Abstract

Since the prehistoric civilizations, man privileges the places where water exists in sufficient quantity and quality for its needs. Rivers and streams have a wide range of environmental problems where marginal instability issues are recurrent. The selection of intervention techniques, in riverbanks, for their stabilization is not always compatible with the objectives and requirements of the Water Framework Directive on the good ecological water status. The problems are aggravated in urban areas by the lack of space, lack of awareness of flood risk and the disordering of the territory.

The main objectives of this study include: the characterization of the main techniques for river and stream banks stabilization, the selection of a methodology and possible indicators to be used in riverbanks stabilization processes; the stabilization techniques to be applied to the case study.

The results presented include the analysis and adaptation of the BEHI METHOD developed by Rosgen in 2001 and additionally, the study of stream bank stabilization techniques for stretch of the Granja stream in the city of Porto. It is believed and expected that, similar to what has been carried in this work, the presentation of results of experiments and studies on rivers and streams rehabilitation will assist water managers in the selection of the best and integrated solutions to increase the success of rehabilitation projects and for the adequate implementation of the Water Framework Directive.

Keywords: River rehabilitation; bank stabilization; erosion; water resources.

Resumo

Desde as civilizações pré-históricas que o homem privilegia os lugares onde existe água, em quantidade e qualidade suficientes, para as suas necessidades.

Os rios e ribeiras apresentam um vasto conjunto de problemas ambientais onde são recorrentes as questões de instabilidade marginal. A seleção de técnicas de intervenção, em margens fluviais, para a estabilização das mesmas nem sempre é compatível com os objectivos e requisitos da Directiva Quadro da Água para o bom estado ecológico da água. Os problemas agravam-se nos aglomerados urbanos pela falta de espaço, a falta de percepção do risco de cheias e o desordenamento do território.

Os principais objectivos deste trabalho compreendem: a tipificação das principais técnicas de estabilização de margens em rios e ribeiras; a seleção de uma metodologia e dos possíveis indicadores a utilizar em processos de estabilização de margens fluviais; a aplicação das técnicas de estabilização ao caso de estudo.

Os resultados apresentados contam com a análise e adaptação do BEHI METHOD desenvolvido por Rosgen em 2001 e para além disso, com o estudo das técnicas de estabilização de margens num troço da ribeira da Granja na cidade do Porto.

Julga-se e espera-se que, similarmente ao realizado neste trabalho, a apresentação dos resultados de experiências e estudos na reabilitação de rios e ribeiras sirva para auxiliar os gestores de recursos hídricos na seleção das melhores e integradas soluções para aumentar o sucesso de projectos de reabilitação e para a implementação adequada da Directiva Quadro da Água.

Palavras-chave: Reabilitação fluvial; estabilização de margens; erosão; recursos hídricos.
1. Introduction

Stream stability is an active process and stream bank erosion is a natural part of this phenomenon, often increased by altering the stream system: erosion rate can result hundreds of times greater than the one occurring in naturally stable streams.

Stream bank erosion increases the sediment that a stream must carry, results in the loss of fertile land and causes a decline in the quality of habitat on land and in the stream; moreover, it can cause structures, constructions and roads damages or collapsing.

Determining the cause of accelerated stream bank erosion is the first step in solving the problem: damaging or removing stream side vegetation to the point where it no longer provides bank stability, can cause a dramatic increase in bank erosion. That is why acting on stream bank erosion requires an understanding of both stream dynamic and management of streamside vegetation.

Beyond phenomenon perception, there are two different approaches to act on stream bank erosion problem: the first one only takes into account the engineering aspect and chooses practice materials according to technical features like strength, technical life, costs, and its ability to solve the problem, so the main goal is to prevent erosion and soil removal. This approach was widely applied for a long time before a social consciousness about this environmental problem started to rise up, and the great part of practices were designed without assessing their impact on components like biota, biodiversity, flora and fauna presence: even if these practices were perfectly able to prevent erosion, they were real ecologic disfigurements.

The second approach also considers and assesses the impact that structures and materials have on environment, the ability to provide biodiversity, to improve biota and the quality of visual impact: these practices are usually known as bioengineering techniques. These engineering measures are typically adopted when stream bank features and vegetating cover are poor or not enough anymore to guarantee erosion protection. It is clear that an unperturbed system is perfectly able to protect itself from massive erosion: vegetation and roots system, beyond a pure environmental importance have the role to improve stream bank and channel bottom roughness and soil strength, to protect soil from flow direct attack, to provide soil drainage and to avoid rilling and intense runoff.

The analysis of all these processes cannot disregard a drastic simplification to summarize, perceive and compare the vast amount of information every component brings; this simplification can be easily achieved through indicators and indexes, meant as direct or indirect, quantitative or qualitative resuming values to provide a representative and easy-to-compare overview on the considered aspect. Indicators and indexes are usually employed to summarize and/or interpret riverine morphologic, hydraulic, biotic, atmospheric, chemical, physical and ecologic features, assess indirectly environmental quality, detect issues and damages in river ecosystem, choose suitable interventions and compare different techniques.

2. Objectives

This study is spread into two parts that developed separately the investigation about these points:

- To find a correlation between erosion potential and stream bank features;
- To provide a methodology to assess and compare stream bank erosion protection measures.

In the first point, stream bank morphology is represented through some natural features as vegetation component, surface coverage, bank slope and roots depth, ranked and summarized by indicators and finally related to a measured erosion amount; then it investigates to find a quantitative correlation between erosion potential and stream bank morphology, performed analysing some case-studies based on BEHI method (Rosgen, 2001). In particular, analysis aims to prove that a different bank configuration can be an incisive factor in causing erosion process, being furthermore possible to quantify this relation and control phenomenon evolution.

In the second part, a methodology is proposed to assess and compare different stream bank erosion protection measures. Methodology building concerns some fundamental steps:

- Work hypothesis formulation;
- Choice of set of equations;
- Choice of set of indicators;
- Choice of computational software.

Following the methodology step-by-step, riverine system and stream bank protection measures are modelled and data entered in the computation software HEC RAS 4.0, so that it is possible to compute and assess several scenarios; moreover, some proposals are given to choose properly system parameters. After computations, results like hydraulic values or water profiles are collected and analysed to define evaluation indicators. Moreover, functional type indicators are extrapolated by reference tables, like estimated costs and environmental restoring ability; all information is gathered, to perform practices evaluation and comparison. To conclude, both proposed investigations want to be effective to increase bioengineering practices or natural techniques usage in stream bank stabilization, providing methodologies and assessment indicators as generic as possible so that those may be easily applied to a vast amount of realities.

3. Investigation 1: Correlation Between Erosion Potential and Stream Bank Features

This first investigation is based on case-studies results which apply BEHI method (Rosgen, 2001). It is a stream bank erosion quantification method that uses two bank erodibility estimation tools: the Bank Erosion Hazard Index (BEHI), and the Near Bank Shear Stress (NBSS). BEHI index is the result of a linear combination of 5 measurable parameters (identified separately from near-bank shear stress in the model), which resume stream bank morphology: Bank Height to Bankfull Height, Root Depth to Bank Height, Root Density (%), Bank Angle in degree and Surface Protection (%).
Table 1. BEHI ranking table, (Rosgen, 2001).

<table>
<thead>
<tr>
<th>Stream Bank Hazard or Risk Rating</th>
<th>Bank Height to Bankfull Height (Ratio)</th>
<th>Root Depth to Bank Height (Ratio)</th>
<th>Root Density (%)</th>
<th>Bank Angle (Degrees)</th>
<th>Surface Protection (%)</th>
<th>Index Totals</th>
</tr>
</thead>
<tbody>
<tr>
<td>Very Low</td>
<td>Value 1,0-1,1</td>
<td>1,0-0,9</td>
<td>100-80</td>
<td>0-20</td>
<td>100-80</td>
<td>5-9,5</td>
</tr>
<tr>
<td></td>
<td>Index 1,0-1,9</td>
<td>1,0-1,9</td>
<td>1,0-1,9</td>
<td>1,0-1,9</td>
<td>1,0-1,9</td>
<td>10-19,5</td>
</tr>
<tr>
<td>Low</td>
<td>Value 1,11-1,19</td>
<td>0,89-0,5</td>
<td>79-55</td>
<td>21-60</td>
<td>79-55</td>
<td>20-29,5</td>
</tr>
<tr>
<td></td>
<td>Index 2,0-3,9</td>
<td>2,0-3,9</td>
<td>2,0-3,9</td>
<td>2,0-3,9</td>
<td>2,0-3,9</td>
<td>30-39,5</td>
</tr>
<tr>
<td>Moderate</td>
<td>Value 1,2-1,5</td>
<td>0,49-0,3</td>
<td>54-30</td>
<td>61-80</td>
<td>54-30</td>
<td>40-45</td>
</tr>
<tr>
<td></td>
<td>Index 4,0-5,9</td>
<td>4,0-5,9</td>
<td>4,0-5,9</td>
<td>4,0-5,9</td>
<td>4,0-5,9</td>
<td>50-59</td>
</tr>
<tr>
<td>High</td>
<td>Value 1,6-2,0</td>
<td>0,29-0,15</td>
<td>29-15</td>
<td>81-90</td>
<td>29-15</td>
<td>60-79</td>
</tr>
<tr>
<td></td>
<td>Index 6,0-7,9</td>
<td>6,0-7,9</td>
<td>6,0-7,9</td>
<td>6,0-7,9</td>
<td>6,0-7,9</td>
<td>70-89</td>
</tr>
<tr>
<td>Very High</td>
<td>Value 2,1-2,8</td>
<td>0,14-0,05</td>
<td>14-50</td>
<td>91-119</td>
<td>14-10</td>
<td>80-90</td>
</tr>
<tr>
<td></td>
<td>Index 8,0-9,0</td>
<td>8,0-9,0</td>
<td>8,0-9,0</td>
<td>8,0-9,0</td>
<td>8,0-9,0</td>
<td>90-100</td>
</tr>
<tr>
<td>Extreme</td>
<td>Value &gt;2,8</td>
<td>&lt;0,05</td>
<td>&lt;5</td>
<td>&gt;119</td>
<td>&lt;10</td>
<td>100-119</td>
</tr>
<tr>
<td></td>
<td>Index 10</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>130</td>
</tr>
</tbody>
</table>

Numerical values are converted from the field measurements to a scaling factor (Table 1) of risk ratings. Moreover, an estimation of erosion rate is measured, enabling an evaluation of total erosion (cubic yards and/or tons of sediment/year). Finally, results are plotted on an experimental graph (see Figure 1). Each point of the graph represents a stream bank section, which brings 3 different kinds of information: a measured erosion rate on y-axis (m/year), a NBSS ranking on the curves (from low to extreme), and a BEHI ranking on x-axis (from low to extreme). BEHI indicators have a key role in the presented investigation: they describe stream bank features, are measurable, ranked and comparable and are related to a specific amount of erosion; moreover, they don’t refer to specific regions, vegetation or river morphology and are measured independently.

The main assumption may then be resumed as: yearly erosion rate on a certain-section is a function of stream bank morphology (so a function of stream bank features) and Near Bank Shear Stress (the “erosion engine”). It can be written as:

\[ E_a = f(\text{BEHI}, \text{NBSS}) \]

where \( E_a \) is the occurring erosion on an a-section. As an example, considering \( a \) a specific section with a certain BEHI index, this one could be changed by improving bank quality (i.e. by vegetation implanting, bank reshaping, revegetation, surface coverage improvement etc) and could cause the decrease of the erosion rate. This makes for sure sense, and the purpose is to quantify this relation: if a consistent number of case-studies based on BEHI method is provided and a way to manipulate and aggregate data together to generalize results is found, the correlation between stream bank morphology and erosion amount may be pointed out as also the erosion decrease when stream bank is restored may be quantified. An essential step to perform this analysis is to build a methodology to extract, manipulate and aggregate data. To pursue those purposes, mathematic relations should allow to work adequately with erosion rates differing on orders of magnitude (note that y-axis is on log scale, see Figure 1); and applied to every pair of possible sections.
After computation, results are analysed performing a statistic analysis in order to draw some conclusions. Chosen mathematic relations are percentage differences and ratios between erosion rates. The undertaken analysis was limited to average parameters and standard deviation calculation; some T-Student tests were also computed to assess results validity.

Let’s now introduce mathematic relations to extrapolate and manipulate data: let be \(a = 1, 2, \ldots, b, \ldots, n\) a generic section belonging to the river to be studied, Figure 2:

![Diagram](image)

**Figure 2. Scheme approach.**

Remember that every \(a\)-section can be identified with a point on the BEHI graph and that in every section both BEHI and NSSB values are estimated (Table 1 and Table 2).

\[
BEHI = \sum_{i=1}^{b} li = BEHI \text{ parameters}
\]

\[
NBSS: f (\text{Shear Stress or velocity gradient})
\]

The first relation that can be defined is the Estimated Erosion Decrease, EED (%),

\[
EED_m = \frac{E_a - E_b}{E_b} \times 100
\]

where:
- \(i, j\) = BEHI values (see Table 2)
- \(y, k\) = fixed NSSB values
- \(i, j = 1, \ldots, 5\)
- \(y, k = 1, \ldots, 5\)
- \(i > j\)
- \(i-j = m\) (number of decreased steps of BEHI value)

\(\alpha_m\) is the number of decreased steps of BEHI value.

Note that in calculating EED, NSSB conditions are generic and not specified, and for the \(a\)-section those can vary from 1 to 5 (Table 2). Finally, EED is computed erosion percent difference, between two sections having different NSSB and BEHI values.

Similarly, a Specific Estimated Erosion Decrease, SEED (%) can be defined,

\[
SEED^y_m = \frac{\frac{E_a^y - E_b^y}{E_b^y}}{\frac{E_a^y - E_b^y}{E_b^y}} \times 100
\]

being \(y\) the fixed NSSB value.

SEED is basically identical to EED, but this time a specific NSSB value is fixed and identical for \(a\) and \(b\) sections. When calculating SEED, it is assumed that

\[
E = f (BEHI)
\]

SEED is the computed percent difference, between two sections, undergoing the same NSSB but with different BEHI index; in this case, \(a\) and \(b\) sections are morphologically different (and this difference depends on \(m\) value) but the “erosion engine” (NBSS) is the same.

Beyond percentages, erosion ratios can be considered. Again, generic or fixed NBSS conditions can be assumed, analysing different sections.

Let’s call Erosion Ratio, \(\alpha_m\), the ratio between \(a\) and \(b\) sections estimated erosion (ft/year) with a difference of BEHI value of \(m\) steps;

\[
\alpha_m = \frac{E_a^y - E_b^y}{E_b^y}
\]

where:
- \(i, j = 1, \ldots, 5\)
- \(y, k = 1, \ldots, 5\)
- \(i > j\)
- \(i-j = m\) (number of decreased steps of BEHI value)

\(\alpha_m\) is useful to compare measured erosion ratio between two sections having different BEHI and NSSB values; note that this corresponds to compare a section with itself, in two different times \(t\) and \(t^*\), when BEHI and NSSB have been modified installing engineering techniques.

Let’s define the Specific Erosion Ratio, \(\rho_m\), the ratio between two different sections estimated erosion (ft/year), with a difference of BEHI values of \(m\) steps undergoing the same NSSB conditions:

\[
\rho^y_m = \frac{E_a^y - E_b^y}{E_b^y}
\]

where:
- \(i, j = 1, \ldots, 5\)
- \(y, k = 1, \ldots, 5\)
- \(i > j\)
- \(i-j = m\) (number of decreased steps of BEHI value)
\( \rho^\gamma_m \) is useful to compare the erosion ratio between two sections having different BEHI and undergoing the same NSSB value; this corresponds to compare a section with itself, in two different times \( t \) and \( t^* \), when BEHI has been modified by installing engineering techniques.

Moreover, different scenarios about shear stress conditions can be estimated with computational software like HEC-RAS; \( \alpha_m \) \( \rho^\gamma_m \) translates measured erosion differences in terms of ratios, and when their magnitude is particularly high, they provide a difference of the order of magnitude of the bank erosion rate.

Resuming, analysis is performed applying the following steps:

- Collect case-studies obtained applying BEHI method;
- Collect results and graphs;
- Calculate EED, SEED, \( \rho_m \), for every possible pair of sections;
- Apply statistical analysis on calculated data;
- Draw conclusions.

### 3.1. Case-studies

The BEHI Rosgen method was applied to three case-studies taken from literature:

- **Case-study 1:** West Fork White River Watershed (WFWRW) (Van Eps et al, 2002): A stream bank erosion inventory was conducted in 2002 to determine the bank erosion potential of stream banks along 64 river kilometres (40 river miles) of the main stream and tributaries of the WFWRW watershed (Figure 3);

- **Case-study 2:** Relationship of BEHI and NBSS to predict annual stream bank erosion rates, based on Colorado US Forest Service data (Rosgen, 2001) (Figure 4);

- **Case-study 3:** Relationship of BEHI and NBSS to predict annual stream bank erosion rates, based on Yellowstone National Park data (Rosgen, 2001). The measured annual, lateral erosion rate for 49 separate sites is plotted for the Front Range Colorado and for 40 sites in the Lamar River Basin Montana (Figure 5).

![Figure 3. Model for predicting stream bank erosion rates in the WFWR watershed.](image)

**Figure 3.** Model for predicting stream bank erosion rates in the WFWR watershed, (Van Eps et al, 2002).

![Figure 4. Graphical model for predicting stream bank erosion rates in the Yellowstone National Park.](image)

**Figure 4.** Graphical model for predicting stream bank erosion rates in the Yellowstone National Park, (Rosgen, 1996, 2001).

![Figure 5. Graphical model for predicting stream bank erosion rates in the Colorado USFS.](image)

**Figure 5.** Graphical model for predicting stream bank erosion rates in the Colorado USFS, (Rosgen 1996, 2001).

### 3.2. Data analysis and results

The first analysed parameter is EED (%), which represents the percent erosion decrease between two sections having a difference of BEHI ranking of \( m \) steps. EED (%) is more significant when \( m=3 \), so when extreme and moderate or very high and low ranked sections are compared: average erosion difference is about 86%, with a standard deviation equal to 13%. Table 3 resumes the EED (%) average values and standard deviations obtained.

<table>
<thead>
<tr>
<th>Table 3. EED (%) analysis results.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>EED analysis</strong></td>
</tr>
<tr>
<td>Average (%)</td>
</tr>
<tr>
<td>Standard deviation (%)</td>
</tr>
</tbody>
</table>

Data analysis is refined with a T-student test analysis, presented in Table 4.
Table 4. EED (%) average, T student confidence test.

<table>
<thead>
<tr>
<th>Average T Student confidence test 95%</th>
<th>m=1</th>
<th>m=2</th>
<th>m=3</th>
</tr>
</thead>
<tbody>
<tr>
<td>T student coefficient</td>
<td>0.05</td>
<td>0.05</td>
<td>0.05</td>
</tr>
<tr>
<td>number of data N</td>
<td>40</td>
<td>25</td>
<td>11</td>
</tr>
<tr>
<td>EED average</td>
<td>50.8</td>
<td>72.8</td>
<td>86.2</td>
</tr>
<tr>
<td>EED dev sta</td>
<td>18.3</td>
<td>16.0</td>
<td>12.9</td>
</tr>
<tr>
<td>T student value</td>
<td>4.0</td>
<td>4.3</td>
<td>5.5</td>
</tr>
<tr>
<td>Erosion decrease % average</td>
<td>min 39.1</td>
<td>59.0</td>
<td>64.6</td>
</tr>
</tbody>
</table>

The following figures show $EED_2$ and $EED_3$ curves computed for the three chosen case studies:

Figure 6. $EED_2$ curves computed on case-study rivers.

Figure 7. $EED_3$ curves computed on case-study rivers.

It is clear that decreasing BEHI works better under soft rather than strong shear stress conditions. SEED analysis is particularly useful to assess what happens when the "erosion engine" (NBSS) is similar between a and b sections, so that erosion is just controlled by stream bank morphology: $E = f (BEHI)$.

It seems that the role of shear stress in affecting river bank stability is clear: the improvement of bank conditions under strong NSSB gives more instable curves rather than under lower NSSB conditions: this is clearly shown in Figure 8. Anyway, when $m=3$ all the curves exceed 50 % of erosion decrease, turning clear that an improvement of river bank conditions reduces total erosion risk.

Figure 8. SEED curves for different NSSB levels.

3.3. Specific erosion ratio analysis

This is a very useful analysis to compare erosion rates between different sections undergoing different or fixed shear stress conditions. Analysis is performed using both $\alpha_m$ [8] and $\rho_m$ [9]. The first value doesn’t take into account particular shear stress conditions. Results are shown in Table 5.

Table 5. Average erosion ratio.

<table>
<thead>
<tr>
<th>Average erosion ratios</th>
<th>$\alpha_1$</th>
<th>$\alpha_2$</th>
<th>$\alpha_3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average</td>
<td>2.3</td>
<td>4.7</td>
<td>10.0</td>
</tr>
<tr>
<td>Standard dev</td>
<td>0.8</td>
<td>0.4</td>
<td>1.4</td>
</tr>
<tr>
<td>Average confidence test 95%</td>
<td>0.3</td>
<td>0.9</td>
<td>3.1</td>
</tr>
<tr>
<td>Data count</td>
<td>41.0</td>
<td>25</td>
<td>13</td>
</tr>
</tbody>
</table>

Let’s focus on $\alpha_3$: its average value is $10 \pm 3.1$, with a standard deviation of 1.4. Having in attention the BEHI experimental graphs (e.g. Figure 1), this means that it seems rather possible to reduce erosion rate of about 1 order of magnitude, when a significant stream bank restoration is performed (BEHI is decreased 3 steps).

Now, let’s analyse the situation under fixed NSSB conditions, for $m=3$, and if a significant reduction of erosion can be noticed anyway. In this case, due to a lack of information, different NSSB conditions were jointly considered: Extreme and Very high NSSB conditions results were computed together, as well as High, Moderate and Low (Table 6):

Table 6. Specific erosion ratio analysis results.

<table>
<thead>
<tr>
<th>Specific erosion ratio</th>
<th>$\rho_{14}^\alpha$</th>
<th>$\rho_{14}^{\alpha_3}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average</td>
<td>8.9</td>
<td>11.2</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>2.2</td>
<td>1.6</td>
</tr>
<tr>
<td>Confidence level 5%</td>
<td>5.5</td>
<td>4.16</td>
</tr>
<tr>
<td>Count</td>
<td>7</td>
<td>6</td>
</tr>
</tbody>
</table>

$\rho_{m}^\alpha$ analysis fixing NSSB conditions can give us the possibilities to improve the quality of previous computations. As shown, even under different NSSB conditions, the specific erosion ratio is again around the order of importance of 10 points. Unfortunately, there is a consistent lack of data which should be incremented to enable defining better results.
Anyway $p_g^{3.2.1}$ value is 11.2: about one order of magnitude difference in terms of erosion can be generally observed decreasing 3 steps BEHI ranking. This analysis could be better performed if a greater amount of data would be available, for example to define $p$ for every specific NSSB condition.

### 3.4. Investigation 1: conclusions

Results show clearly how bank morphology can affect the erosion process. The differences in terms of yearly erosion rate between two sections are particularly evident when $m=3$: in this case, a reduction of 86% (see Table 3) of total eroded sediment is averagely estimated, while erosion rate quotient is about 10 (see Table 4), so corresponding to more or less one order of magnitude.

Also when $m=2$ results are encouraging; erosion percentage difference and erosion rate quotient are respectively 73% and 4.7.

Analysis was performed taking different sections two-by two, but nothing avoids extending results on a particular section before and after restoring interventions: BEHI index evolution can be controlled changing bank features, and so it would be possible to quantify benefits and obtain an estimation erosion decrease.

For example, obtaining a decrease of one order of magnitude would mean a bank erosion reduction from metres to centimetres or from centimetres to millimetres, just by improving bank features.

Moreover, $p_g$, $a_m$, and $a_n$, can be used as coefficients to estimate obtainable erosion decrease by acting on stream bank features, when the amount of yearly erosion in a certain area is known.

Another hint that this methodology can provide is when a low BEHI index is computed even though erosion is a visible, huge phenomenon on the area: a further improvement of stream bank features is probably not worth to reduce erosion, and stronger solutions have to be designed; for example, this can be a design criteria to exclude bioengineering works, preferring stronger solution.

Unfortunately, a real weakness point in this analysis was the lack of available case studies: even, if BEHI method does not restrict usage to particular land morphologies, collected data refer to three particular situations that cannot guarantee the applicability of the obtained results on every kind of river.

Is it clear that a wider number of data would allow a more accurate statistical analysis; anyway, results encourage investigating more in depth, especially thinking about all possible applications.

General results are encouraging and can be an incentive to go further on this kind of investigation, especially when intervention goals concern an eco-sustainable riverine restoration, which aims to avoid hard practices preferring natural and ecologic solutions while preventing erosion. In order of that, a draft for analysis possible application is proposed, which will not be developed in this context but can be a hint for future works.

Suggested steps are the following:

1. Select a river;
2. Select a specific number of sections, then measure BEHI and NBSS index on each one;
3. Select a time range to observe erosion; one year is recommended, to consider the entire hydrologic year. When shorter time is chosen, analysis cannot disregard to take into account typical seasonal effects on discharges, stream power and water levels, which affect obviously erosion process;
4. Calculate EED, SEED and erosion ratios; these values refer to a specific situation and are supposed to be representative just for the analysed river;
5. Select a group of sections, according to erosion problem and necessity to design stream bank protection measures; for the a-section it is:

$$ a \begin{cases} BEHI = i \\ NBSS = y \\ E = E_a \end{cases} $$

6. Design a new stream bank morphology configuration on each section considering reshaping, surface cover improvement, revegetation and so on, in order to take down highest BEHI parameters (Slope, Root density etc...). Leading to:

$$ a \begin{cases} BEHI = i \\ NBSS = y \\ E = E_a^* \end{cases} $$

Where $E_a^*$ is the erosion supposed to occur during the observation time with the new stream bank configuration. Erosion can be then estimated as:

$$ E_a^* = \frac{E_a}{a_m} \quad [10] $$

or

$$ E_a^* = \frac{E_a}{\rho_m} \quad [11] $$

where $m = i – j$, if NBSS conditions are steady. Similarly, $E_a^*$ can be estimated from EED or SEED values.

### 4. Investigation 2: Stream Bank Protection Measures

#### 4.1. Assessment methodology

The proposed methodology is a tool to assess stream bank protection practices:

- Traditional practices;
- Bioengineering practices.

This methodology is built to give a particular attention to problems related to the two typologies: while traditional methods have generally poor restoration ability but are generally more resistant to flow attack, bioengineering practices have good environmental impact but scarce ability to undergo medium to strong flows.

Moreover there are practices that have to satisfy some objectives, Table 7.

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**Proposta Metodológica de Avaliação da Estabilização das Margens em Processos de Reabilitação Fluvial. O Caso da Ribeira da Granja, Porto**
Table 7. Erosion protection measures goals.

<table>
<thead>
<tr>
<th>Primary aims</th>
<th>Secondary aim</th>
</tr>
</thead>
<tbody>
<tr>
<td>Give stabilization to the river bank (guarantee protection from erosion, hard stream attack, protect nearby roadways, recreation areas, etc); Prevent floods in the area; Restore environment; Give space to the river but also to recreation areas; Reduce sediment supply, land loss; Improve visual values; Improve fish habitat and biological diversity; Create a natural stable river; Guarantee ability to withstand floods; Be self-maintaining; Be cost-effective; Improve water quality.</td>
<td>Reduce shear stress; Reduce velocities; Guarantee a greater roughness but also sustainable outflow; Modify channel geometry.</td>
</tr>
</tbody>
</table>

The proposed methodology concerns a process to follow and a set of control equations, Figure 9.

- **Shear stress equation:**
  
  \[ \tau = \gamma hS \]  
  
  where:
  
  - \( \tau \) - shear stress, Pa (N/m²);
  - \( \gamma \) - unit weight of water (N/m³);
  - \( h \) - depth of flow (m);
  - \( S \) - slope of energy grade line (m/m).

- **Critical shear stress Shield’s equation:**
  
  \[ \tau_c = \theta gd (\rho_s - \rho) \]  
  
  where:
  
  - \( \tau_c \) - critical shear stress (N/m²);
  - \( d \) - particle size (m);
  - \( g \) - 9.8 (m/s²);
  - \( \rho_s \) - particle density (kg/m³);
  - \( \rho \) - water density (kg/m³);
  - \( \theta \) - form factor.

This equation is used to find critical shear stress, defined as the minimum shear stress to start particles motion.

- **Discharge equation:**
  
  If discharge is steady, in any cross-sections we have:
  
  \[ Q = V A \]  
  
  where:
  
  - \( Q \) - discharge (considered steady) (m³/s);
  - \( V \) - mean velocity of flow (m/s);
  - \( A \) - Section area (m²).

- **Permissible velocity:**
  
  \[ V_p = \frac{0.189 R^3}{n} \frac{1}{\tau_p} \]  
  
  where:
  
  - \( \tau_p \) - permissible shear stress (psf);
  - \( V_p \) - permissible velocity (fps);
  - \( R \) - Hydraulic radius (feet);
  - \( n \) - Manning’s roughness coefficient.

- **Manning’s equation:**
  
  \[ V = \frac{\sqrt{R^3}}{n} \]  
  
  The hydraulic radius \( R \) is defined as:
  
  \[ R = \frac{A}{P} \]  
  
  where:
  
  - \( A \) - Wet area (m²);
  - \( P \) - Wet perimeter (m).

- **Roughness computation equation:**
  
  Cowan (1956) developed a procedure for estimating the effects of these factors to determine the value of \( n \) for a channel.

  This equation is useful to estimate Manning’s roughness coefficient, when channel and stream banks features are given, especially in terms of shape, granulometry, vegetation, obstacles, etc.

  \[ n = m^* \sum_{i} n_i \]  
  
  where:
  
  - \( n \) - Manning’s roughness coefficient;
  - \( n_i \) - Control parameters for roughness;
  - \( m^* \) - meanderization of channel.

Moreover, we need:

1. Work hypothesis;
2. Application tools:
   - HEC-RAS 4.0 and North American Green Company ECMDS software;
   - A table to assess and compare practices.

The process will be following introduced and discussed step-by-step, aiming at being as general as possible to be applied with no particular restrictions; moreover, some proposals are discussed and justified. Basically, practice assessment is performed filling an matrix of indicators, after several scenarios are computed.

Assessment indicators can be classified as follows:

**Technical features indicators (group 1):**

This category includes engineering evaluation, research and development (R&D) information associated with design, production, operation, use, and/or maintenance of an equipment, machine, process, or system.

Stream practice technical features can be resumed in a group of indicators that provides information about application field ranges in terms of permissible velocities, shear stress, temperature, soil humidity, etc; they are usually provided by constructors or available in literature;
Proposta Metodológica de Avaliação da Estabilização das Margens em Processos de Reabilitação Fluvial. O Caso da Ribeira da Granja, Porto

Reference conditions indicators (group 2):
Provide information about morphologic or hydraulic parameters as reference flow velocity, shear stress, flooded area, temperature etc. Those indicators can be measured or estimated; when variable profiles are computed, they should be resumed in a unique, representative value;

Feasibility practices indicators (group 3):
These parameters intend to assess practice applicability. In this work, the applied criteria are permissible velocity and permissible shear stress methods, which consist in a comparison between channel reference values (measured, or estimated) and practice technical features: we want to propose some indicators, some of them built ad hoc, easy to calculate and comparable, as a tool to assess practice feasibility;

Functional characters indicators (group 4):
Can assess practice effectiveness, ability to pursue restoration goals, and can be employed to perform a comparison between different techniques. They are usually available in literature.

To perform evaluation, for every practice, the parameters presented in Table 8 are required.

The first step is to define riverine area and parameters characterization to enter data in HEC-RAS; of course, software modelling needs restrict parameters choice, which will influence the quality of results.

The proposal here presented is to assess stream bank protection measures considering 3 discharges occurrence times: 100 years (discharge to assess centenary flood effects), 10 years (average bioengineering practices time required for vegetation to develop completely) and 1,5 years (bankfull discharge occurrence time (Leopold, 1964), so perpetual solicitations here called “ordinary conditions”).

This choice may seem strange, but during investigation it was noticed that some lining revetments showed a good ability to face centenary floods, while ordinary conditions were too strong to be undergone.

An important parameter is roughness, which controls energy loss; it can be calculated indirectly by Manning’s equation, considering channel and stream bank features (Chow, 1959; Benson and Dalrymple, 1967), or computed by North American Green ECMDS 4.31 Software, useful to calculate n for highly vegetated stream bank, grass linings and riprap.

After all requested parameters are entered in HEC-RAS, reference conditions can be estimated.

This scenario gives back some velocity and shear stress profiles, used to perform a comparison with practice permissible values in order to choose feasible measures.

This classic methodology, often found during investigation is however discussable: all computed water, velocity and shear stress profiles are the result of interaction between an hydrologic input - discharge - and a particular morphologic situation, and a change of just one of these components, modifies hydraulic profiles.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Provided information</th>
<th>Group</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau_p$</td>
<td>Pa, m/s</td>
<td>Practice permissible values of $\tau_p$ and $V_p$ available in literature or provided by constructors</td>
<td>1</td>
</tr>
<tr>
<td>$V_f$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\tau_p, V_p$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$t_1=2$ years</td>
<td></td>
<td>Estimated hydraulic solicitation, and considering $V_f$ and $\tau_p$ (see figure 10); variable spatial distribution computed by HEC-RAS</td>
<td>2</td>
</tr>
<tr>
<td>$t_2=10$ years</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$t_3=100$ years</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\tau_s$</td>
<td>Pa, m/s respectively</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$V_f$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\theta_j = \frac{\tau_p}{\tau_s}$</td>
<td>-</td>
<td>Resistance to shear stress solicitation depending on flood occurrence time</td>
<td>3</td>
</tr>
<tr>
<td>$\chi = \frac{V_p}{V_f}$</td>
<td>-</td>
<td>Resistance to velocity solicitation depending on flood occurrence time</td>
<td>3</td>
</tr>
<tr>
<td>$T$ (occurrence time =100 years)</td>
<td>hours</td>
<td>Estimated practice collapsing time; values are available in literature or provided by constructor</td>
<td>3</td>
</tr>
<tr>
<td>Flooded Area</td>
<td>m$^2$</td>
<td>Estimated flooded area, computed by HEC-RAS</td>
<td>2</td>
</tr>
<tr>
<td>t=100 years</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Costs</td>
<td>Available currency</td>
<td>Approximate cost estimation; current costs are provided by constructor</td>
<td>4</td>
</tr>
<tr>
<td>Recreation</td>
<td>Aesthetic value</td>
<td>Practice restoration ability; reference tables are available in literature</td>
<td>4</td>
</tr>
<tr>
<td>Wildlife habitat</td>
<td>Qualitative</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Considering and manipulating both discharge and Manning’s equation:
$$V \ast f_1(h) = \frac{f(h) \dot{V}}{n} = \text{steady}$$
[19]

When stream bank is modified by installing erosion protection measures, then Manning’s $n$ is modified: both velocity and flow height change to keep equations constant.

We are designing punctual or extended erosion protection measures that just after placement change channel and stream bank shape and roughness; it is clear that this new condition changes velocity and shear stress profiles, water height, water profiles etc.

So, being computed scenarios for two different realities (before and after technique placement), an estimation based on a simple comparison between actual shear stress and installation permissible values is not realistic. An actual condition computational run is anyway useful to establish average outflow conditions: a primary evaluation gives an idea about solicitations magnitude, to perceive hydraulic potential features, so that:
• $\chi, \theta >> 1$ practice is feasible;
• $\chi, \theta \approx 1$ practice is feasible;
• $\chi, \theta << 1$ practice is not feasible.

Moreover, flood risk comparison before and after practice placement enables pointing out eventual dangerous increases on population safety that shall has the priority on stream bank protection.

An important step is that $V_f \tau_f$ values can be estimated based on the corresponding computed profiles: during investigation, it was noticed that designers usually consider $V_f$ and $\tau_f$ average values along the channel, but when local variations increase or decrease dramatically a parameter distribution, the risk is to underestimate stream power in many sections (as exemplified on Figure 10, correspondent to the Case Study described in 4.2.) and practices can be easily dragged away.

Aiming to take that into suitable account, we propose to consider the value of the parameter that is not exceeded in 80% of sections ($V_{80}, \tau_{80}$).

A fundamental work hypothesis to $V_{80}$ to be realistic, is that local fluctuations are evident, random and equally distributed along channel.

After a set of practices is chosen and different scenarios computed, all the requested parameters and indicators can be extrapolated to fill Table 8; finally, erosion protection measures can be assessed and compared.

### 4.2. Case study application and results

The proposed methodology is now applied to a case-study, a project kindly provided by ARH Norte (Administração da Região Hidrográfica do Norte, PT) and executed by IHRH of FEUP, for Imoalde (Figure 11).

The project deals with a river situated in Porto urban area named Ribeira da Granja and proposes to deviate a specific channelized river stretch into a new carved opened-air channel; moreover, the project proposes a riprap lining as stream bank protection measures.

Starting from project available data, we propose alternative stream bank practices by applying the proposed methodology (Table 9).

Applying the methodology and filling the assessment table, Table 10 is obtained; bold marked cells refer to best performances, while italic ones refer to the worst.

The following assumptions can be addressed as: generally, riprap and live stakes is an expensive but good solution, which joins the strength of a rock revetment with the benefits of plantation, and increases structure ability to undergo strong floods and satisfies sustainability criteria. On the contrary, grass lining is a weak technique, which can be adopted as a cheap solution but can collapse within few hours under strong flows; moreover, the type of chosen lining grass depends on ordinary flow strength and soil features. Turf reinforcement mat is also a not expensive, environment improving technique, which must be well dimensioned especially in the bottom where it there is usually no vegetation.

It can increase notably flow velocity and decrease shear stress in the channel, as well as flooded area, so it is better to apply where low speeds are typical, to avoid structure collapse under strong floods; moreover, it requires particular attention just after installation, when not vegetated.

Original project designed riprap has of course, good resistance to flow but the worst restoring ability as we already expected.

![Image](image_url)

**Figure 10.** Investigation 2 Case Study: variable local fluctuations are evident, random and equally distributed along channel. Shear stress average value is 77.5 Pa while $\tau_{80}=120$ Pa. In this example, average stress is underestimated in 40 % of total sections (red dot on graph) and 4 times smaller than maximum value. This case is just an example, but representative of those situations where oscillations around average are big.
4.3. Investigation 2: conclusions

In this specific case, stream bank protection solution that gives worst performance is grass lining, while the best is Turf Reinforcement Mat (TRM). Beyond a specific assessment, the proposed table (Table 10) takes into account important logistic parameters and helps to have an overview about achieved goals giving information about stream bank protection measures restoration ability, resistance to flow, flooded area and costs.

Methodology procedure is easy, cheap, fast to develop and requires just an initial effort to collect required parameters; moreover, both proposed software can be downloaded free of charge from respective web sites. The result is an easy-to-read table, which allows a fast installation assessment and comparison and can be useful when specific priorities are assigned; it is anyway suggested to test it on a larger number of case-studies; moreover, a wider amount of reference table should be collected.
The entire work here presented allowed to explain and detail methodologies that can have a role in stream bank erosion assessment, especially in riverine restoration process; it is anyway recommended to develop deeper both investigations protection measures, and be a good incentive in achieving environmental protection and restoration.

<table>
<thead>
<tr>
<th>Indicators</th>
<th>Grass lining</th>
<th>Vegetated Rip Rap</th>
<th>Turf mat</th>
<th>Rip Rap</th>
</tr>
</thead>
<tbody>
<tr>
<td>V ordinary (m/s)</td>
<td>1.5</td>
<td>0.91</td>
<td>1.9</td>
<td>1.5</td>
</tr>
<tr>
<td>V 100 years (m/s)</td>
<td>3.1</td>
<td>1.65</td>
<td>3.8</td>
<td>2.6</td>
</tr>
<tr>
<td>r 100 years (Pa)</td>
<td>161</td>
<td>161</td>
<td>111.69</td>
<td>142</td>
</tr>
<tr>
<td>Permissible velocity (m/s) *</td>
<td>Depends on grass type; =1.5 D50 &gt; 300mm</td>
<td>3.5</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>Resistance to velocity $\chi$, t=2 years</td>
<td>1</td>
<td>3.3</td>
<td>1.8</td>
<td>2</td>
</tr>
<tr>
<td>Estimated 100 years flood collapsing time (h)**</td>
<td>2.5 - 3</td>
<td>Unlimited</td>
<td>6</td>
<td>15</td>
</tr>
<tr>
<td>Permissible shear stress (Pa)***</td>
<td>201.1</td>
<td>300</td>
<td>383</td>
<td>219.9</td>
</tr>
<tr>
<td>Resistance to shear stress $\theta$ (ratio); t= 100 years</td>
<td>1.25</td>
<td>1.8</td>
<td>3.42</td>
<td>1.6</td>
</tr>
<tr>
<td>Flooded area (m2)</td>
<td>1021.67</td>
<td>1041.8</td>
<td>1001.63</td>
<td>1099.34</td>
</tr>
<tr>
<td>Cost (USA 1000$ 1994)****</td>
<td>13,562</td>
<td>45,113</td>
<td>15,500</td>
<td>41,333</td>
</tr>
<tr>
<td>Recreation*****</td>
<td>Fair</td>
<td>Fair to good</td>
<td>Fair</td>
<td>Fair</td>
</tr>
<tr>
<td>Wildlife habitat</td>
<td>Fair</td>
<td>Negligible</td>
<td>Good to very good</td>
<td>Negligible</td>
</tr>
<tr>
<td>Aesthetic value</td>
<td>Good</td>
<td>Good to very good</td>
<td>Good to very good</td>
<td>Fair</td>
</tr>
</tbody>
</table>


References


Guide for selecting manning's roughness coefficients for natural channels and flood plains. United states geological survey water-supply, paper 2339.

HEC-RAS 4.0 reference manual, USACE Army Corps of Engineers.


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