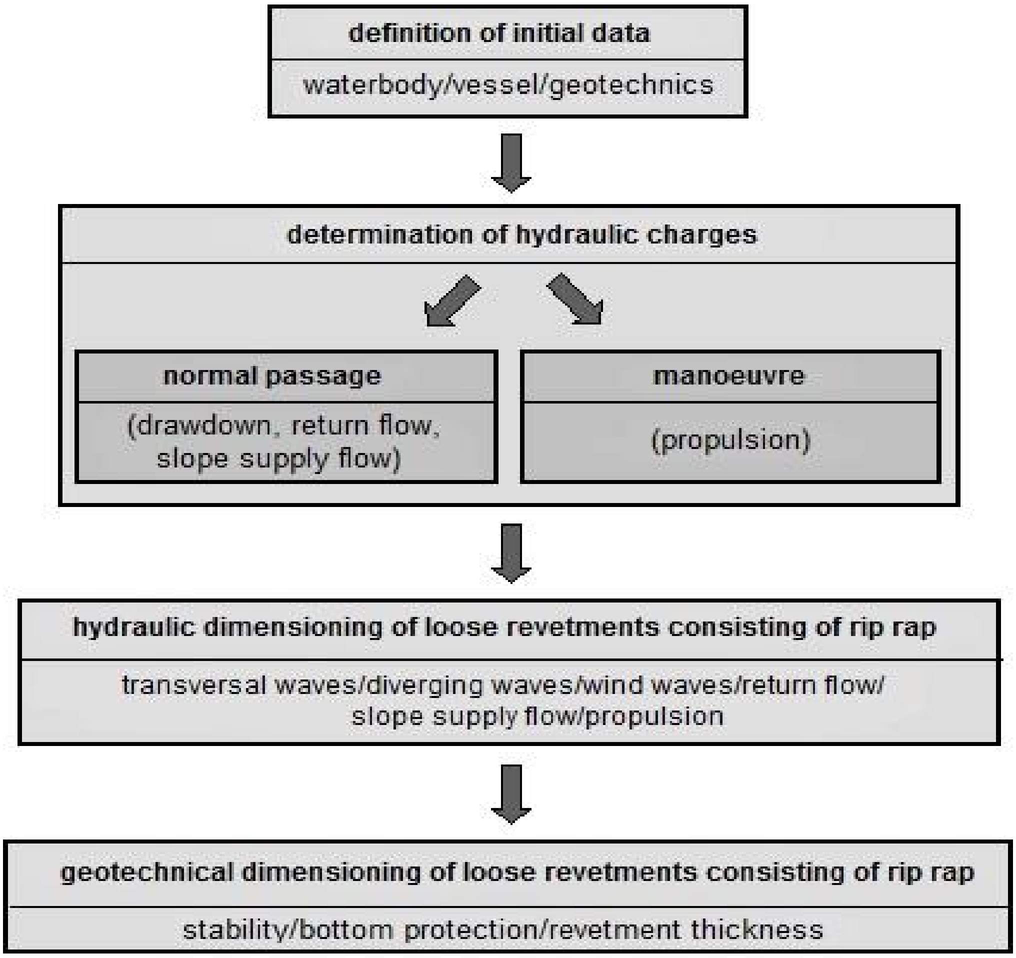
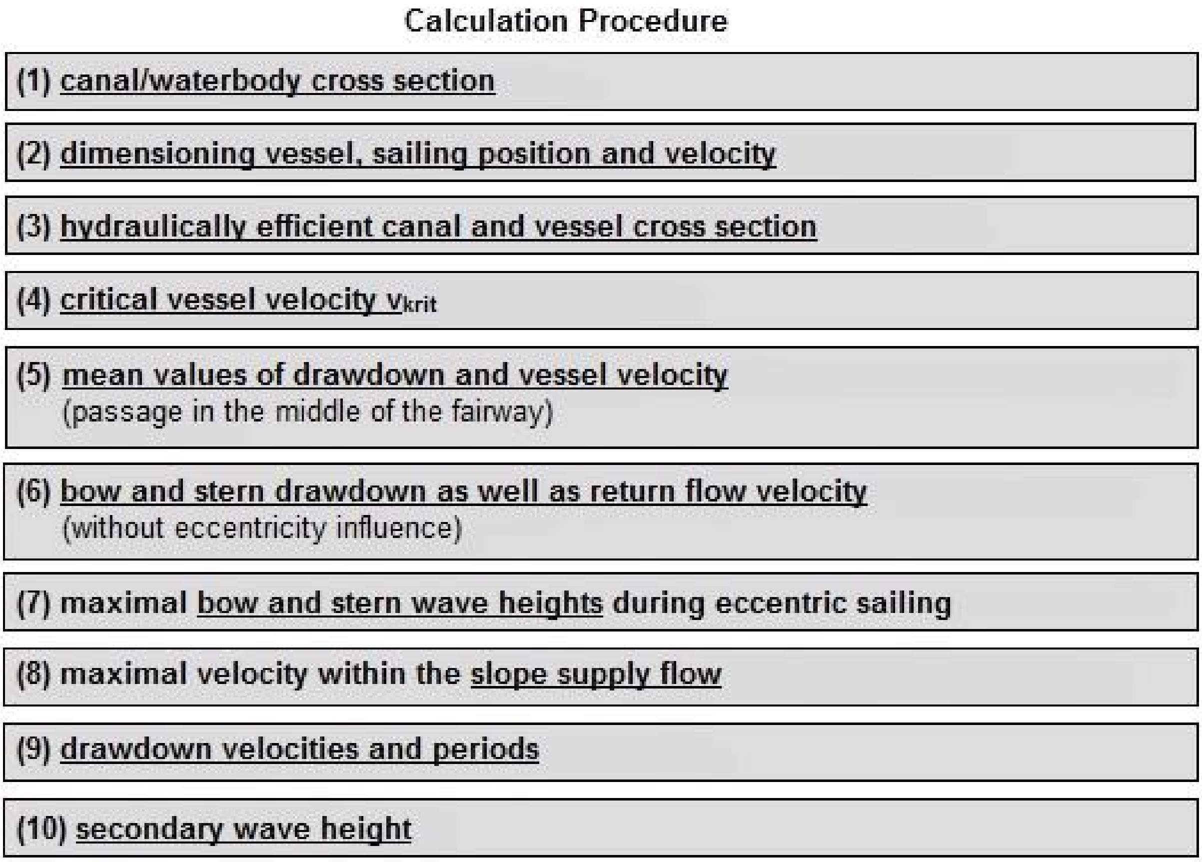


Figure 1 Main structure of the GBB for the dimensioning of loose revetments

The GBB offers the possibility to include the following categories of influence quantities for the dimensioning of bank revetments:

- vessel type, vessel parameters and draught
- vessel velocity, position, trim and sailing situation
- shape and general parameters of the canal cross section, slope inclination
- primary and secondary waves
- return and slope supply flow
- revetment category, acceptable grain size distribution range, net density

The following part contains a short description of the determination procedure of hydraulic load charges according to particular steps and a minimum of technical formulas (cf. figure 2). Details covering this topic can be found in GBB 2004 and GBB 2010.



Calculation Procedure

(1) canal/waterbody cross section

(2) dimensioning vessel, sailing position and velocity

(3) hydraulically efficient canal and vessel cross section

(4) critical vessel velocity v_{krit}

(5) mean values of drawdown and vessel velocity
(passage in the middle of the fairway)

(6) bow and stern drawdown as well as return flow velocity
(without eccentricity influence)

(7) maximal bow and stern wave heights during eccentric sailing

(8) maximal velocity within the slope supply flow

(9) drawdown velocities and periods

(10) secondary wave height

Figure 2 Calculation process for the determination of hydraulic charges in order to dimension loose revetments according to GBB

(1) Canal/waterbody cross section

At first, the considered canal and/or waterbody cross section has to be defined. This cross section can correspond with an ACTUAL state if a posteriori calculations have to be conducted. It can also correspond with a TARGET state if design is taken into consideration. At this point, it is important to keep in mind that canal water cross sections are usually taken fully into consideration, whereas river and particularly lake cross sections are taken into consideration to a lesser degree (cf. **(3)**).

(2) Design vessel, sailing position and velocity

Prior to every calculation, one or multiple dimensioning vessels have to be stated; thus, their parameters such as bow, hull and stern shape as well as draught have to be defined. Technical data of propulsions and rudders have to be provided if manoeuvres have to be taken into consideration in the dimensioning.

The sailing position, which is the distance between vessel axis and the bank, is decisive for the magnitude of bank charges. The closer the vessel is sailing along the bank, the higher is the hydraulic load. In canals, vessels normally sail in the middle of the fairway if solely on the watercourse; sailing positions closer to the banks are solely taking place during preparations for encounters or in case of over takings.

The choice of relevant vessel velocity is essential. The closer the chosen velocity approaches the critical vessel velocity, the higher the impacts. In GBB, usually 97% of the critical vessel velocity is recommended for the dimensioning of an extended construction. In other instances, the admissible vessel velocity can be the basis of calculation if it is guaranteed that vessels operate at this velocity. Smaller percentages of the critical vessel velocity can be applied as well, for example in order to provide technical-biological bank protection measures at respective boundary conditions. Furthermore, the available power of the vessel propulsion has to be considered as the vessel power is crucial for the vessel velocity and might thus lead to a limited ship speed.

(3) Hydraulically efficient canal and waterbody cross section

The area of the waterbody cross section which is particularly responsible for the drawdown and return flow and which determines the effective (=equivalent) canal profile is depending on the calculational waterbody width $b_r = A/h$ (cf. figure 3), the effective influence width of the return flow area b_E and the localisation of the vessel (=eccentricity) within the waterbody cross section. Three generally differing widths are occurring (cf. figure 3): canal situation, shallow water situation and transition situation.

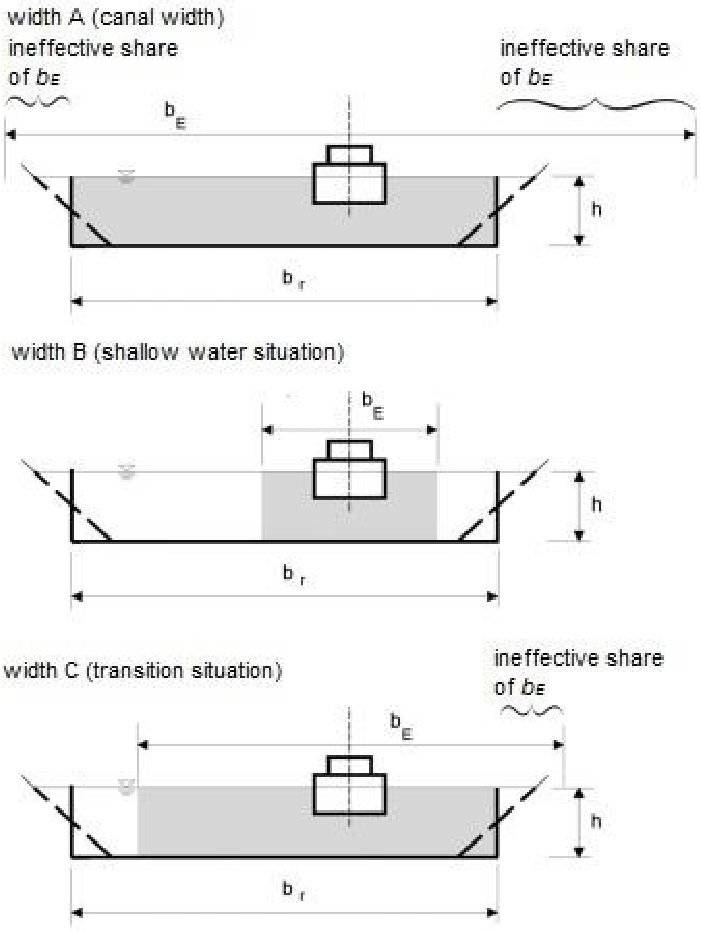


Figure 3 General situations for the ratio of the influence width of return flow area b_E to the design waterbody width b_r according to GBB 2010 (BAW, 2011)

The following approach, which is depending on the vessel type, is valid for b_E:

$$b_\mathrm{E} = \frac{\pi}{2}\,(L + f_\mathrm{B}\,B)$$

The influence of the vessel type is covered by a factor f_B; for common inland vessels, this factor is f_b=3. If vessels are sailing in canals, width A is valid. If vessels are sailing in wider rivers or lakes, width B or C has to be considered. The procedure of such cross section conditions is further taken into consideration in GBB 2010, chapter 5.5.1.1 and shortly explained in this paper in chapter 2.2.

Applying the one-dimensional canal theory, energy losses that occur in the boundary layer which originate from the flow around the ship hull between bow and stern can be disregarded. In order to include these effects, an effective vessel cross section area $A_{S,eff}$ that has its maximum at the stern (index $_H$) has to be defined; it can be calculated as follows:

$$A_{\mathrm{S,eff,H}} = A_{\mathrm{S,H}} + \delta_{\mathrm{1H}} \left(B_{\mathrm{m}} + 2\,T_{\mathrm{m}}\right)$$

$$A_{\mathrm{S,H}} = T_{\mathrm{H}}\, B_{\mathrm{H}}\, \gamma_{\mathrm{H}}$$

$$\delta_{\mathrm{1H}} = 0{,}645\, L_{\mathrm{H}} \left(1{,}89 + 1{,}62\, \log_{10} \frac{L_{\mathrm{H}}}{K_{\mathrm{SS}}}\right)^{-2{,}5}$$

The following parameters are taken into account: the cross section parameters at the stern (B_H, T_H) the mean vessel parameters (B_m, T_m), the development length of the boundary layer between bow and end of the main bulkhead (L_H), the equivalent sand roughness of the vessel skin (K_{SS}) as well as the block coefficient of the vessel cross section in the stern section (γ_H).

(4) Critical ship speed v_{krit}

A characteristic value of the interaction between ship and waterway is the critical vessel velocity v_{krit}. The following formulas are applicable for the critical vessel velocity and its respective mean water level drawdown $\Delta\bar{h}_{\mathrm{krit}}$:

$$\Delta\bar{h}_{\mathrm{krit}} = x_{\mathrm{krit}}\, h_{\mathrm{m}}$$

$$v_{\mathrm{krit}} = y_{\mathrm{krit}} \sqrt{g h_{\mathrm{m}}}$$

The calculation of the values x_{krit} and y_{krit} is conducted iteratively with the aid of multiple auxiliary functions, which are linked with the following parameters of the canal and the vessel:

$A_{\mathrm{K,äqui}}$	equivalent canal cross section [m^2]
$A_{\mathrm{S},eff}$	effective vessel cross section [m^2] allowing for boundary layer effects at bow and stern
b_{WS}	width at water level [m]; $b_{\mathrm{WS}} = b_{\mathrm{WS,äqui}}$
h_{m}	mean water depth [m], $h_{\mathrm{m}} = A_{\mathrm{K,äqui}} / b_{\mathrm{WS,äqui}}$
m	slope inclination [-]; $m = m_{\mathrm{K,äqui}}$
n	cross section ratio [-]; $n = n_{\mathrm{äqui}} = A_{\mathrm{K,äqui}} / A_{\mathrm{S,eff}}$

Displacers (e.g. cargo vessels) normally do not exceed this hydraulic boundary value. The closer the vessel speed to v_{krit}, the higher the power demand. A closer approach to v_{krit} triggers a disproportional increase in a variety of effects that are linked with the critical vessel velocity such as drawdown, wave generation, return flow and slope supply flow. Figure 4 illustrates a typical diagram of the correlation between increasing vessel velocity and mean drawdown.

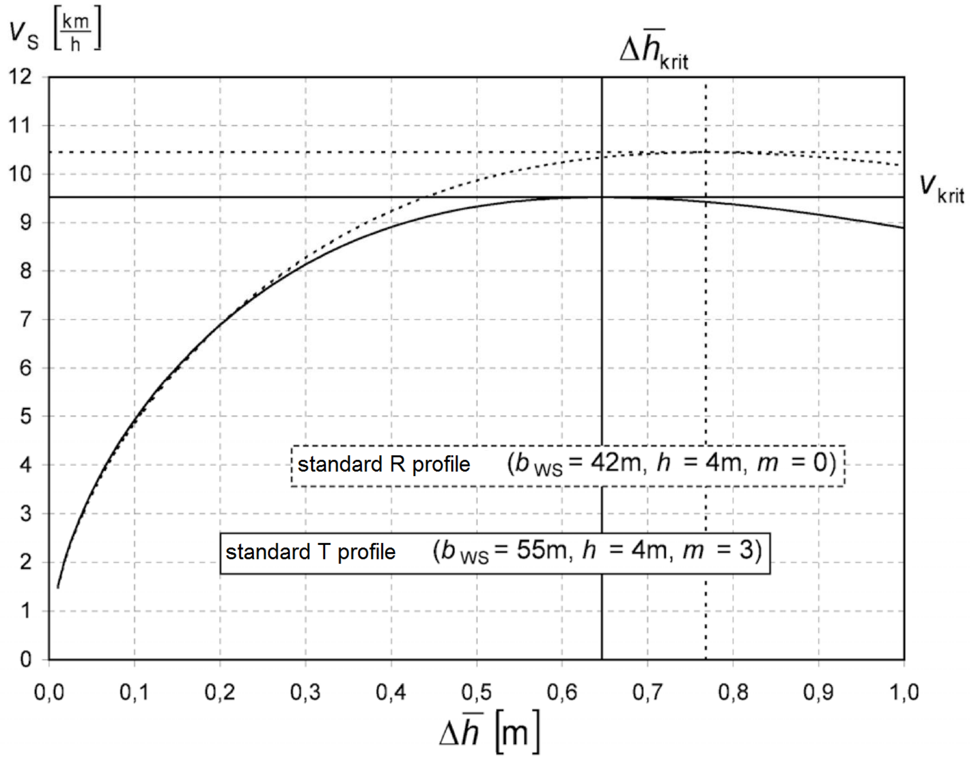


Figure 4 Vessel velocity v_S and mean drawdown Δh correlation in the regular trapezium and rectangle-trapezium-profile, calculated according to the one-dimensional canal theory for the passage of a motor cargo vessel (L=110m, B=11,4m, T=2,8m, δ_{1H} =0,19m)

(5) Mean drawdown and mean return flow velocity values

Based on the above mentioned parameters, the mean water level drawdown $\Delta\bar{h}$ has to be determined for the passage in the middle of the fairway for a chosen design vessel velocity v_S:

$$v_S = \sqrt{\frac{2\,g\,\Delta\bar{h}}{\alpha_1\left(\frac{A}{A-\Delta A}\right)^2 - 1}}$$

The solution of the formula is conducted iteratively. The chosen parameters are the canal cross section (A), the cross section reduction in the canal following vessel cross section and drawdown (ΔA) as well as a correction coefficient (α_1), which describes the effects of the proximity of actual and critical vessel velocity.

This enables the calculation of the return flow velocity $\bar{v}_{rück}$ for passages in the middle of the fairway, averaged for the cross section:

$$\bar{v}_{rück} = \frac{\Delta A}{A - \Delta A} v_S$$

An abating behaviour (cf. 2.2) for the values of the return flow velocity as well as for the drawdown appears between vessel and bank causing diminished values for $\bar{v}_{\text{rück,u}}$ and $\Delta\bar{h}_{\text{u}}$ at the bank, which have to be included into further calculations.

(6) Bow and stern drawdown as well as return flow velocity (without eccentricity influence)

In the following step, maximal water level drawdowns at the bow and stern close to the bank are determined, at first without eccentricity influence. The following formula can be applied for the bow with a mean water level drawdown along the bank at the bow ($\Delta\bar{h}_{\text{u,Bug}}$):

$$\Delta\hat{h}_{\text{u,Bug}} = 1{,}1\,\Delta\bar{h}_{\text{u,Bug}}$$

The following formula is applicable for the stern with a mean water level drawdown along the bank at the stern ($\Delta\bar{h}_{\text{u,Heck}}$):

$$\Delta\hat{h}_{\text{u,Heck}} = C_{\text{H}}\ \Delta\bar{h}_{\text{u,Heck}}$$

The factor C_H combines effects originating from the vessel type, load, and trim as well as transversal water level inclination.

(7) Maximal bow and stern wave heights during eccentric sailing

In the following part, the eccentricity will be included into the calculation. The values of the wave height are increasing significantly the closer the distance to the banks. The increase of height is depending on the conditions of the cross section area between vessel and bank with reference to the canal cross section (on passages in shallow water with reference to the equivalent canal cross section area). The following formula applies for the maximum value of the bow wave height at bank that is closer to the vessel on eccentric passages:

$$H_{\text{u,Bug}} = (2{,}0 - 2\frac{A'}{A})\Delta\hat{h}_{\text{u,Bug}}$$

Concerning the maximum value of the stern wave height, the following formula can be applied with the cross section ratio *A'*/*A* according to case analyses in figure 3:

$$H_{\text{u,Heck}} = (2{,}0 - 2\frac{A'}{A})\Delta\hat{h}_{\text{u,Heck}}$$

The influence of the vicinity to the bank on the return flow velocity is small and can thus be disregarded.

(8) Maximal velocity within the slope supply flow

A slope supply flow that is parallel to the bank appears at the slope in both breaking stern waves and non-breaking stern waves as well as at passages close to the bank. The flow velocity $u_{\max}$ in this slope supply flow, which hits the bank at the revetment, reaches at major wave heights the maximal vessel velocity v_s. For minor waves heights, the slope supply flow is significantly depending on the vessel velocity to wave proliferation velocity ratio and the Froude number $\tilde{Fr}$. The corresponding formulae are as follows:

$$u_{\max} \approx 0{,}3\, v_s \qquad \text{for } \tilde{Fr}^2 > 1{,}83$$

$$u_{\max} \approx 0{,}3\, v_s + 0{,}7 \left(1 - \frac{\tilde{Fr}^2 - 0{,}71}{1{,}12}\right) v_s \qquad \text{for } 0{,}71 \le \tilde{Fr}^2 \le 1{,}83$$

$$u_{\max} \approx 1{,}0\, v_s \qquad \text{for } \tilde{Fr}^2 < 0{,}71$$

(9) Drawdown velocities and periods

Within the sequence of calculations, the next step entails the determination of drawdown periods separated according to bow and stern drawdown and the corresponding drawdown velocities. These values, whose correlations can be seen in figure 5, are essential input values for the geotechnical dimensioning.

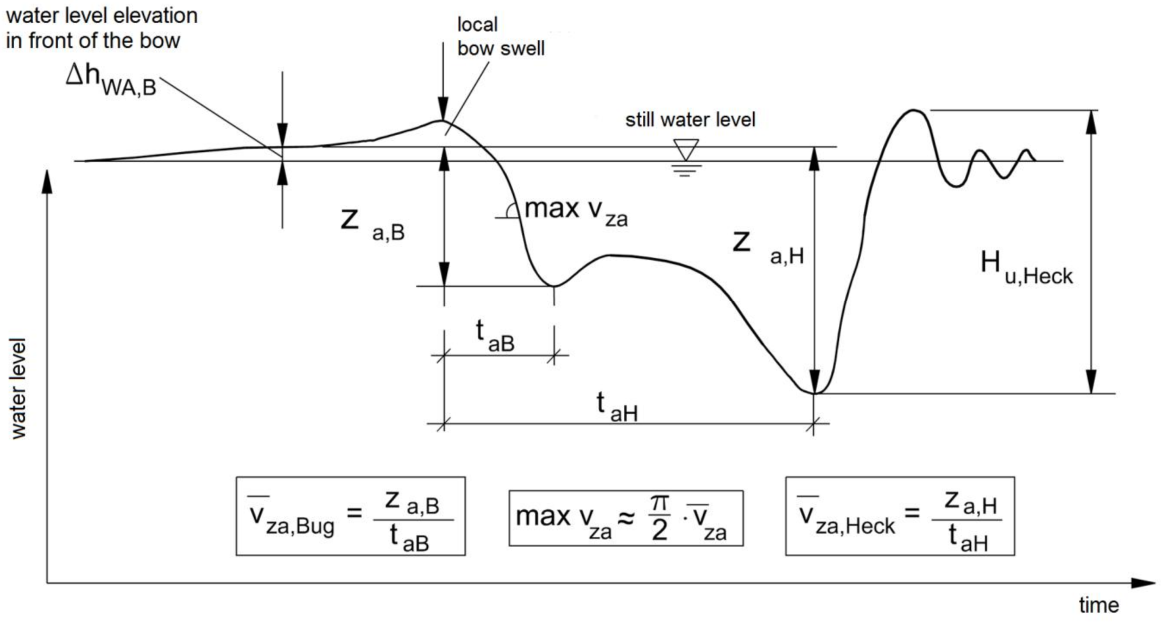


Figure 5 Basic correlation between drawdown at the bow $z_{a,B}$ and at the stern $z_{a,H,}$ the corresponding drawdown period t_a as well as the drawdown velocities

The maximally fast water level drawdown at the bow $z_{a,B}$ and at the stern $z_{a,H,}$ is a result of the following formulae:

$$z_{a,B} = H_{u,Bug} \left(0{,}91 + 0{,}09\, f_{\Delta h_{WA,B}}\right)$$

$$z_{a,H} = 0{,}1\, f_{\Delta h_{WA,B}}\, H_{u,Bug} + H_{u,Heck} - \frac{1}{2} H_{Sek,q}$$

The formulae contain the maximal values of the wave heights at the bank which is closer to the vessel during eccentric passages at the bow as well as stern ($H_{U,Bug}$ and/or $H_{U,\ Heck}$), a factor for the reduction of the influence of the water surface elevation in front of the bow ($f_{\Delta h_{WA,B}}$) and a proportion of the secondary wave height of absolute stern waves ($H_{Sek,\ q}$) at the stern (cf. chapter 7.1.2 in GBB 2010 for further details).

The following drawdown periods at the bow $t_{a,B}$ and stern $t_{a,'H}$ are linked with big and modern cargo vessels depending on the effective distance to the bank (u_{eff} ; distance between vessel axis and design bank line at still water level) and the vessel velocity above bottom ($v_{SüG}$).

$$t_{\mathrm{a,B}} \approx 1{,}7 \frac{u_{\mathrm{eff}}}{v_{\mathrm{SüG}}}$$

$$t_{\mathrm{a,H}} \approx t_{\mathrm{a,B}} + \frac{L_{\mathrm{pris}}}{v_{\mathrm{SüG}}}$$

Details concerning this particular area and information on drawdown periods of secondary waves can be found in chapter 5.5.4.8 in GBB 2010 (BAW, 2011).

(10) Secondary wave height

Next to primary wave heights, which are usually corresponding with the design wave height, smaller and short-period secondary waves that are created at the bow and stern sometimes play a particular role as well. The secondary wave height, which reaches its maximum on the interference line of bow and stern diverging waves (cf. figure 6), can be calculated using the following approach:

$$H_{\mathrm{Sek}} = A_{\mathrm{W}} \frac{v_{\mathrm{s}}^{8/3}}{\mathrm{g}^{4/3}\, (u')^{1/3}} f_{\mathrm{cr}}$$

The formula contains the wave height coefficient A_W, which depends on the shape of the hull, vessel parameters, draught and water depth, the vessel velocity v_s, the distance between hull and bank line *u'* and a velocity coefficient f_{cr},, which considers the increasing influence if the critical vessel velocity exceeds 80% of the critical vessel velocity.

In case of pure stern transversal waves, the following approach can be applied for the secondary wave height:

$$H_{\mathrm{Sek,q}} = A_{\mathrm{W}} \frac{v_{\mathrm{s}}^{2}}{g} \left(\frac{B}{2\,u} \right)^{1/2} \left(f_{\mathrm{cr}} + f_{\lambda} \right)$$

In this approach other important input variables are the vessel width B, the distance u between vessel axle and bank line as well as the wave length coefficient f_λ, with the aid of which the overlapping of stern transversal waves and the bow transversal wave can be captured.

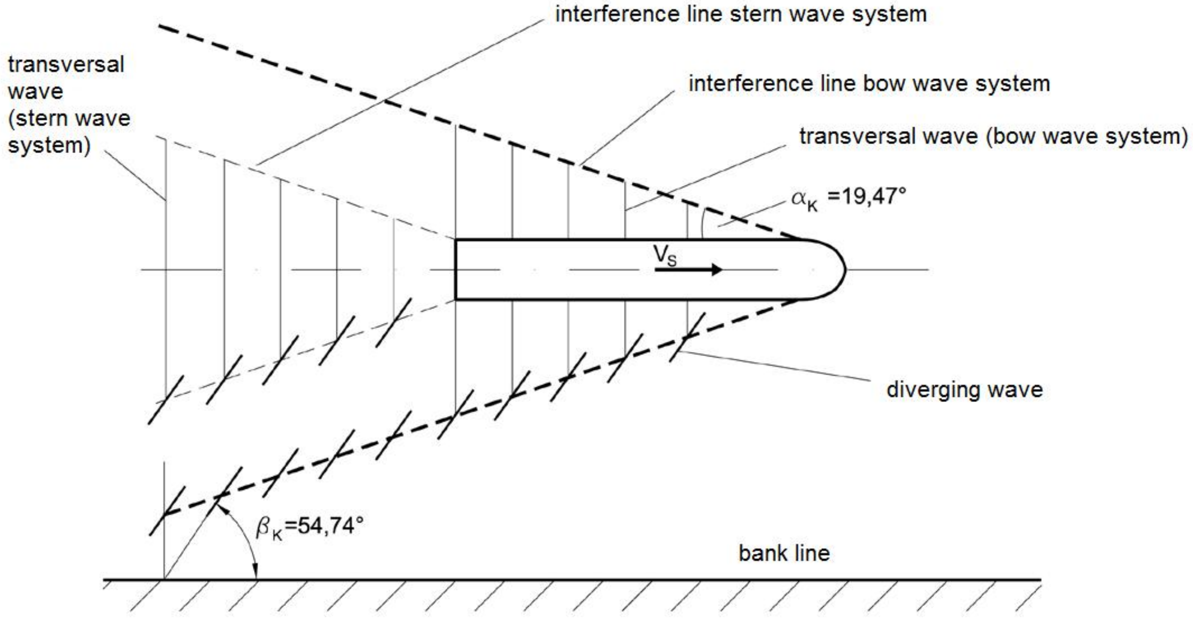


Figure 6 Secondary wave system for $Fr_h \leq 0{,}8$

2. Adaptation of the GBB to random profiles

2.1 Compensatory trapezoid profile

In order to apply the calculation procedures of the GBB on free flowing water bodies, natural cross sections (QP) have to be replaced by geometrically simplified compensatory trapezoid profiles (ETP). As the ETP is supposed to represent the surfaces of the natural cross section for different conditions, the following criteria have to be taken into consideration for each cross section:

- various research conditions such as the initial state and the geometry according to the planning
- different water levels such as low, mean and high waters, water levels in the summer or winter as well as upper and lower operating water level BW_o and BW_u.

Consequently, a variety of particular ETPs has to be designed.

A compensatory trapezoid profile has to entail the following criteria:

- area equivalence of the ETP and the original QP (limited to the influence width); the area equivalence of the return flow field in particular has to be maintained
- bottom height equivalence within the fairway width
- areas that lie behind local shallow water are regarded as hydraulically irrelevant (assumption: they are not reached by the flow).

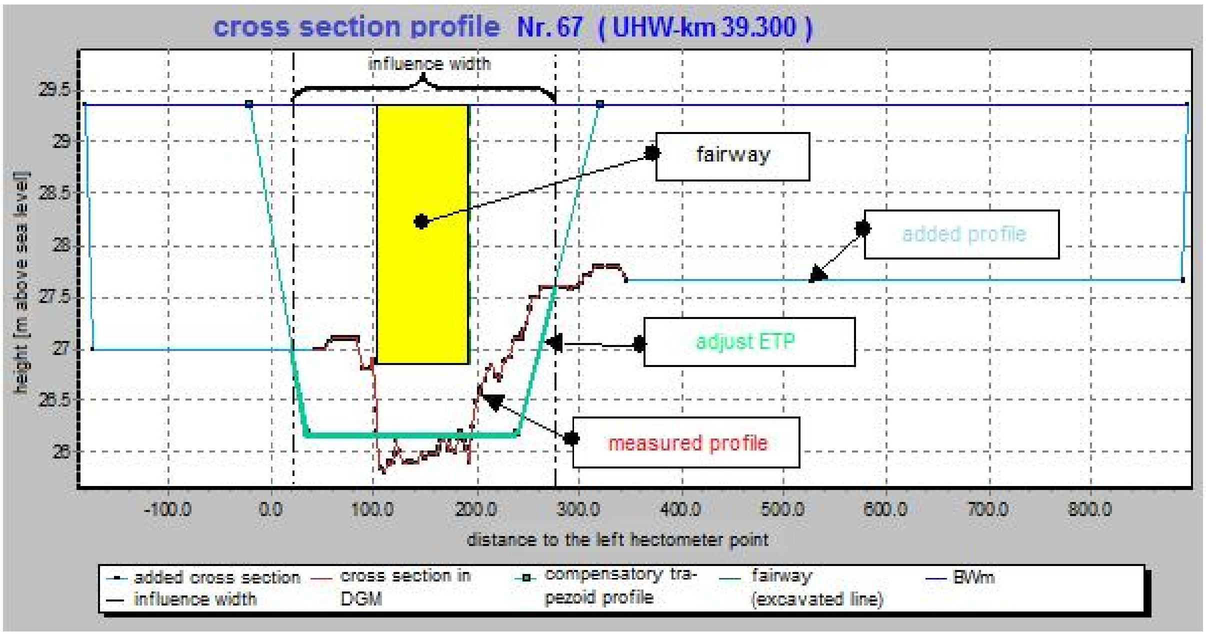


Figure 7 Draft of a compensatory trapezoid profile based on UHW-km 39.300; furthermore, explanation for the addition of cross sections with bank points beyond the DTM

Figure 7 exemplifies the determination of a compensatory trapezoid profile at the lower Havel waterway (UHW), which required the design of a special software that fulfills the aforesaid requirements. The application if this software is further explained in (BAW, 2008).

2.2 Abating behaviour

In uncommon situations that are not similar to situation in canals the change of calculated vessel wave heights between the vessel and the bank have to be taken into consideration. Width B (shallow water) and C (transition situation) are occurring (cf. figure 3). A growing distance between vessel and bank leads to a higher abating of magnitude. This abating behaviour is explained in chapter 5.5.1.1 in GBB 2010 (BAW, 2011).

A diagram of a motor cargo vessel shall illustrate this effect (figure 8). The diagram was conducted for a motor cargo vessel with a length of approximately 110m and width of 11.5m; $L_{eff}/B \approx 10$ thus applies for the array of curves parameter. The ratio $u_{r,rts}/b_r$ represents the distance between vessel and bank ($u_{r,rts}$ - calculational distance to the right bank, b - calculational width of the waterbody). A passage close to the right bank is given for $u_{r,rts}/b \approx 0$ whereas a passage distant to the right bank is given $u_{r,rts}/b \approx 1$. If the vessel is sailing close to the right bank, a fast abating can only be observed in large waterbody widths (e.g. for $b_r = 5$ L). The tighter the canal cross section, the later it is possible to observe the abating while the distance to the bank is growing. In the tight regular trapezoid profile ($b_r = 1/2\ L_{eff}$) only a minor abating of 5% can be registered. The abating of a wave that is triggered by a passage close to the bank on the opposing side is increasing, the higher the increase of waterbody width in comparison to the vessel length:

$b_r = ½\ L_{eff}$	corresponds with a regular trapezoid profile ➔ abating to 95%
$b_r = L_{eff}$	corresponds with the waterbody width that is equal to the vessel length ➔ abating to 60%
$b_r = 2\ L_{eff}$	corresponds with the waterbody width that is equal to the twofold vessel length ➔ abating to 20%
$b_r = 5\ L_{eff}$	corresponds with the waterbody width that is equal to the fivefold vessel length ➔ abating to 3 %

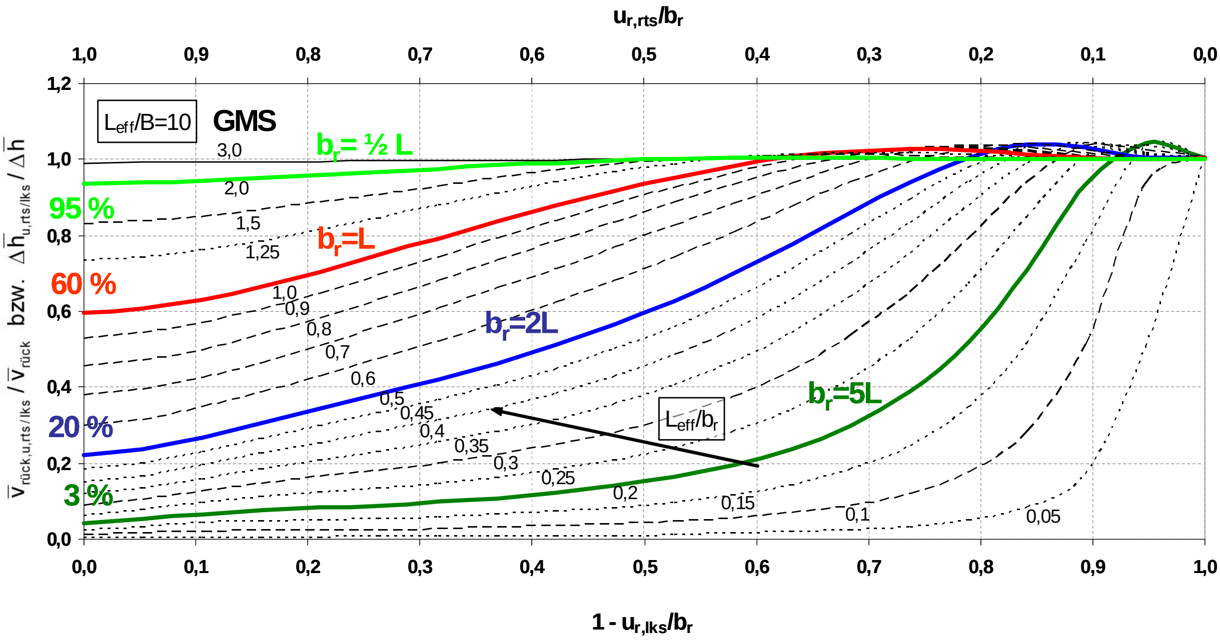


Figure 8 Diagram of the abating behavior (explanation included in the text)

3. Literature

(BAW, 2004) Bundesanstalt für Wasserbau
Grundlagen zur Bemessung von Böschungs- und Sohlsicherungen an Binnenwasserstraßen (GBB 2004)
BAW-Mitteilung Nr. 87
Eigenverlag, Karlsruhe 2004

(BAW, 2011) Bundesanstalt für Wasserbau
Grundlagen zur Bemessung von Böschungs- und Sohlsicherungen an Binnenwasserstraßen (GBB 2010)
BAW-Merkblatt
Eigenverlag, Karlsruhe März 2011

(BAW, 2008) Bundesanstalt für Wasserbau
Ausbau der Unteren Havel-Wasserstraße (UHW-km 32,610 – 54,250) – Schiffs- und winderzeugte Wellenhöhen –
Gutachten BAW-Nr. 3.04.06303.01 (Text- und Anlagenband)
Eigenverlag, Karlsruhe September 2008