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Original Research

Innovative Nature-Friendly Concept of Bank Stabilization and Its Effectiveness Evaluation

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Abstract

Bank erosion can lead to land loss and increased sedimentation rates, which can alter the important ecosystem services of the water body. Currently, innovative nature-friendly approaches to bank stabilization have been encouraged over the “hard” civil engineering measures. In this study, the impulse for implementing an innovative stabilization technique arose when parts of the banks of the Hulín post-mining sandpit were transformed into a two-meter-high erosion wall, and a technical stabilization structure was neither feasible nor appreciated by the general public for recreation or nature protection. Therefore, a new design of a so-called "half-bowl" sloping with additive nature-friendly stabilization measures SMs (grassing, willow cuttings, gravel bed, etc.) was tested. The evaluation of individual SMs consisted of: 1. visual assessment; 2. wave run-up modeling; and 3. granulometric analyses. All three tests indicated that a good degree of stability was achieved. At the same time, a comparison to biological (mild sloping with grassing) and technical (retaining wall) alternatives was also carried out. Both the low financial cost and relatively low land area requirements indicate that this approach offers a promising nature-friendly solution for bank stabilization in similar lakes.

Keywords: shoreline stabilization, water reservoir, gravel and sand mining, bank erosion mitigation, post-mining lakes

Introduction

Bank erosion in reservoirs can lead to several problems and challenges. Most notably loss of land and property and increasing sedimentation rates can alter important ecosystem services of the water body [1]. The basis for stabilization measures for banks of both watercourses and reservoirs is an assessment of the bank from the perspective of the material it consists of, the existing slope inclination, and the current elements of natural or artificial stabilization [2]. Regarding banks of reservoirs, they can be damaged if the following factors are present concurrently [3]: the bank is made of erodible material (a coast beaten by waves for thousands of years is beyond the scope of this article); the bank inclination is greater than 5% - i.e., it is not a beach type of bank, which can resist water waves in the long term; the fetch length is sufficient to produce a wind wave - this means about 100 m and more (however, this depends on several parameters such as the terrain configuration and the presence of obstacles in the wind direction) [4]. If

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these conditions are not present concurrently, the bank erosion damage is small or nonexistent. The situation is different in the specific case of shipping transport routes parallel to the banks, in which case the waving of the surface caused by the movement of the vessels takes priority. Still, the two conditions mentioned above must be present at the same time. Apart from waves caused by wind, vessel movement, or a combination of both, the banks of reservoirs are also damaged by other types of erosion (e.g., water flowing down the slope, wind, and frost). However, in the case of water reservoirs, wave damage is the most common agent of bank destabilization.

If the basic assessment of the current state of the riparian area concludes that erosion damage to the bank is likely to occur and develop, one of the standard bank reinforcement methods is typically designed. Apart from the construction of retaining walls and other purely technical elements of stabilization, the basis of reinforcement is usually bank sloping, most often from 1:1.5 to 1:3. This is followed by a stabilization of the footslope forming the bank, or a direct stabilization of the bank at the site of the most likely damage [5]. If it is possible to use technical elements of stabilization to the necessary extent (stone riprap, concrete, steel elements, or their combinations), long-term bank stability is usually achieved. However, the situation is different in cases where technical measures cannot be applied i.e., in territories with some kind of special nature protection, in areas that are inaccessible by machinery, in areas where the financial cost would be inadequate, etc. In these cases, stabilization is designed as only biological or biotechnical [6]. Innovative nature-friendly approaches have been encouraged over the above-mentioned “hard” civil engineering measures for recovering naturalness on stabilized riverbanks and other positive effects [7]. Researchers, including members of our team, have long focused on innovating elements of biological and biotechnical stabilization, such as new designs of multi-row woven fences, stabilization cylinders at the slope bottom, the selection of more suitable tree and shrub species [8], and other techniques. Unfortunately, these elements of reinforcement structures offer the best results only in certain cases - at banks with a small inclination, banks consisting of materials at the edge of erodibility, etc.

In this study, the impetus for more intensive research came from the commercial sector, aiming to develop, test, and implement an appropriate stabilization technique for the banks of flooded gravel pits and sand pits, where mining has ceased but highly unstable banks continue to experience landslides. Mining companies are typically required to prepare a rehabilitation plan in cooperation with other stakeholders, taking into account a set of variables and criteria such as groundwater levels, final pit and waste dump landforms, stabilization and revegetation strategies, land tenure, land use regulations, stakeholder interests, and the pre-mining environment [5]. These post-mining lakes often quickly become important features of the landscape with distinct functions: the large water surface creates a new ecosystem, often supporting endangered species of animals or plants. Additionally, these areas are attractive for recreation, including swimming, fishing, and other water sports [9]. After technical recultivation, the slopes are usually stabilized at a 1:1 or 1:2 ratio, which is steep and prone to bank erosion. Additionally, “hard” civil engineering stabilization structures are neither feasible nor appreciated by the general public for recreation or nature protection [10].

As said above, a low slope reinforced with biological elements can resist damage to some extent. However, in our case, a two-meter-high erosion wall had already developed at the site. In this case, achieving the desired low slope of approximately 1:10 to 1:15 would require a slope length of 20 to 30 m, which is not feasible due to property constraints. Thus arose the need for an innovative approach to bank stabilization oriented towards a higher degree of erosion control while limiting the unreasonable high area requirements. Therefore, we designed and tested the so-called "half-bowl profile" for the bank slope. Here, we present our approach, testing method, and observed efficiency to offer an alternative for similar sites in the future.

Material and Methods

Study Site Description

The experimental mining site was named Hulín after the closest municipality and is situated close to the border of the South-Moravian floodplain and the Carpathian uplands. The area is characterized by the wide floodplain of the River Morava. Mean annual temperature approaches 10 °C and annual precipitation reaches around 630 mm (Czech Hydrometeorological Institute CHMI, 2022). Winds blow mostly in a northerly or northwesterly direction. The typical mosaic of floodplain fluvisols is characterized by the occurrence of different soil types (from coherent clay to permeable sands and gravel). The need for stabilization and erosion mitigation measures in the shoreline zone of the Hulín post-mining lake was driven by the ongoing extensive erosion of the banks. The most endangered parts are the southwestern banks where the wind fetch is the longest (Fig. 1). The original banks after the technical recultivation were shaped to steep slopes 1:1 to 1:2. The banks of the flooded sandpit consist of easily washable and erodible material, with the fetch length of the wind exceeding 700 m, making them highly susceptible to erosion [3]. By 2019, the shoreline retreat had reached 10 m, and the erosion wall height exceeded 2 m.

Design of the Experiment

In 2019, three distinct stabilization measure types (SM I, II, and III) were realized together with an

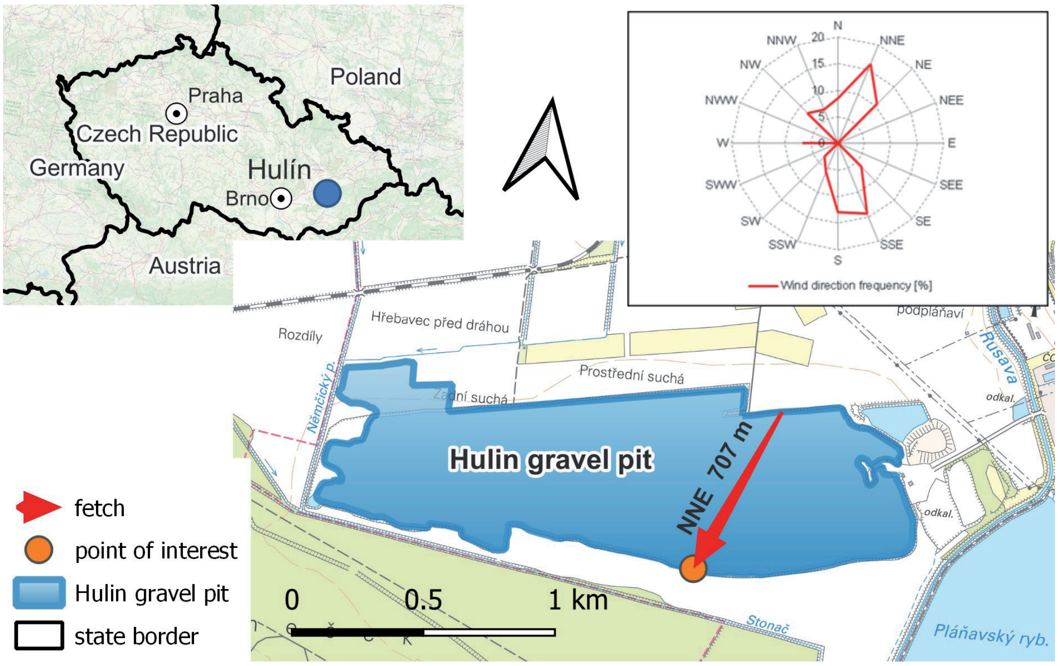

Fig. 1. Localization of the post-mining lake Hulín. The longest wind fetch is presented as a red arrow and red polygons in the top right indicate predominant wind directions in percentages. It shows that the bank of interest is often exposed to winds coming from the northeast.

unstabilized part of the bank (UNS) as control (Fig. 2). A fundamental element of the proposed experimental SMs was the use of bank sloping in the form of the so-called "half bowl". The principle of the newly designed modification was the construction of a gradually increasing slope of the banks, namely a slope of 1:10 (section A in the length of about 5 - 7 m), a slope of 1:5 (section B in the length of about 5 m) and a varying final slope until the top of the abrasion cliff is reached (Section C). Due to the exceptionally dry years of 2017 and 2018 (537 mm and 424 mm of precipitation, respectively), the water level in the reservoir dropped, allowing the exposed part of the erosion platform to be used for implementing stabilization measures in 2019. The experimental plots were situated on a straight section of the south-western bank where the wind fetch and resulting erosion processes are the longest. The experimental plots were 10 m wide neighboring each other so that soil and wind conditions could be considered similar (Fig. 2).

An experimental plot with stabilization measure SM I – sloping was carried out in the form of the above-described "half-bowl" shape. Two rows of logs above each other, stabilized by piles were implemented in section A (in the lowest part with the smallest inclination 1:10 close to the actual water level). On the steeper section B (1:5), grass mixtures were sown and natural regeneration of individual or groups of shrubs was expected.

SM II – again, sloping was carried out in the form of the above-described "half-bowl" shape. Section A was stabilized using a layer of gravel, grain size ca. 6–8 cm, a thickness of ca. 0.3 m, and 3 m wide. On the steeper section B (1:5), grass mixtures were sown and natural regeneration of individual or groups of shrubs was expected.

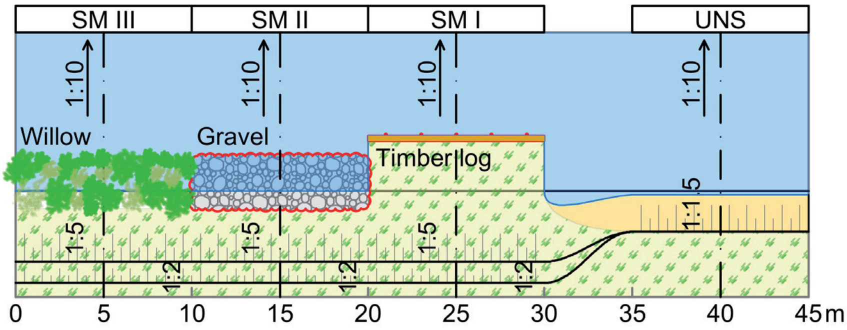

Fig. 2. The floor plan of the experimental design. Three types of experimental stabilization measures (SMs) were placed along the shoreline in a 45-meter-long stretch neighboring each other in the most eroded part of the reservoir banks.

SM III – again, sloping was carried out in the form of the above-described "half-bowl" shape. Section A was stabilized using a belt of willow stem cuttings, Salix viminalis, 4–5 m wide, in a quincunx pattern of 0.4 x 0.4 m. On the steeper section B (1:5), grass mixtures were sown and natural regeneration of individual or groups of shrubs was expected.

Experimental plot UNS – part of the existing bank neighboring SM I was left untouched as control. The material of the erosion platform was sampled and a detailed granulometric analysis was performed. This plot served as the reference area.

The Evaluation of the Effectiveness of the SMs

The evaluation of individual SMs was threefold and consisted of: 1. visual assessment; 2. wave run-up modeling; and 3. granulometric analyses.

1. The visual assessment was carried out several times a year. During these monitoring visits, photos were taken; specific parameters were observed such as the height of the abrasion cliff, the survivability of the planted plants, the state of the technological measures, and the overall state of the reservoir banks.

2. The wave run-up modeling was performed according to the Czech Technical Standard (CSN 75 0255) “Calculation of wave effects on waterworks and weir basins” valid from 1988 [11]. The calculation methods of the CSN 75 0255 are based on the commonly used principles of regular and irregular wave theories with some modifications following the research in the fetch-limited conditions on dam reservoirs. The irregular wave theory assumes a linear superposition of several linear wave components and each individual wave can be expressed by its local maximum (wave crest) and minimum (wave trough) of water surface fluctuation. Wave train analysis is based on statistical processing of observed data represented by a record of water surface motion at a given point from which the empirical basis was derived [12]. One of the necessary parameters is significant wave height ($H_{13\%}$) which represents the height with a 13% probability of exceedance (equation 1):

$$H_{13\%} = 0.0026\frac{{u_{10}}^{1.06}F^{0.47}}{g^{0,53}}\ [m] \tag{1}$$

where the longest fetch length in Hulín reservoir is F = 707 m, g = 9.81 $m\cdot s^{-2}$ and the model scenarios assumes design wind speeds u_{10} as 10, 15 and 20 $m\cdot s^{-1}$.

Wave run-up is the maximum super-elevation of the wave, which climbs the slope above the water level in a calm state - still water level (SWL). It can be defined as a local maximum of instant super-elevation of the water level on the shore. The method of calculating the height of the wave run-up according to CSN 75 0255 is based on the value of wave height of 1% exceedance probability $H_{1\%}$ [11]. The wave run-up of 1% exceedance probability $R_{1\%}$ is calculated by this formula (equation 2):

$$R_{1\%} = k_d k_p H_{1\%}\ [m] \tag{2}$$

where k_d is the roughness coefficient and k_p is the coefficient based on the angle of bank slope α, wavelength $L_{0,}$ and wave height $H_{1\%} = 1.4H_{13\%}$.

The evaluated stabilization measures consisted of milder sloping of shoreline in the contact area of SWL and bank (186.40 m.a.s.l.). The hypothesis was that milder bank slopes (SM I–III) induce lower wave run-up, as the energy dissipates more evenly in the surf zone, significantly limiting the wave load on the bank and making the shoreline more resistant to erosion.

3. In 2019 and 2021, composite soil samples were taken from the abrasion platform (section A) and were evaluated to allow a comparison of the eroded material that was being swept away to the reservoir. The grain (particle) size distribution curve was created by a combination of sieve analysis and hydrometer test according to the Czech Technical Standard (ČSN EN ISO 14688-2) [13]. The hypothesis was that implementing the “half-bowl” sloping would result in more fine-grained material remaining on the abrasion platform. The change in granulometry could therefore serve as an indicator of its effectiveness in protecting the banks.

Results and Discussion

The new bank profile design, described as the "half bowl," was successfully implemented in the sand and gravel pit at Hulín (Fig. 4). The sloping in the form of three continual slope inclinations (1:10, 1:5, and 1:2) proved to be a good practice. The height of the sloped bank with a 2 m erosion wall dropped to about a half compared to UNS. The gravel layer on SM II showed anti-abrasion effectiveness immediately after implementation, but slightly reduced the ability of roots to form new shoots and develop, resulting in a lower willow density compared to SM I and III, where *Salix viminalis* cuttings manifested the ability to enroot between 95-100%. Thus, the gravel belt may be recommended more as a preventative measure for more erosion-stressed banks. An unexpected development was observed at the log vane installed on SM I. Initially, the stone riprap was partially dismantled by people, followed by the repeated dismantling of the logs themselves. This type of stabilization had to be repaired repeatedly, but it can be assumed that this is a relatively serious problem, especially in areas with frequent people movement and recreation. Thus, the planting of the willow belt on SM III in combination with reeds, which showed a very high receptivity rate and quickly overgrew the banks, showed a virtually identical anti-abrasion performance compared to the technical features on SM I and II. Sloping plays an important role in the

Table 1. Grain size distribution of the composite samples taken from the abrasion platform before (2019) and after (2021) the realization of the SMs. The effective increase was calculated as values from 2021 divided by values from 2019.

Sieve size	Cumulative volume in 2019	Cumulative volume in 2021	Effective increase
0.002	0.00%	0.16%	-
0.004	0.00%	0.19%	-
0.005	0.00%	0.28%	-
0.007	0.00%	0.33%	-
0.010	0.00%	0.46%	-
0.015	0.00%	0.53%	-
0.026	0.00%	0.58%	-
0.040	0.00%	0.63%	-
0.063	1.05%	2.63%	249%
0.125	1.70%	3.33%	196%
0.25	1.99%	4.64%	233%
0.5	2.83%	11.61%	410%
1	4.37%	17.14%	392%
2	16.28%	23.26%	143%
4	27.30%	41.82%	153%
8	38.79%	61.24%	158%
16	58.54%	85.45%	146%
31.5	86.62%	100.00%	115%
63	100.00%	0.00%	0%

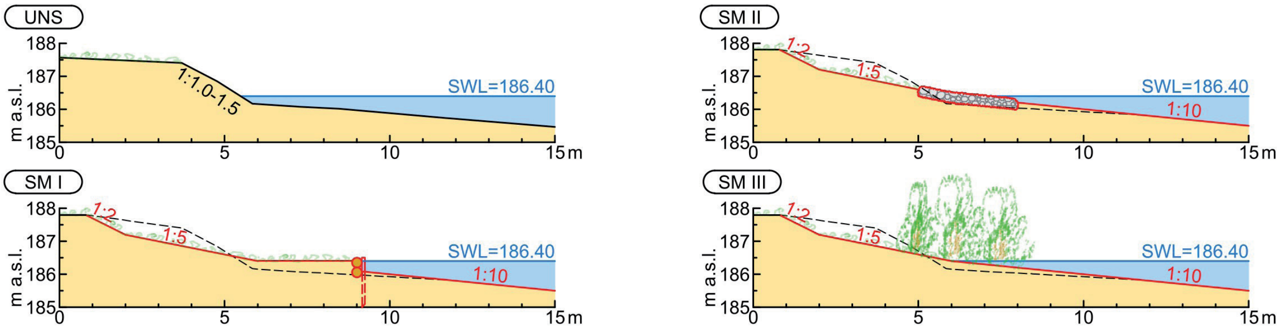

Fig. 3. The cross-sectional profiles of the gradually increasing "half-bowl" sloping shape and the various additive stabilization measures in individual SMs.

stability of the banks as indicated by the cross sections of SM I, II, III and adjacent unstabilized bank (UNS) with modeling of wave run-up caused by the wind $u_{10} = 20\ \mathrm{m{\cdot}s^{-1}}$ (Fig. 5, only the most extreme wind scenario is shown). The $H_{13\%}$ wave reached 0.41 m high and the diverse shoreline shapes induced different wave run-ups $R_{1\%}$. E.g. in the case of SM II, the mild slope of 5% resulted in only a 0.1 m high run-up as compared to the UNS 1.09 m run-up which corresponds to almost 90% greater effectiveness. SM III completely eliminated the wave load through a combination of an obstacle object (timber log) and an upper 3% slope. Wave run-up caused by wind is widely recognized as one of the main factors that trigger unprotected soil bank slope instability [14]. There are several examples of modern shoreline technical stabilization measures. On heavily stressed sea banks, the so-called stair-type seawall, with individual step heights typically set between 0.2 and 0.3 m, is often utilized. These are "hard" civil engineering structures with great effectiveness. However, the recommended step height has primarily been questioned, with models showing that the best results could be obtained

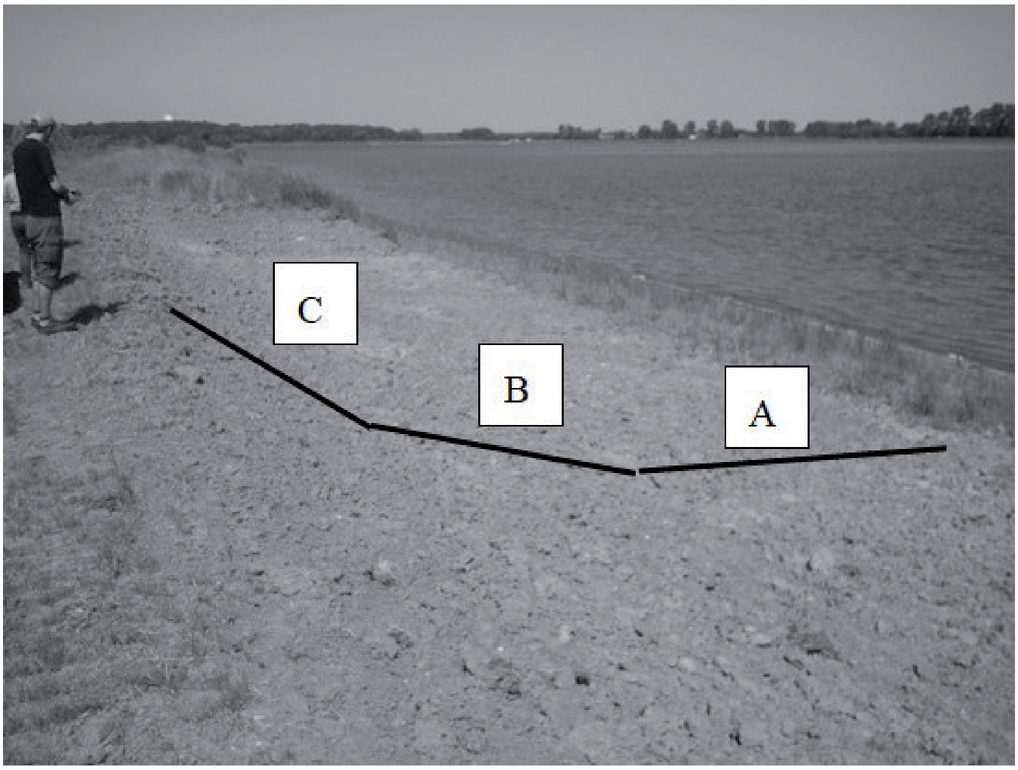

Fig. 4. Slope adjustment in the form of the "half bowl". Section A - slope 1:10, section B - slope 1:5, section C – variable slope 1:2.

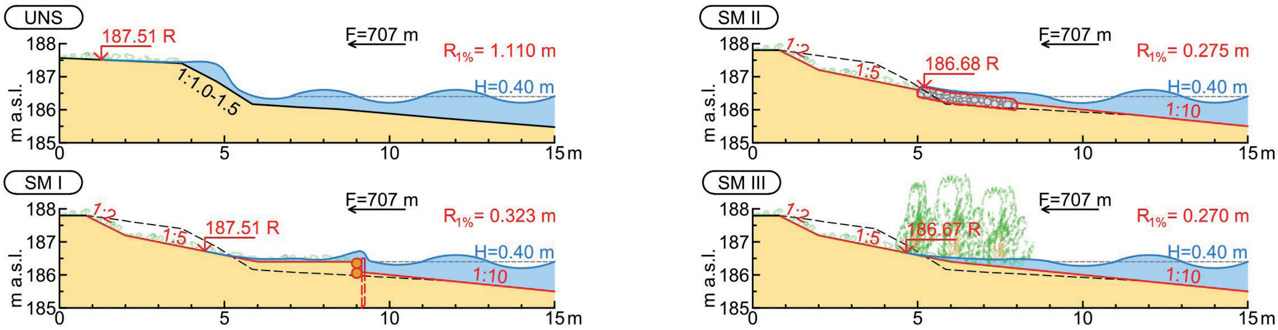

Fig. 5. Wave run-up in cross-sections at different SMs (five times vertical exaggeration).

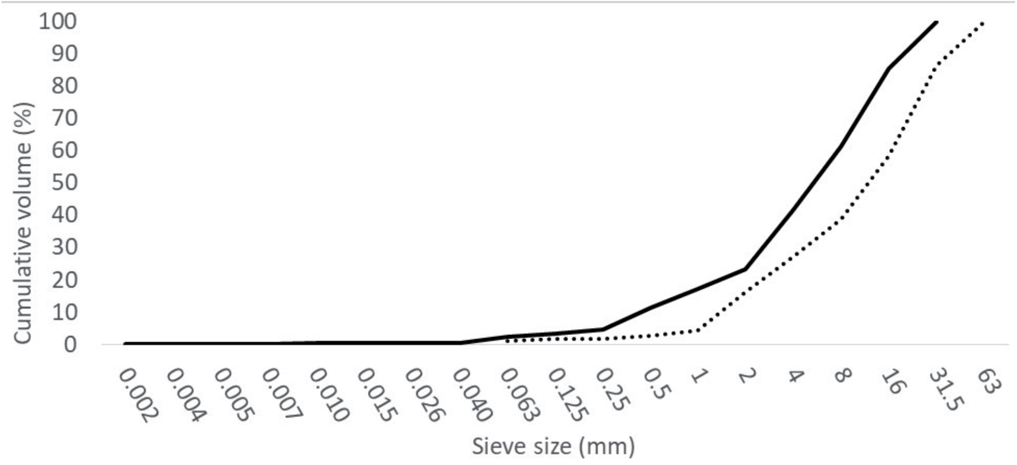

Fig. 6. Comparison of the grain size distribution curve of the composite samples taken from the abrasion platform before (2019) and two years after (2021) the realization of the SMs.

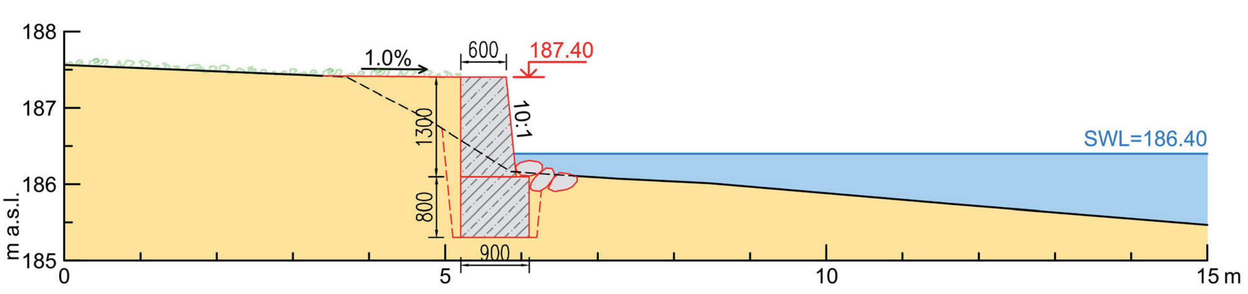

Fig. 7. Cross-section of a retaining wall used as a representative alternative for a technical bank stabilization measure.

with steps 1.0–1.4 m high [15]. At that point, for the experimental locality, there is functionally little to no difference between a natural abrasion cliff two meters high and an artificial structure of similar height. Another popular option for bank protection is the so-called partially or fully mortar-grouted riprap revetments. Due to their roughness, porosity, and permeability, they are reported to reduce wave run-up even more than smooth impermeable revetments [16]. Using grouted ripraps would probably help with the issue of people dismantling the stones, however, the financial costs, technological difficulties, and low ecological benefits associated with their construction are limiting for its usage in the described conditions.

According to the granulometric curves, changes in the grain sizes are evident. The fine-grained material was less washed into the reservoir and more of it remained on the erosion platform. (Fig. 6). The finest material (below 0.063mm) appeared on the platform in 2021, which was absent (completely washed away), in 2019. Apart from the finest material, the highest increase in the volume of the remaining particles was observed in the sizes between 0.5 and 2 mm (4 times more was left on the platform after sloping). The granulometric curve for 2021 reached 100% of the volume at the particle sizes below 31.5 mm as opposed to 64 mm in 2019. This means that the sloping in the form of the “half-bowl” shape not only prevented fine material from being washed back into the reservoir but also limited the movement of larger grains (above 31.5 mm) into the reservoir in the first place. The combination of milder sloping and the willow obstacle on the erosion platform helped dissipate the energy of the incoming waves as well as limited the amount of fine-grained eroded material that would otherwise be swept to the reservoir with the returning wave. This way, significantly more of it remained on the abrasion platform (Table 1). This indicates that such bank stabilization could, in a few years, lead to a more natural bank sloping due to sedimentation of the fine-grained material on the abrasion platform. While it is challenging to precisely calculate the effectiveness of reeds and other vegetation growing at the footslope in mitigating bank erosion in the field, our observations suggest that their presence significantly improved bank stability. This aligns with other studies, such as one from a much larger reservoir in China, where the presence of reeds at the footslope reduced the bank collapse width to 60% and the collapse volume to only 31% compared to non-vegetated parts of the banks [14].

The challenges related to bank stability on a global scale are most significant in oceanic and coastal regions, where considerable focus has been placed over the last decades on combating coastal habitat loss and preserving ecosystem services [17]. In inland areas such as Central or Eastern Europe, however, bank stability is also an important challenge due to the high amount of artificial post-mining lakes. There is growing recognition that abandoned pit lakes can be a huge liability for a number of environmental and safety reasons. Most notably, unstable sidewalls lead to landslides, and steep sidewalls accompanied by risks of falling and drowning [18]. Conversely, well-managed pit lakes have the potential to become beneficial assets to the landscape as ecological reserves, recreation areas, water supplies for irrigation, and much more. There are however a lot of gaps in our current understanding of these ecosystems and their end-use potential and we have to deal with a lack of available data. At the same time, it is now clear that pit lake research merits more promotion by the mining industry and regulatory authorities [19]. In this sense, the fact that the presented study resulted from an inquiry and subsequent cooperation with a private company is encouraging, as it indicates a shift in the private sector's understanding of the importance of these areas.

Our study focuses on a specific type of post-mining pit originating from a sand and gravel open-cast mine located in the floodplain of the Morava River. Compared to other common types of open mining, such as coal and ore mining, which are often associated with issues like natural radioactivity and elevated metal levels [20], or lignite mining, which is associated with low pH [21] and requires some form of neutralization, sand and gravel pits generally exhibit much better water quality. They are recognized as potential hotspots of aquatic habitat diversity, notably due to their wide range of water trophic gradients and hydromorphological conditions [19, 22]. These gravel and sand pits are thus subjected to increased human pressures because of recreation, swimming, fishing, and other leisure activities. Even

Table 2. The financial costs of bank stabilization are standardized to one meter of shoreline. The comparison includes the innovative "half-bowl" approach, mild sloping (1:10) with grassing as a biological alternative, and a two-meter-high retaining wall as a technical alternative.

Work activity	"Half-bowl" approach	Biological alternative	Technical alternative
Earthworks (EUR)	52,51	115,00	61,20
Grassing (EUR)	1,96	18,86	1,89
Willow stand establishment (EUR)	16,43	0	0
Construction work (EUR)	0	0	818,82
Total (EUR)	70,91	133,85	881,90

Note: * The costs were calculated from standard engineering price tables of main construction production (HSV), price system 2024/I, software KROS 4 (ÚRS CZ a.s., 2024). Czech crowns were recalculated to EUROs using the current exchange rate (1:25,47)

though gravel and sand pits represent only a part of the post-mining lake phenomenon, they are of utmost importance for sustainable landscape management for the reasons described above. At the same time, the need for construction sand as a commodity is expected to increase in the near future in response to the large-scale infrastructure development needed for global low-carbon transition [23]. It is therefore likely that sand and gravel mining pits will play an even more important role in the future. Our research aims to contribute as a piece of the puzzle of sustaining the stability of these ecosystems.

Conclusions

On the most erosion-stressed part of the bank of the Hulín post-mining sandpit, a new design of sloping the bank into the shape of a so-called "halfbowl" was tested. The sloping design of three continuous, gradually increasing slopes of 1:10, 1:5, and 1:2 (Fig. 3) proved to be highly effective. The original length of the sloping bank with a 2 m erosion wall of the unstabilized reference section of the shoreline was reduced to about half in the stabilized sections. The wave run-up mitigation effect reached between 90-100% among individual SMs and the granulometry analyses indicated that all SMs were very effective in limiting twice and more of the amount of fine material being washed from the erosion platform thus mitigating the siltation processes. All three tests indicate that this approach to bank stabilization offers a promising nature-friendly alternative to civil engineering stabilization methods.

The effectiveness of stabilization measures was affected both by different wind conditions that change the wave run-up (Fig. 5) and accompanying bank vegetation (biological stabilization measures). Our results affirm the hypothesis that the milder the shoreline slope, the less energy is exerted on the bank, primarily because the waves traverse a longer surface zone, dissipating their energy over a greater distance [4]. Consequently, milder slopes are more quickly occupied by stands of bushy willows, further enhancing shoreline stability. Steep slopes with ongoing wave-induced erosion prevent vegetation growth, resulting in increasingly rapid shoreline retreat. The combination of mild sloping and vegetation obstacles seems to be the most effective erosion mitigation procedure. A slightly different situation occurred in SM III, where at the beginning the gravel layer increased the effectiveness, however, it also reduced the roots' ability to produce new shoots and develop, i.e. it reduced the thickening of the natural willow belt. Therefore, the plot without the gravel layer manifested a nearly comparable effect in the long term. The erosion platform always caught coarse grain material, and fine grain material was gradually washed into the reservoir. The planting of a willow belt manifested good effectiveness; however, the effectiveness was better in combination with reeds which developed spontaneously.

The described effect of mild sloping and biological stabilization on bank stability was likely less pronounced throughout the experiment, primarily due to a significant reduction in the sandpit water level during the dry years of 2018 and 2019, sometimes falling below the SM constructions. In 2021, the water level reached its original height again. However, significant wave load on the shore at the SMs was only observed a few times, occurring during periods of higher water levels. In the subsequent years, 2022 and 2023, the water level decreased again for the majority of the year, making further monitoring impossible. A decrease in the water level of similar water bodies is to be expected in the region due to the effects of climate change [24] and should be accounted for in the planning process of both technical recultivation and subsequent bank stabilization endeavors.

To enable an overall evaluation of the described innovative "half bowl" shape approach and its potential, we compared it to two other commonly used alternatives. Technical stabilization was represented by a "hard" civil engineering approach resulting in a 2 m high retaining concrete wall and biological stabilization was represented by mild sloping (1:10) with grassing over the same height. The "half-bowl" shape required approximately 6 meters of land compared to approximately 20 meters for standard mild sloping (1:10) and around 2 meters for an equivalent technical measure—a concrete wall of corresponding size (Fig. 7). For a 100 m shoreline, this corresponds to 600 m², 2000 m², and 200 m², respectively. This indicates that the tested innovative approach offers a much more reasonable area requirement as compared to its commonly used biological alternative. At the same time, the financial costs differ greatly in the case of these three approaches (Table 2). Unsurprisingly, the retaining wall as a technical alternative was the most expensive. However, not only does such a construction offer the highest security, but it also requires the least amount of land. The innovative "half-bowl" approach was found to be cheaper than its biological alternative, mainly because of the lesser extent of earthworks (much shorter sloping). Combining the two parameters—area requirements and price—the innovative "half-bowl" approach appears to offer reasonable stabilization effectiveness and a smart alternative to standard biological bank stabilization, particularly in areas where "hard" civil engineering measures are too expensive or otherwise infeasible.

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Conflict of Interest

The authors declare no conflict of interest.

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