AN EXAMINATION OF PROPOSALS FOR BANK STABILIZATION: THE CASE OF THE BRNO WATER RESERVOIR (CZECH REPUBLIC)

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Abstract

The design of reliable bank stabilization of streams and dams, functional from a long-term perspective, has been long discussed worldwide. For centuries, we have been dealing with the problem of depositing the flow-transported material and material from eroding banks or soil washed off directly to the reservoir due to surface erosion. The main stress has been laid on the minimum amount of this transported material and on minimized wash off into the stream channel. Significantly less energy has been put into reservoir bank stabilization. This problem is solved in this article and results are presented.

Shrnutí

Posouzení návrhů na stabilizaci břehů: Případ přehrady v Brně, Česká republika

Návrhy spolehlivé stabilizace břehů toků a přehrad, funkční z dlouhodobého hlediska, jsou již dlouho diskutovány po celém světě. Po staletí jsme se zabývali jako lidstvo problematikou ukládání transportovaného materiálu a materiálu z erodovaných břehů nebo zeminou, která je smývána přímo do nádrže v důsledku povrchové eroze. Hlavní důraz je kladen na minimalizaci množství tohoto transportovaného materiálu a minimalizaci smyvů do koryta toků. Podstatně méně energie bylo vkládáno do oblasti stabilizace břehů nádrží. Tento problém je řešen v článku a jsou prezentovány výsledky.

Keywords: *erosion, vegetation, geosynthetics, Brno Water reservoir, Czech Republic*

1. Introduction

Reservoir bank erosion may occur in two ways. A major problem is usually aeolian erosion caused by wave action (from wind). Although, problems are also caused by wave action caused by the movement of boats, fluctuating water levels, cycles of frost and snowmelt, etc., not to mention erosion caused by direct anthropogenic interference, initial bank instability of the newly filled reservoir, etc. The subject of the grant project GAČR 103/04/0731 and follow-up projects was to design reliable, cost-effective stabilization of banks exposed to abrasion by using biological or biotechnical stabilization elements. One option is to design biotechnical bank stabilization with geosynthetic nets (geonets). Geonets may be used directly as a stabilization element for reservoir banks susceptible to less serious bank erosion or as a functional supplement to the biotechnical bank stabilization. Here, the main stabilization element is usually a riprap toe, and further reinforcement may be designed up the bank with earth armouring – using geonets. It is worth explaining at the beginning what a bank susceptible to abrasion means.

The Brno Water reservoir was chosen as a model area. For the water reservoir localization – see Fig. 1. The Brno Water reservoir is located in the Podkomorský les Forest northwest of the Brno city, on the Svratka River. It is one of water works the history of which dates back before

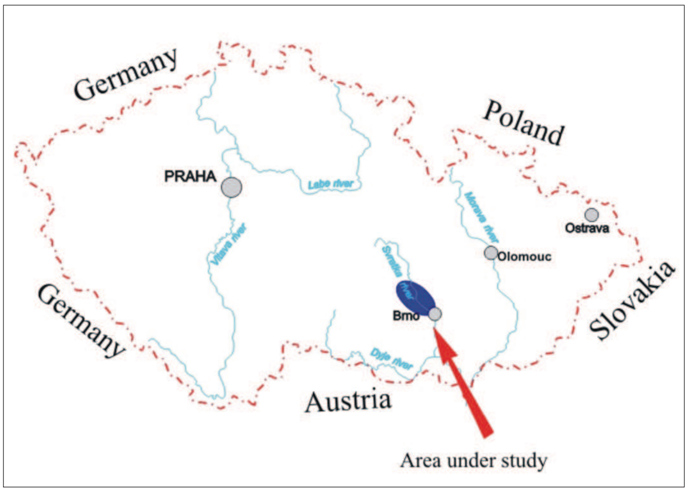


Fig. 1 Area under study

World War II. The water reservoir was put into operation in 1940. The main purpose for the water reservoir construction was to ensure a sufficient amount of irrigation and drinking water for the Brno agglomeration, and the next purpose was protection from floods. From the very beginning, it was planned also as a source of energy and a place for recreation.

Water capacity is 21 million m^3 and altitude is 229.08 m a.s.l. The reservoir occupies an area of about 270 hectares, has a length of 10 km and stretches up to the town of Veverská Bitýška. The maximum reservoir depth is 23.5 m (Šlezingr, 1998).

The underlying bedrock of the reservoir is built mainly of the Brno pluton. The Svratka R. cuts its valley through massive diorite rocks bordering a greater part of the left bank of the main reservoir basin. In the middle part of the reservoir, diorite alternates with biotitic granite, only the end of the inundated area is reached by Permian conglomerates of the Boskovická brázda Furrow, continued by a narrow stripe of upper Devonian limestones. To the southwest of the reservoir, the depression in the Brno pluton is filled by the Tertiary clay (Kubíček, 1987).

Linhart (1954) states that loess is eroded by flowing water more than other rocks, so the occasional torrent rains formed a narrow gorge with vertical walls at the Brno water reservoir, in rare cases reaching a depth from 8 to 10 m. When examining the effect of water on the coast, wind and water level surface have to be taken into account. The prevailing wind direction at the Brno water reservoir is northwest and the abraded coast area is situated just against the prevailing winds. Waves occurring in this area are high from 50 to 100 cm and surf is very effective. In addition to the waves of wind and waves caused by motor boat traffic especially in spring and summer months, can we observe free and forced waves.

For bank abrasion to form and develop, three basic conditions must be met concurrently (Šlezingr, 2011):

1. Reservoir bank slope exceeding 5–7%,
2. Reservoir bank consisting of erodible material, and
3. Wind "run" on the water level reaching towards the problematic bank (see points 1 and 2) of at least dozens of metres. Upon meeting these conditions, a formation and subsequent development of bank abrasion may be anticipated almost surely (the Osada locality on the Brno reservoir may be mentioned as an example, Fig. 2 – see cover p. 3). However, all three conditions must be met at the same time; otherwise no significant abrasion/erosion would occur (e.g. banks of the Brno reservoir in the Kozí Horka locality). The extent and dangerousness of bank erosion depend on the combination of the above factors. The biggest problems occur with steep slopes formed of easily eroded material (e.g. loess) in shoreline areas with a wind run of many kilometres.

2. Material and methods

Agharazi (2004) carried out research in the region of Gharechy River (Iran). The region was visited to consider tree cover effects on decreasing bank erosion. Four treatments were chosen as follows: 1) direct way with the tree cover, 2) indirect way without the tree cover, 3) meanders with trees, and, 4) meanders without trees. Field observations show that there were serious erosion and destruction in outer bends without the tree cover. In direct ways and outer bends with willow trees which grew in two rows at the river bank, erosion and destruction were under control. In direct ways without trees, more erosion and destruction in erect parapets occurred because of underscouring and overturning of parapets. Trees were taken from the flooded and coastal fields of this region. It is recommended that in erect parapets, one row of cut willow and on low slopes two or three rows of cut willow are cultivated.

As revealed by experiments (e.g. Šlezingr, 2010, 2007), river beds with cohesive sediments under constant flow conditions stabilize themselves after showing extensive initial erosion. During erosion, grain size distribution of the upper soil layer considerably changes. Neither clay nor silt nor sand were oriented in a preferential direction. Every alteration of flow conditions however, causes adaption of water content in soil, changing the soil properties. It is for this reason that the hydraulic behaviour of the bed differs considerably from that of a technical rough surface. (Krier, Schroeder, 1988).

Another example is the Harland Creek, in east-central Mississippi. It is a rapidly migrating, meandering stream that is experiencing severe bank erosion. More than 9,000 willow (*Salix nigra*) posts were emplaced in February 1994 by the U.S. Army, Corps of Engineers in an effort to stabilize the eroding stream banks using an experimental bioengineering technique. Monitoring of this stream reach and the willow post bank stabilization resulted in a data base to assess willow mortality as related to bank aspect, post diameter, cover, and base elevation above low water. Monitoring has also resulted in the development of revised construction guidelines. The survivability of the posts, a necessary condition for long-term success, was found to be on average 81% in May 1994, 43% in October 1994 and 41% in August 1995. Even with survivability as low as 29–34% at specific bending reaches, willow posts are documented to be successful in bank stabilization for the period of monitoring as compared with more traditional riprap stabilization methods. Guidelines for improved survivability and recommended site selection are presented. The cost of willow post bank stabilization is less than riprap, which is the traditional form of bank protection, and willow posts can be emplaced using readily available equipment and materials. (Watson et al., 1997).

Kubíček (1987) found out that the abrasion progress rate is dropping in the same way as the abrasion volume depending on time, in the case of the Brno reservoir. On steep slopes a hollow is formed in the summer season due to the action of waves.

Root-shoot dimensions and dry biomass of samples of ten dominant species from the bank profiles of the Neebing-McIntyre Floodway, Thunder Bay (Ontario, Canada) were significantly different from one micro-habitat to another. These differences were used as the basis for interpreting the allocation of energy in different components of plants that helped them colonize specific micro-habitats along the bank profiles of the floodway. Thus, *Deschampsia flexuosa*, the dominant plant on the bank slope, allocates about 90% of its biomass in its shallow but dense root systems (compared to its shoots), which provides protection to the bank slope from surface runoff. *Alnus rugosa* and *Salix bebbiana*, dominant on erosional scarps, allocate almost equal amounts of biomass in their above-ground and below-ground components, but have long tap roots, which help them colonize the steep scarp face. Plants on the bench and under-water shelf, such as *Juncus nodosus* and *Saggitaria latifolia*, allocate disproportionately large amounts of biomass to their above-ground components, which are exposed to the dynamic forces of waves and currents. Overall, the study indicates that root-shoot architecture and biomass can be used as biotechnical criteria in selecting riparian plants for bank stabilization of flood control channels. (Mallik, Rashid, 1993).

Geosynthetic meshes (geomeshes) ENKAMAT 7220, 7010 and Tensar Mat were used for „earth armour". A number of obtained specimens of particular geomeshes were examined, even in laboratory conditions, including their technical parameters. After fitting the three types of geomeshes (ENKAMAT 7220, 7010 and Tensar Mat) in the modified slope (laying and fixing of geomesh + filling) we proceeded to plant cuttings of suitable woody plants chosen beforehand. They were selected species of shrubby willows, namely Salix fluviatilis, Salix purpurea and Salix triandra. Of course, a number of plantations in experimental boxes had to be ruined due to educational reasons in the course of the experiment. Differences in the receding shore line between the slope stabilised with a suitable earth armour supported by root systems of selected woody plants and the slope stabilised only with using biological stabilisation, i.e. only willow cuttings without the earth armour, were visible after one vegetation season. (Šlezingr, 2007).

3. Theory

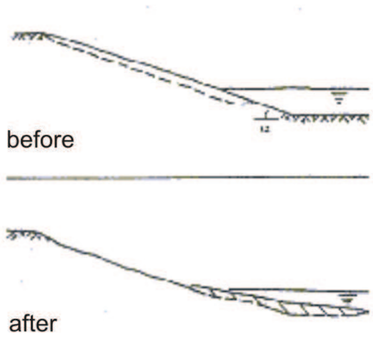
The aim of this article is to present newly designed bank stabilization with the use of geonets (geo-mattresses). They are used relatively often for bank stabilization, but mostly in road, railway and civil engineering. They have only been used rarely for the stabilization of stream banks and reservoir shoreline (Fig. 3).

A big advantage of earth reinforcement – i.e. the use of geonets (geo-mattresses), with the contribution of root systems of suitable woody plants and herbs – is their "invisibility" in the stabilized bank. Geonet is incorporated into the bank, upon laying it is filled with bank soil, becoming a part of it. In a bank slope of approximately 1 : 2, it takes a stabilizing function, one could say, in the horizontal direction, while the root system plays the same role in a more vertical direction. The combination of these two systems provides for a greater soil "bonding" in the created earth armouring, enhancing its stability.

During the work on the above mentioned grant project, partial tasks of bank slope stability were resolved. We focused on ascertaining root tensile strength, joint action of roots and soil, selection of suitable woody plants, problems of suitable earth reinforcement design and the method of its working into the bank.

Before presenting some results, it is important to present a scale of possible bank erosion. This problem was studied by Lukáč and Abaffy (1980), by Šlezingr (2005) among others.

Fig. 3: Sample of one type of spatial geonets, which can serve as a stabilizing element in the body of the slope (photo M. Šlezingr)

<table>
<tr>
<td>a) surface
• mild bank slope
• usually non-cohesive soil
• erosion almost parallel to the slope
• vegetation may help stabilization</td>
<td>
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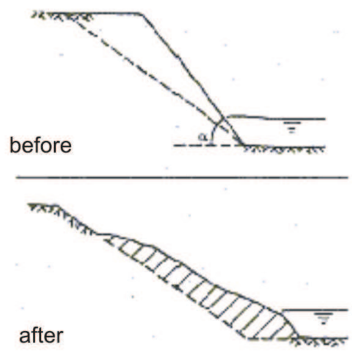
<td>b) sheet
• steep or vertical bank slope
• often non-cohesive soil</td>
<td>
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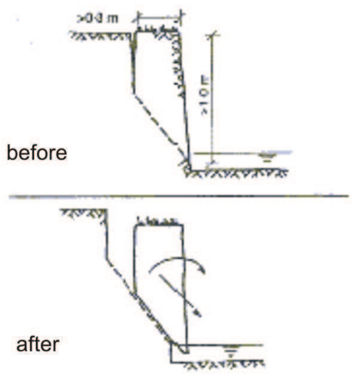
<td>c) planary
• almost vertical banks
• deep tension crack
• occurs in shear or over-tipping
• risk increases if the crack is filled with water
• partially influenced by ground water</td>
<td>
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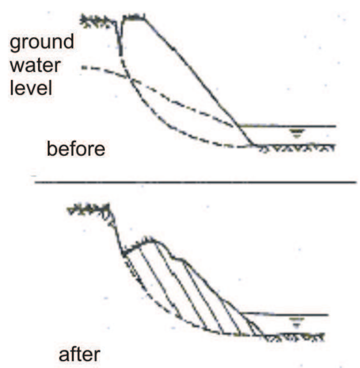
<td>d) rotational in homogenous materials
• usually in medium high or steep banks
• usually in coherent materials
• ruptures disturb stability, especially if filled with water
• significantly influenced by ground water level</td>
<td>
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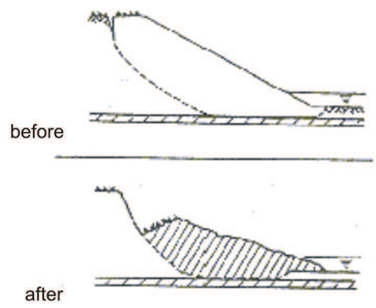
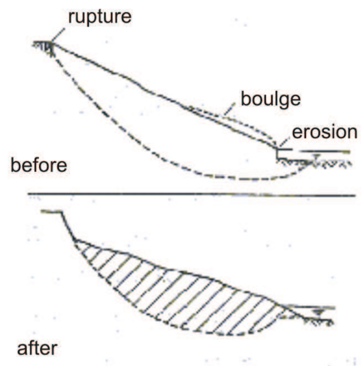
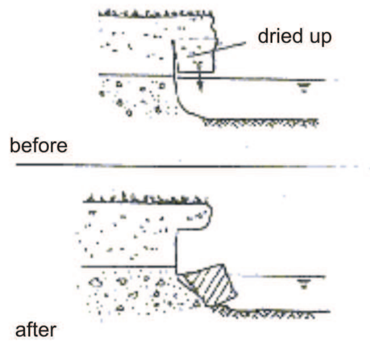
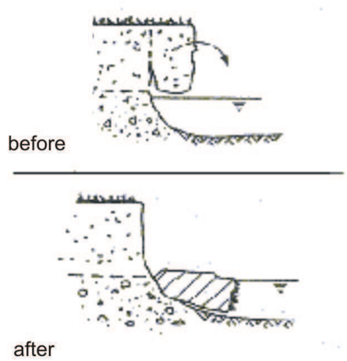
Tab. 1: Possible bank erosion (Valouchová, 2004) – to be continued

e) rotational with the depleted zone • the failure zone shape depends on the location of depleted zone • similar properties as d) type	
f) massive rotational failure • bank erosion threatens the stability of the entire surrounding valley • big volume of failure material rupture • in the upper part, bulging over toe or noticeable movement are signs of possible erosion	
g) erosion of non-homogeneous (composite) bank I • appears only when the top coherent layer is above erodible sand / gravel • lower overhanging part damaged by tension	
h) erosion of non-homogenous (composite) bank II • appears similarly as type g) • tensile failure in the upper soil, followed with rotation • after the fall of the block, vegetation usually remains intact • damage may also be due to sliding	

Tab. 1 – continue

4. Results

In previous chapters, we presented a basic idea of bank stabilization by means of earth reinforcement consisting of geonets (geo-mattresses) overgrown with the root system of suitable woody plants.

Now we will focus on the presentation of particular application possibilities. One possibility is to use geo-mattresses, which are laid on the surface of a prepared slope, and subsequently filled with a layer of approx. 3–5 cm of soil, which is seeded with suitable grass. In this case, the stabilized area is minimally protected against erosion in the first weeks; bank stabilization only starts to be effective after the grass turf becomes established. Subsequently – for a period of several months – a sufficient root system capable of growing through the geo-mattress is being established, fixing properly to the slope. This stabilization becomes fully functional after several months; some authors suggest that full functionality is reached only in the following vegetation season (Šlezingr, 2005; Švecová, Zeleňáková, 2005; Zeleňáková, 2007).

A precondition is that water flow rate and hence bank stress are not high in the first months after the installation of the stabilization elements, otherwise they would be damaged.

However, if the geo-mattress is placed on a bank sloping directly to the river channel, it is most probable that soil will be taken away including vegetation seeds from the geo-mattress structure. Stabilization is then not efficient.

Therefore, procedures were designed to stabilize the slopes – banks also under these conditions. One option is to use grown turf with the geo-mattress, anchoring it to the slope. The geo-mattress is thus a part of the turf. Most often used are geo-mattresses wrapped with soil and grass seeds. The stabilization turf belt is brought to the place of laying at the stage of grown grass with a sufficiently developed root system growing through the geo-mattress. This is laid in belts on the prepared bank. The turf must be properly anchored using stakes, or also metal pins approx. 0.3 m long are often used.

Subsequently, the slope stabilized with the pre-grown grass turf with a geo-grid may also be planted with shrubs or trees. In this event, it is necessary to cut the geo-mattress. It is recommended to cut it crosswise to create four points and to insert the plant in the cut. Afterwards, it is necessary to put anchoring around the plant so as not to damage stabilization around the cut.

Another method is to combine vegetation and the structure reinforced with geosynthetics with a wrapped front. This hybrid structure is based on bio-stabilization by so-called brush-layering (Fig. 4) and reinforcement of a steep slope. Brush-layering means installing branches

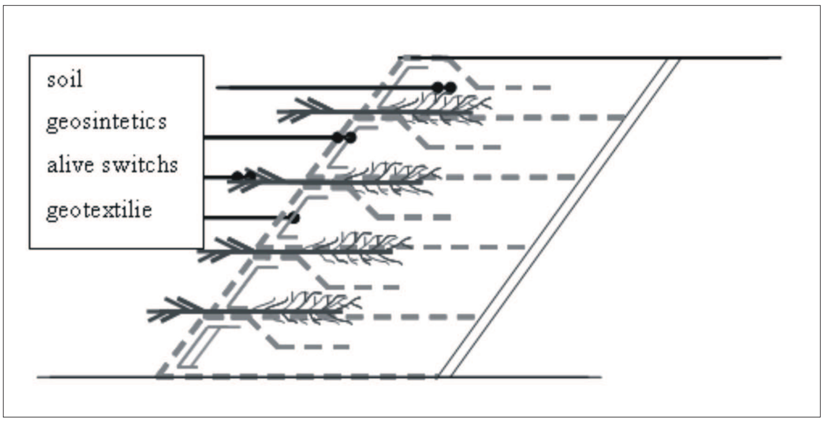


Fig. 4: Shoreline stabilization scheme (Úradníček, Šlezingr, 2007)

in the ground, among the layers in the case of a fill, or in the hole in the case of a vegetated slope. It is used for slopes from 1 : 2 and less. If we want to create a steeper slope, we must give preference to using soil. This is done by means of geosynthetics-geogrids, which help form slopes up to 90°. A new structure is created by placing branches at the point of reinforcement. These would gradually strike roots, growing through the geogrids (hole size of approx. 10 mm), reinforcing the structure further. Because the geogrids may have openings which are much bigger than earth particles, the latter may fall through the holes. Therefore, a geotextile is used at the front, with μm-sized holes, capturing even very fine particles. A characteristic cross section of this hybrid stabilization system is depicted in Fig. 5.

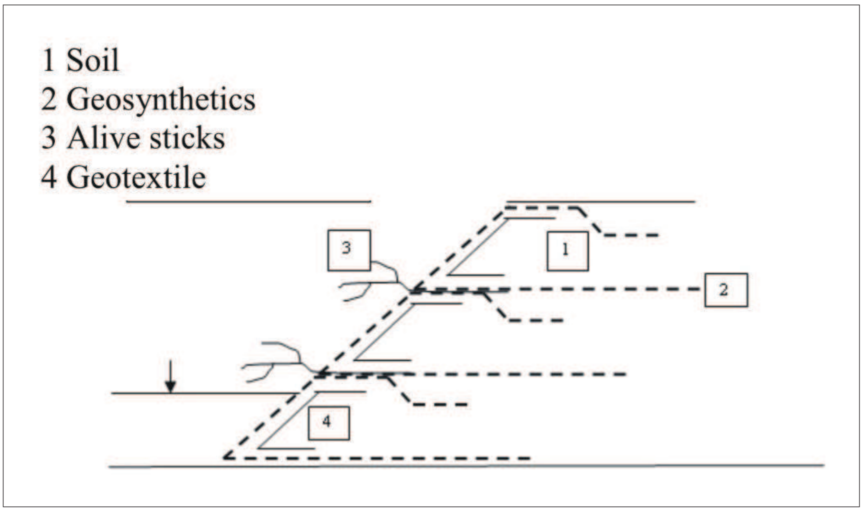


Fig. 5: Reinforced structure combined with vegetation – scheme (Úradníček, Šlezingr, 2007)

Summary of experimental results – the Bílovec irrigation reservoir

The Bílovec irrigation reservoir is located south of Brno, near the municipality of Velké Bílovice, on the Prušánka stream.

Abrasion has considerably damaged the south-eastern part of the bank where abrasion damage reaches a height of about 2 m. In 2003, stabilization with geonets was installed and since then the condition of the bank has been monitored. The detailed has been monitored for 8 years, whereas the experience with the stabilization in the Brno Reservoir is only three years in duration.

The basis for the modification and installation of stabilization elements was a bank slope 1 : 1.7. The stabilization geonet was fixed to the bottom by a series of willow sticks of Salix fluviatilis species. Cuttings of this species were also used higher on the slope as a part of stabilization. They were planted in four rows with twenty individuals each in a square spacing of 0.4 × 0.4. Twenty-five meters of the bank were stabilized using ENKAMAT 7220 geonet and with the help of the root system of woody plants and grass (Fig. 6). The adjacent part of the bank was stabilized in the same way, only without the geonet. In this way, a site for comparison was created. Since then, the condition of the bank has been monitored regularly.

The effect of the stabilization was manifested as early as in the first growing season when the retreat of bank line at the comparison site was clearly visible. The bank stabilized with the geonet was not damaged (Fig. 7 – see cover p. 3).

The stabilized bank was not considerably damaged in the following years; the comparison site had to be partially repaired in 2008. Thanks to good experience with the stabilization using geonets and pre-grown stabilization carpets, the same method was used for the Brno reservoir in the localities of Osada and Rokle.

Fig. 6: Geonet was attached to the bottom range of Salix fluviatilis rods 0.7 m in length. Subsequently, geonet stabilized the slope of the same kind of willow cuttings in four rows. In conclusion, we stabilized the slope by a layer of soil of about 3 cm and sown grass mixtures (photo: M. Šlezingr)

5. Discussion

The above stated possibility of stabilization was tested in our conditions at the Bílovec irrigation reservoir and partially also on the Brno Water reservoir banks. The stabilization was installed in a bank with major stress by water runoff and treading. After three years, it may be stated that stabilization also worked well in the conditions when broken woody vegetation was additionally "planted" into the stabilized shore (Reservoir Bilovec, Brno – Osada and Rokle).

The stabilization effect of this structure is questionable to a certain extent with significant wave action or flowing water. The bank of the irrigation reservoir in Bílovec has been stabilized like this for seven years and only local erosion by wave action is observed. Vegetation (both herbs and shrubs) has grown through the geonet very suitably, stabilizing the toe of the endangered bank and slopes. In the area of water flow, it would have probably been more suitable to choose a vegetated stone stabilization toe, supplemented with bank stabilization using soil reinforcement.

6. Conclusions

A summary of the experimental results is presented from the "stabilization of the Bílovec reservoir bank" The basis of the experiment was verification of the effectiveness of bank stabilization using a geosynthetic net and with the help of the root system of woody plants and grass.

The results are as follows:
1. 25 m of endangered bank were stabilized, using geonet ENKAMAT 7220, four rows of *Salix fluviatilis* cuttings, each with 20 individuals, a grass mixture,
2. In the first year, all 80 cuttings stroke root (100% survival rate),
3. In the following years, two individuals died; abundant natural succession appeared in the stabilization, mainly in the herbal layer, and
4. When compared to the control site, the bank stabilized with the geonet is markedly better reinforced and resists waves. Unfavourable changes are only visible at the bottom of the slope where stabilization sticks of *Salix fluviatilis* were planted as the root system of willows has been uncovered and the geonet has appeared.

After eight years of regular monitoring of the stabilized area we can consider the experiment successful. The bank reinforced biotechnically with the geonet resists waves substantially better than the bank reinforced only biologically. After this experience the experiment was transferred to the banks of Brno Reservoir. Three years later we can conclude that the stabilization using geonets has proven successful even there (the assessment of effects of various types of geosynthetics is currently under investigation).

Bank stabilization of dams is an important prerequisite for ensuring the long life and utility value of water area. Especially the life of reservoirs is often defined particularly by the time until they become silted. It is often not the dyke stability that is limiting, but rather the stability of banks, the extent of wash off from surrounding lands and the quantity of sediments transported by the flow.

The design and implementation of suitable bank stabilization is a task being undertaken at many specialized and scientific workplaces. Today, this does not merely concern the simple employment of technical stabilization elements – because the stabilization of many kilometres of banks of water streams and dams is significantly influenced by the character of the surroundings, vegetation and the entire complex ensuring environmental stability of the alluvial plain. Therefore, various types of biotechnical and biological bank reinforcement are being designed, verified and implemented.

One of the possible and non-traditional designs is the use of geosynthetics for stabilization of streams and dams. These materials are not natural, but in spite of the fact, they can significantly contribute to suitable bank stabilization. They form internal earth armouring, which is – with the help of suitable rooting – a highly efficient stabilization factor. The problem consists namely in the selection of suitable types of geo-mattresses (geonets, geogrids, etc., according to the purpose of application) and their subsequent installation in the slope forming the bank of a stream or reservoir. Further, we have to carefully consider the selection of suitable grass and/or woody plants and select only from native species; species of invasive character should be avoided. This is a relatively complex topic, which has been dealt with in separate publication (Uradníček, Šlezingr, 2007; Míča, 2006; Powrie, 2004, etc.).

In the current report, we have focused on the justification of the suitability of this stabilization material and on the presentation of designed structures. Geosynthetic nets (geonets) and/or geo-mattresses are produced in a wide range of (for our application) more or less suitable shapes and forms. Their purpose is a decisive factor in their selection. For stabilization of a slope forming a bank of a stream or a dam, we prefer three-dimensional geo-mattresses with a thickness of ca. 2 cm, consisting of matted thin plastic fibres suitable to be overgrown with roots. As a matter of course, hygiene and other certificates are needed. The strength characteristics should be as follows: tensile strength at least 1–3 $kN.m^{-1}$.

Upon being installed in the slope, geo-mattresses significantly help stabilization, especially, in combination with the root system growing through them. For this reason, it is also necessary to select suitable woody plants.

For the stabilization of banks in areas more exposed to flow or wave action, we suggest using a pre-grown turf with the internal reinforcement by geo-mattress. This pre-grown turf is then installed in the bank for stabilization. It is necessary to properly fix them to the slope and subsequently let them become "established".

It is also possible to use willow shoots as a part of bank stabilization. By their planting in the slope, the stabilization effect of geosynthetics is enhanced.

Acknowledgements

The research reported here refers to Research Project No. MSM 6215648902.

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Initial submission 26 February 2011, **final acceptance** 13 December 2011

Please cite his article as:

ŠLEZINGR, M., FIALOVÁ, J. (2012): An Examination of Proposals for Bank Stabilization: The Case of the Brno Water Reservoir, Czech Republic. Moravian Geographical Reports, Vol. 20, No. 2, p. 47–57.

MORAVIAN GEOGRAPHICAL REPORTS

Aims and Scope of the Journal

Moravian Geographical Reports [MGR] is an international peer-reviewed journal, which has been published in English continuously since 1993 by the Institute of Geonics, Academy of Sciences of the Czech Republic, through its Department of Environmental Geography. It receives and evaluates articles contributed by geographers and by other researchers who specialize in related disciplines, including the geosciences and geo-ecology, with a distinct regional orientation, broadly for countries in Europe. The title of the journal celebrates its origins in the historic land of Moravia in the eastern half of the Czech Republic. The emphasis at MGR is on the role of 'regions' and 'localities' in a globalized society, given the geographic scale at which they are evaluated. Several inter-related questions are stressed: problems of regional economies and society; society in an urban or rural context; regional perspectives on the influence of human activities on landscapes and environments; the relationships between localities and macro-economic structures in rapidly changing socio-political and environmental conditions; environmental impacts of technical processes on bio-physical landscapes; and physical-geographic processes in landscape evolution, including the evaluation of hazards. Theoretical questions in geography are also addressed, especially the relations between physical and human geography in their regional dimensions,

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The journal, Moravian Geographical Reports, publishes the following types of papers:

(1) **Original scientific papers** are the backbone of individual journal issues. These contributions from geography and regionally-oriented results of empirical research in various disciplines normally have theoretical and methodological sections and must be anchored in the international literature. We recommend following the classical structure of a research paper: introduction, including objectives (and possibly the title of the general research project); theoretical and methodological bases for the work; empirical elaboration of the project; evaluation of results and discussion; conclusions and references. Major scientific papers also include an Abstract (up to 500 characters) and 3 to 8 keywords (of these, a maximum of 5 and 3 of a general and regional nature, respectively). With the exception of purely theoretical papers, each contribution should contain colour graphic enclosures such as photographs, diagrams, maps, etc., some of which may be placed on the second, third or fourth cover pages. For papers on regional issues, a simple map indicating the geographical location of the study region should be provided. Any grant(s) received to support the research work must be acknowledged. All scientific papers are subject to the peer-review process by at least two reviewers appointed by the Editorial Board. The maximum text size is 40 thousand characters + a maximum of 3 pages of enclosures. The number of graphic enclosures can be increased by one page provided that the text is shortened by 4 thousand characters.

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