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Design concept for technical-biological bank protection measures at German waterways

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ABSTRACT: To improve the ecological condition of inland waterways in Germany, extensive bank redesigns are planned over the next few years. In areas where bank protection is indispensable, nature-orientated measures using plants are to replace the existing rip rap whenever possible to create more habitats for plants and animals and more structural diversity. So far, relatively little experience has been gained with technical-biological bank protection measures on waterways with the current shipping loads. On the basis of various research results and experiences from both a large-scale field experiment on the river Rhine near Worms and from small rivers without shipping, a first design concept for the engineering practice of the German Federal Waterways and Shipping Administration was developed and integrated into a software. In addition to dimensioning rip rap revetments, it is now possible to dimension bank protection with plants as well. The concept includes four design standards offering a differentiated design depending on the safety requirements for the particular bank. The special features of living building materials, the hydraulic effects, the geotechnical failure mechanisms to be investigated and the individual design steps are presented. Furthermore, the benefits of instream measures parallel to the bank are addressed.

KEYWORDS: Technical-biological bank protection measures, design concept, inland waterways, excess pore water pressure, erosion

1 INTRODUCTION

The banks of inland waterways are exposed to hydraulic loads due to shipping and natural influences. In order to protect the adjacent terrain, existing infrastructure and to guarantee the safety and ease of navigation, sloped banks are often secured with revetment made of riprap (Figure 1 left). The design is based on a proven set of technical guidelines (in particular BAW, 2011) and decades of practical experience. As part of the implementation of the European Water Framework Directive bank protection structures should be designed in a more natural way in the future in order to create more habitats for plants and animals along waterways and to increase structural diversity. One way of achieving these goals is to replace the existing riprap revetment with environmentally friendly bank protection designs using plants that protect the banks and at the same time enhance them ecologically (for example with willow brush mattresses, see Figure 1 right). Other examples of such technical-biological bank protection measures (TBBP) include pre-cultivated plant mats, reed gabions and vegetated riprap; more are given e.g. in PIANC (2025).


Figure 1. Riprap (left) and technical-biological bank protection measure with willow brush mattresses (right).

Experience with TBBP on waterways with the current shipping load is still limited, but an initial procedure for dimensioning such bank protection measures was developed with the DWA code of practice M 519 (2016). The concept was integrated into the existing "GBBSoft" software for riprap revetment, which is based on BAW (2011). The extended "GBBSoft+" software can now be used to dimension technical-biological bank protections as well as technical revetments. Key aspects of the design concept and new findings are presented in this paper.

2 DESIGN ASPECTS OF TECHNICAL-BIOLOGICAL BANK PROTECTIONS

The following boundary conditions and effects are decisive for the design of bank protection: Waterway and bank geometry, the properties of the soil in the bank and adjacent bed area, relevant water levels, water level fluctuations and natural flow velocities as well as the hydraulic impacts from shipping. Figure 2 shows a schematic cross-section of a bank slope with a TBBP. Plants suitable for bank protection only grow above mean water level (or normal water level for impounded waterways), because this embankment area is only occasionally submerged and exposed to hydraulic impacts only during higher water levels. The embankment below mean water level will generally still have to be protected by riprap. Above mean water, the goal is to secure the bank either purely with vegetation or as a combination of vegetation and technical components, depending on the magnitude of the hydraulic load. Only in case of very high hydraulic loads a purely technical protection will still be necessary.

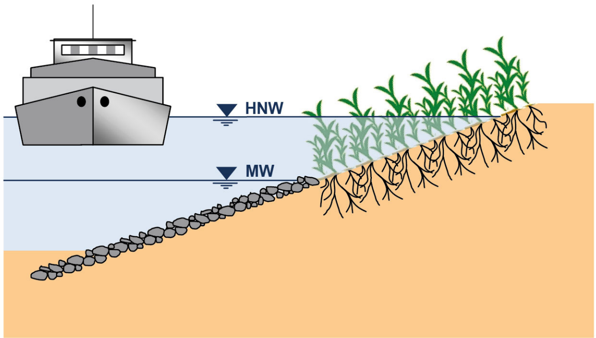

Figure 2. Schematic cross-section of a bank slope with technical-biological bank protection above and riprap below MW (mean water level), HNW = Highest navigable water level.

The hydraulic effects on the bank and the necessary geotechnical verifications are explained in section 2.1 and 2.2, respectively.

2.1 *Hydraulic loads on the bank*

Hydraulic loads on the banks of waterways are caused by natural and ship-induced currents and waves. Ship-induced loads occur when a ship is travelling through a body of water as a result of local and temporary changes to the water surface and the currents around the ship. The so-called primary wave field is made up of the bow and stern wave, the drawdown as well as the return current and slope supply flow (Figure 3). In addition, secondary waves are created by the contour changes at the bow and stern. They become relevant at greater distances from the shore and for pleasure craft. The drawdown of the water level next to the ship on the bank is decisive for the design of the bank protection with regard to shallow failure mechanisms. The ship-induced waves, the return current, the slope supply flow and the natural current can lead to surface erosion at the bank. In free-flowing waterways, natural water level fluctuations must be considered with regard to the effects on the development and long-term vitality of the plants used for bank stabilisation.

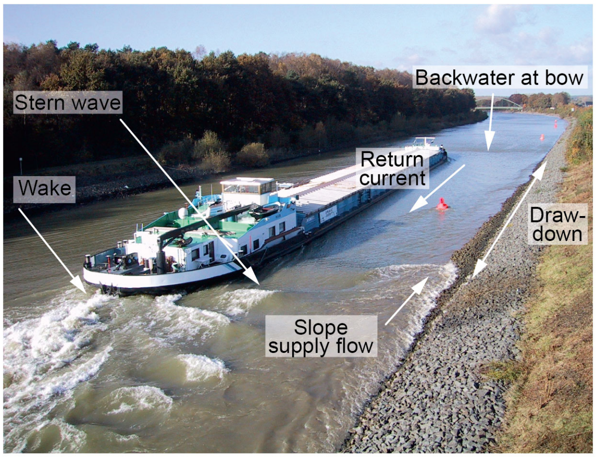

Figure 3. Hydraulic loads on the bank and bed while a ship is passing in a canal.

2.2 *Geotechnical verifications*

The concept presented takes into account the local stability of the bank. The overall stability must be verified in advance for all relevant design situations in accordance with DIN EN 1990 (Eurocode 7) in conjunction with DIN 1054 and DIN 4084, regardless of the type of bank protection. Local failure mechanisms to be examined are explained below.

2.2.1 *Shallow sliding failure parallel to the slope surface and hydrodynamic soil displacement*

The drawdown next to the ship can cause excess pore water pressure in the soil and thus reduce the local stability of the bank when the ship passes.

A change in water level would lead to an immediate pressure change in the pore water if the pore space were completely saturated with water. However, it has been proven in field measurements (Köhler, 1989) that microscopically small gas bubbles are trapped in the pore water in the relevant slope area, which significantly influences the physical behaviour of water. Due to the compressibility of the gas-water mixture, the pore water pressure reactions occur with a significant delay.

The ship-induced drawdown leads to reduced effective stresses in the soil. Due to Boyle-Mariotte's law (the product of pressure and volume of an ideal gas is constant under isothermal boundary conditions), the gas bubbles contained in the pore water expand. However, this is only possible to the extent that the pore water can be displaced. Pressure equalisation is associated with a pore water flow directed towards the lower pressure potential. If the rate of pressure change, i.e. the drawdown rate v_{za} = drawdown height z_a /drawdown time t_a is greater than the hydraulic permeability of the soil k_f, an excess pore water pressure Δu develops. This has its greatest value immediately after the drawdown and dissipates completely over time (Figure 4).

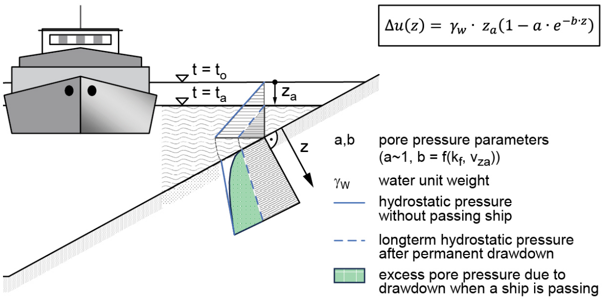

Figure 4. Schematic representation of the excess pore water pressure in the soil when a ship passes, calculation formula according to BAW (2011).

Due to the excess pore water pressure, the effective stresses in the soil and, thus, the holding frictional forces can be reduced to such an extent that a bank slides on a failure surface parallel to the slope. Furthermore, loosening can occur near the surface as a result of soil liquefaction, which leads to hydrodynamic soil displacements downstream of the embankment. In case of revetments made of riprap, the surface weight of the cover layer of armourstones increases the stress level in the subsoil to such an extent that sliding failure and soil liquefaction near the surface are prevented.

These failure mechanisms concern the embankment area below the lowered water level due to navigation. Therefore, the mechanisms only play a role for the plant-based bank protection on waterways with fluctuating water levels, where these bank protection measures can be submerged during higher water levels. Here, the stability of the embankment must be ensured by the technical-biological bank protection if relevant excess pore water pressures occur. However, purely plant-based bank protection measures, such as living brush mattresses or plant mats, do not have a surface weight like an armourstone layer. They can, therefore, only be used if the verification does not require a surcharge. Otherwise, appropriate technical components with the required weight have to be chosen (e.g. chamber revetments, vegetated riprap).

The soil-stabilising effect of plant roots (root reinforcement) is not yet considered in the verifications, as the permanently effective root properties of the relevant plants (e.g. willows) are still being researched. See Eisenmann (2015) for initial research results.

2.2.2 *Surface erosion*

The loads from currents and waves caused by shipping and natural currents can lead to surface erosion on the bank. Protection is required if the existing soil itself is not resistant to erosion. If bank protection with plants is used, these must themselves be erosion-resistant. In this regard there is still little experience with ship-induced loads on waterways. For this reason, the load limits for erosion stability that have so far been determined mainly on smaller rivers without shipping were first adapted for waterways and then permissible near-bank flow velocities, shear stresses and wave heights were specified for ten technical-biological construction methods. These measures and the permissible hydraulic impacts are described in detail in the DWA code of practice M 519 (2016).

2.2.3 *Material discharge from the slope (filter stability)*

As mentioned before, the drawdown of the water level during a ship passage can lead to excess pore water pressures and, accordingly, to pore water flows directed perpendicular to the top edge of the slope. If the flow forces or hydraulic gradients are sufficiently large, internal erosion can occur in the form of suffusion and erosion. Irrespective of the actual design, the transport of soil must be prevented by a filter-stable structure of the bank protection itself and the transition to the subsoil. In many cases, geotextile or grain filters are suitable, as is the case with riprap revetments. For ecological reasons, a biodegradable geotextile should be used where possible to avoid creating a permanent barrier for microorganisms in the bank area. Details on the development of biodegradable geotextiles can be found in Fleischer et al. (2022). The geotextile is only required for the initial stage of the plant-based bank protection until sufficient roots have grown, which can then take over the filter function themselves. Initial studies with willow brush mattresses have demonstrated this effect (Sokopp, 2017).

3 DESIGN CONCEPT

The design concept only considers the upper embankment area above the mean water level MW (see Figure 2), which is relevant for bank protection with plants. It is assumed that a revetment already exists or has been dimensioned in the underwater area.

The aim of the design is to find the optimum bank protection for a specific case, which sufficiently protects the bank and at the same time maximises its ecological enhancement. Additionally, it is checked whether bank protection can be dispensed with completely.

A distinction is made between four design standards (DS 0, I, II and III) with different safety requirements for the bank area (see Table 1, according to DWA (2016), DS 0 added). DS 0 applies in cases where unlimited bank erosion or deformation is permissible due to a lack of safety relevance and the corresponding effects on the waterway are tolerable. In this case, bank protection can be dispensed with entirely. On the other hand, no bank instabilities are permissible at all in DS III. This design standard is generally used by the German Federal Waterways and Shipping Administration for technical revetments following the requirements according to BAW (2011). When designing bank protection with plants and the project-specific boundary conditions are favorable (for examples see Table 1), the design standard can be reduced to DS I or DS II. In this case lower ship-induced hydraulic loads on the bank are taken into account.

This allows a differentiated design of bank protection with plants, depending on whether a stable bank must be guaranteed or whether bank deformations can be permitted or are even desirable.

Table 1. Design Standards (DS).

DS	0	I	II	III
BD	unlimited permissible	limited permissible	low permissible	not permitted
SR	none	minimal	low	high
FP	no	no	no	yes
MI	unlimited permissible	limited permissible	low permissible	not permitted
AS	unlimited	large	low	none

BD = bank deformation/erosion, SR = safety relevance, FP = flood protection function, MI = material input into fairway, AS = availability of space close to the bank (e.g. adjacent infrastructure like paths, roads, buildings, dikes, etc.)

The design concept is based on various criteria that are tested in several consecutive steps:

- Technical criteria (verification of stability)
- Biological engineering criteria (recommendations for suitability)
- Ecological criteria (achievement of the ecological objective)
- Constructive design of the selected protection measure

The individual steps of the assessment are briefly explained below. A more detailed description can be found in Fleischer et al. (2021) or Söhngen et al. (2018).

3.1 *Technical criteria*

In order to prevent sliding failure and hydrodynamic soil displacement, the first step is to check whether a surface weight on the embankment is required. In this case, TBBP with appropriate technical components must be used to ensure the required weight per unit area.

Subsequently the safety against surface erosion of the embankment itself without any protection is analysed. If the soil is erosion-resistant and no surface weight is required, bank protection can be dispensed with altogether and any existing bank protection can be removed. A bank protection made of plants only can be chosen, if safety measures against surface erosion are required, but there is no surface weight necessary.

Which type of TBBP is eventually appropriate is decided by comparing the respective permissible limit values for maximum wave height, current velocity and shear stress with the loads occurring close to the bank in the specific case.

In order to increase the applicability of bank stabilisation with plants or even to dispense with bank protection altogether, it is recommended to check in each case whether it is possible to reduce the load on the bank or whether adjacent land is available to flatten the slope. For example, indirect (pre-embankment) measures in front of the bank (e.g. longitudinal structures consisting of fascines, palisades, sheet piles, stone walls or groynes) can reduce bank loads. This requires sufficient space in the waterway.

The result of the technical criteria determines whether bank protection is necessary and, if so, whether the bank protection measure can be purely plant-based or whether technical components are necessary.

3.2 *Biological engineering criteria*

In the next step, the technically applicable measures are examined according to qualitative bioengineering criteria. The existing soil, the slope gradient and the hydraulic loads are used for this purpose. For these qualitative boundary conditions, experience from rivers without navigation is available, which was transferred to canals, impounded and free-flowing rivers in DWA (2016). This shows whether the measures applicable according to technical criteria are recommended, conditionally recommended or not recommended from a bioengineering perspective.

3.3 *Ecological criteria*

The bank protection measures determined according to the technical and bioengineering criteria can guarantee the bank protection required in accordance with the selected design standard. The final goal is to achieve the maximum possible ecological enhancement with the selected bank protection measure compared to riprap. To this end, the ecological objectives in the specific case and the ecological effectiveness of the applicable measures must be assessed. The existing ecological deficits, the site-specific colonisation potential of the considered bank area and the resulting ecological requirements for the bank protection measures must be determined in advance. Therefore, a collaboration between engineers, biologists and ecologists is useful and necessary. There is still little experience on the ecological effectiveness of technical-biological bank protection measures on inland waterways. However, extensive new findings on nine different construction methods were obtained in a field test on the Rhine after six years of monitoring. These are documented in BAW/BfG/WSA (2020), including detailed analyses of the ecological effectiveness with regard to various animal and plant species.

3.4 *Constructive design*

The result is a technically applicable and ecologically optimised technical-biological bank protection measure for the specific application. In the final step, this measure is to be designed in accordance with the calculation results:

- The layer thickness of the bank stabilisation resulting from the required surface weight must be ensured by the TBBP measure.
- The filter stability in the bank area must be guaranteed by design. For this purpose, the structure of the bank stabilisation measure must be checked to see whether a filter-stable structure to the in-situ soil and within the bank stabilisation itself is provided. If this is not the case, additional filters must be installed.
- Selection and arrangement of suitable and structurally sufficient fastening elements, e.g. stakes and crossbars, as well as the realisation of sufficient foot protection at the bottom of the TBBP.
- The selection of suitable plants for a TBBP primarily depends on the bank protection requirements and the desired ecological function of the target vegetation. For the bank protection function, the plants should have certain biotechnical characteristics. These include rapid growth (short initial stage), an elastic structure (flexibility), flooding tolerance, a high sprouting capacity, tensile roots and the ability to regenerate quickly.

For further information on constructive design, see DWA (2016). Specifications for various technical-biological measures that have already been successfully tested on inland waterways not only provide design information for planning and implementation, but also indicate current application limits (available at http://ufersicherung.baw.de).

4 CONCLUSIONS

The design concept described above and implemented in the GBBSoft+ software provides a sound procedure for planning and dimensioning technical-biological bank protection as part of the ecological redesign of inland waterways.

Research is being continued into, among other things, the stabilising effect of plant roots relevant for bank protection. With the expected results and the increasing experience from the practical application of the design procedure on inland waterways, it is planned to specify and further optimise the concept and to extend it to other TBBP measures.

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