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Study of Erosion Control Techniques Applied to Hydroelectric Power Plants Reservoir Margins

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Abstract

This paper aims to provide relevant information on erosion control processes at water reservoir marginsunder tropical conditions. This large-scale streambank erosion control study is located on the margins of the water reservoir at Volta Grande Hydroelectric Power Plant in Brazil. This reservoir lake occupies an area of 220 km^2, and is located in the border of the states of Minas Gerais and São Paulo. Three experimental sites, with fast bank retreat, were identified for the implementation of these erosion control works: Pier (2,700 m^2), Baia (3,524 m^2), and Miguelopolis (1,280 m^2), in a total study area of 7,500 m^2 and length of 500 m, around the reservoir lake. Eleven different bioengineering treatment techniques, vegetated and armored techniques, were implemented on 27 parcels on these three study-areas, as follows: Straw logs and Coir logs (biologs); three metallic gabions coated with polymers and PVC- bags, box, and mattress; Polypropylene (PP) P550 geotextile; PP geotextile C350; Sintemax geotextile; MacMat geotextile; and wood crib wall. Laboratorial and field testings and measuremnentsincluded geotechnical studies, fertility, turbidity, wind velocity, wave height, stratigraphy of the study area, and *in situ* permeability. All obtained geotechnical results pointed that the streambank soil is erosion prone. Collected data over a period of three years were summarized in a Performance Matrix. Turbitidy, wave height and wind velocity measurements were difficult to correlate, and could not provide much information on soil loss. Thus, to gather more data on the sediment acumulated in front of each treatment, differential bathymetry was performed nd plotted by using ArcGIS map algebra. Under the studied conditions, the best bioengineering techniques were armored techniques such as Gabion mattress associated with geotextile, and rip rap associated with Gabion mattress, whereas vegetated biologs and crib walls had the worst performance. Also, the use of vegetation soley was not an efficient method for controlling erosion.

Keywords: Shoreline Protection, Soil Bioengineering, Streambank Erosion Control.

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Literature Review

Accelerated soil erosion rate, either natural or anthropogenic, results in the loss of fertile and increased sedimentation of waterways. FAO (2015) states that, most likely, the range of soil loss by water erosion is about 20-30 Gt yr^{-1}, corresponding to an estimated economical loss of 400 billion dollars yr^{-1}. Thus, controlling erosion processes has become a very important subject and an object of a great number of studies. In the last decades, the focus of erosion studies became widespread. It incorporated besides the traditional agriculture concerns, such as the loss of fertile topsoil, and it also included concerns related to the significant impairment of waterways due to sediment deposition. This current research also addresses the erosional processes that can take places on cohesive streambank soils at the margins of hydroelectric power plants water reservoirs. Despite the great amount of research on predicting erosion on cohesive streambank, the subject has remained difficult. Three main processes have been identified in streambanks as responsible for the soil loss: subarearial erosion, fluvial entrainment or scour, and mass failure (Grove et al., 2013; Thorne, 1982). Subaerial erosion is often regarded as a preparatory process, in contact with air, aiming to lower the shear strength prior to fluvial erosion. It exclude processes during periods of inundation. Fluvial entrainment or scour, is the direct removal of sediment by the river hydrological processes. Physically, a rotational failure can often be identified in the field by the deep seated, curved failure scars; intact bank failure blocks back-tilted towards the scar; and arcuate shape of the intact bank line behind the failure mass (Thorne, 1993). The failed material may not be a coherent block(s), and may occur as a wet flow (Thorne, 1993). Researchers have been pointing out that fluvial entrainment and mass failures are often interlinked (Darby et al., 2007; Rinaldi and Darby, 2008; Rinald and Nardi, 2013) with the basal undercutting of a riverbank lowering the bank factor of safety (FS), so that riverbanks with an excess basal capacity (Osman and Thorne, 1988) are likely to become unstable. Mass failures would be expected to occur in areas of high banks and leave signature failure scars and blocks that can be interpreted to infer process(es). Some other researchers incorporate a fourth category named cantilever failure. Cantilever failures may also occur in more cohesive or massive sediments due to pop-out failures. The basal removal of sediment by seepage can cause failures in the lower bank, leaving a characteristic alcove-shaped indentation and failed blocks pushed out, or down slope, of the indentation (Dapporto et al., 2003). The upper bank is left unsupported and vulnerable to cantilever failure.

Role of Vegetation

Vegetation plays an important role in controlling streambank erosional processes, as it protects the soil from rain splash and subsequent detachment from the soil matrix. Roots and root architecture can reinforce soil, increase slope stability due to the added apparent cohesion given by roots (Gray & Sotir, 1996; Zhang Chao-Bo et al., 2014). The apparent root cohesion is a product of the root cross-section area per unit area of soil and root tensile strength (Wu et al., 1979).

The soil reinforcement provided by roots was derived from modified Coulomb's Law shear strength equation, as an added increment of shear strength, ΔS (Waldron, 1977):

$$S = c + \Delta S + \sigma_N \tan\varphi \quad (1)$$

$$\Delta S = TS\,(\sin\theta + \cos\theta \tan\varphi)\,(A_r/A) \quad (2)$$

Where ΔS is the root additional shear resistance; φ is the internal friction angle, σ_N is the normal pressure, A_r/A is the ratio of root cross-section area per unit area soil of the shear plane, TS is the tensile strength of the roots, and Θ is the angle of the shear plane.

Vegetation through its fine root architecture provides additional soil resistance to erosional processes and entraps the soil into the soil matrix. Finer roots are stronger and provide more resistance than thicker roots (Ye et al., 2017). Much research has been produced on use of vegetation to control erosional processes (Gray and Sotir, 1996; Zhang Chao-Bo et al., 2014; Ye et al 2017, Coelho, 2001b). However, depending on the site conditions, inert elements need to be add.ed to the vegetation to provide more reinforcement. The combination of inert elements with plants is known as bioengineering techniques. In summary, bioengineering techniques is a combination of biological, mechanical, and ecological concepts to control erosion and stabilize soil through the use of vegetation or a combination of vegetation and construction materials (Coelho, 1999; Gray & Sotir, 1996). Even though bioengineering techniques for erosion control have been around for centuries, it was only in the last decade that it became widely used due to its intrinsic advantages: low implementation cost, low greenhouse gases footprint, preservation of local biodiversity and habitats, and better landscape aesthetics, among others (Gray and Sotir, 1996; McCullah and Gray, 2005; Morgan, 1994; Coelho, 1999; NRCS, 2012, Coppin and Richards, 1990).

In this study, a wide range of bioengineering techniques are proposed to control erosion, by providing resistance and protecting the bank against aerial, fluvial, mass and cantilever failures. It aims to provide relevant information on the erosional processes at reservoir margins, which are very significant in Brazil, where the perimeter of all Brazilian water reservoirs for hydroeletric power plants is about the same as the Brazilian coast perimeter – 6,000 km.

Methodology

Site Description

Three study areas named Pier, Baia and Miguelopolis covering 7,500 m^2 were selected on the margins of the water reservoir lake at the Volta Grande hydroelectric power plant, which is located at the borders of Minas Gerais and São Paulo states, Brazil, and ocuppies an area of 220 km^2. The three study areas were selected based on the following criteria: (i) the streambank was actively retreating through a combination of fluvial erosion, mass and cantilever failure; and (ii) the streambank soil profile and geomorphology were similar to those observed at other sites along the water reservoir.

On these three study areas, 28 parcels of bioengineering techniques were implemented and monitored for three years.

Climate of the study areas is classified as Cwa according to Koppen, that means tropical savannah, moist and hot, with a dry season from April to September, and 80% of rainy pseason lasts from October to March. The mean annual temperature is 23.5^{o}C, with minimum temperature around 16.5^{o}C and maximum temperature around 29.2^{o}C. The annual precipitation for the study area is around 1,400 mm. The streambank soil profile is characterized by homogeneous red latosol (Oxisol, according to US Soil Taxonomy).

Starting in the 1940s, native vegetation has been replaced with planted pastures of *Brachiaria decumbens and Hyparrenia rufa*. In the 1990s, *Pennisetum purpureum* was planted in the area in an attempt to stabilize and mitigate the erosive effect of waves on the reservoir streambanks. However, the approach was not successful.

Bioengineering Techniques

Vegetation in combination with a wide range of inert elements (bioengineering techniques) was implemented in the study areas. It includes rolled erosion products (RECPs) made of synthetic (geotextile) or natural materials (straw or coconut fiber) were implemented either by itself, or combined with armored engineering erosion control techniques (gabion, and crib wall) in the three study areas. They were: (i) rolled erosion product - C350 – produced by North American Green (NAG), USA; (ii) rolled erosion product -P550 – NAG/USA; (iii) crib wall; (iv) rip rap; (v) rip rap + vegetated bag Gabion; (vi) vegetated biologs filled with straw; (vii) vegetated biologs (filled with straw) + Sintemax geotextile from Deflor Bioengineering/Brazil; (viii) vegetated MCMat (Maccaferri/Brazil) + bag Gabion; (xix) vegetated biologs filled with coconut fiber (coir logs); (xx) vegetated biologs with coconut fiber + Sintemax; (xxi) vegetated Gabion (4m); (xxii) vegetated mattress Gabion (5m); (xiii) Sintemax and MacMat.

A seed cocktail was spread over all treatment parcels. It has shown to provide success (Coelho and de Brito Galvão, 1998; Coelho et al., 2001a; Coelho et al., 2001b). The seed cocktail included the species as follows: *Brachiaria humidicola, Pannisetum purpureum, Panicum maximum, Camipim, Mimosa sp., Cajanus* *cajan, Melia azedarach, Clitoria racemosa, Schinus mole, Enterolobium contorstisilquim*, and *Anadenanthara sp*.

Testings

Laboratorial and field testings and measurements included a wide range of geotechnical studies (Atterberg Limits, granulometry, density, *in situ* permeability Guelph, shear strength with soil and soil/roots soil survey), soil fertility, and laboratory turbidity measurements of water samples collected in front of each treatment, measurements of wind velocity, and wave height. These last three were done twice a month for three years.

Results/Discussion

The following findings are focused only on the Pier study area, which encompasses 11 treatment parcels, occupying an area of 2,700 m^2 and length of 212m.

Based on results from Atterberg Limits, soil granulometry, and in situ Guelph permeability testings, soils were classified as erosion prone (sandy-clayey silt, non plastic, with permeability in the range of 10^{-4} cm/s). Except for potassium values, which presented low values, all remaining soil macronutrients (P, Ca, Mg, Al, H+Al, organic matter) were in the normal range (Embrapa, 2011). The soil pH was 6.6, slightly acid. Soil erodibility measured according to Wishchmeir and Smith (1978) was about 0.41.

Figures 1 to 3 depict the implementation of the selected bioengineering treatments, and at after the vegetation growth.

Figure 1a. *Coconut Fiber Biologs Covered by RECP from Deflor, at Pier, in 2002*

Figure 1b. *Same Area with Consolidated Vegetation, at Pier, in 2007*

Figure 2a. *C350 from NAG/USA in 2002*

Figure 2b. *C350 from NAG/USA at Beginning of Consolidating the Vegetation*

Figure 3a. *Implementation of Gabion Mattress in 2002*

Figure 3b. *Gabion Mattress at Beginning of Vegetation Consolidation in 2004*

Data collected on wind velocity, turbidity and wave height did not seem to provide much information on sediment accumulation in front of each treatment. In this sense, a performance matrix was created to gather all field observations made throughout 3 years.

Table 1 presents the performance matrix in where each treatment was rated using the following criteria: streambank integrity against erosion; vegetative cover growth, costs, structural integrity, need for maintenance, aesthetics and landscape integration, and regrowth of native vegetation.

Table 1. *Performance Matrix of all Treatments Located on Pier Study Area (2700 m^2)*

Variable	**Weight**	**Value**									
Treatment		**P1**	**P2**	**P3**	**P4**	**P5**	**P6**	**P8**	**P9**	**P10**	**P11**
Erosive spots/ toe integrity on streambank	High – 0 Intermediate – 1 Low – 2 Inexistent – 3	0	1	3	2	3	3	2	2	2	2
Vegetative cover growth	Bare (<30%) – 0 Low vegetative cover (30 to ≤ 50%) – 1 Average vegetative cover (>50-≤ 70%) – 2 High vegetative cover (>70-100%)- 3	0	3	3	3	3	3	3	3	3	3
Cost of treatment (R$ /m^2 of margin to be treated)	Very High (> 300) – 0 High (150-300) – 1 Average (50- 150) – 2 Low (<50) – 3	2	3	2	1	0	0	2	2	2	1
Structural Integrity after 24 months	Serious damage (> 30% of the total) – 0 Average damages(10-30% of the total) – 1 Low level of damage (<10% of the total) – 2 No damage - 3	0	1	3	1	3	3	2	2	2	1
Need for maintenance	High (> de 5 times) – 0 Average (3 to 5 times) – 1 Low (1 – 2 times) – 2 No need – 3	0	1	2	3	3	3	0	0	1	0
Landscape Integration (aesthetics)	No integration with local landscape – 0 Integration with local landscape after 12 months - 1 Integration with local landscape after 6 months - 2 Integration since the startup -3	0	2	2	1	1	1	2	2	2	1

Regrowth of Native vegetation on top of the parcel	Absence of native flora – 0 Presence of 1-3 native species – 1 Presence of 3-5 species – 2 Presence of more than 5 native species – 3	1	1	2	3	3	3	1	1	1	0
	TOTAL	3	12	17	14	16	16	12	12	13	8

Legend: P1 – vegetated biologs (filled with straw) + Sintemax geotextile from Deflor Bioengineering/Brazil; P2 – rip-rap; P3- rip-rip + bag Gabion; P4- MacMat geotextile from Maccaferri/Brazil + bag Gabion; P5- rip-rap + Gabion mattress; P6 – Gabion mattress + MacMat geotextile from Maccaferri/Brasil; P7 – rip rap; P8- geotextil P550 from North American Green/USA; P9 - geotextil C350 from North American Green/USA.

According to Table 1, the treatments that performed the best were as follows: P3 followed by P5, P6, P4 and P10.

Although this table can give information on the overall performance of each treatment, it does say very little about sediment deposition in front of each parcel. Also, turbidity data varied so much that it became difficult to see any trend as function of wind velocity/direction, wave height, and specific treatment.

It was decided then to use differential bathymetry (final bathymetry – initial bathymetry) developed using in ArcGIS map algebra, to identify soil loss/accumulation in front of each treatment (Figure 4).

Figure 4. *The Differential Bathymetry Ploted Using ArcGIS*

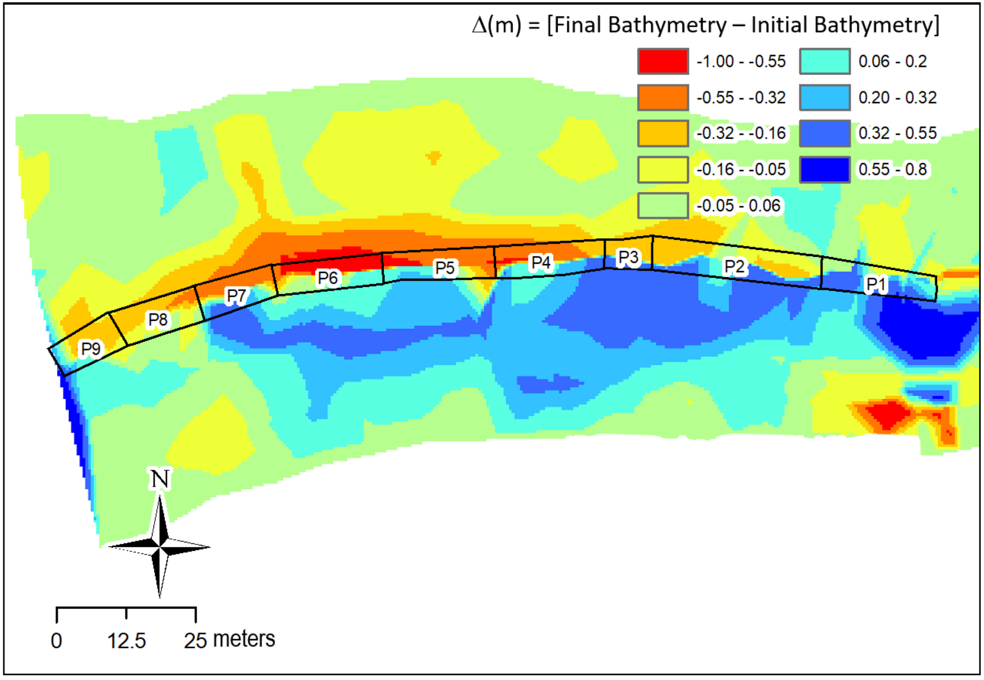

Figure 4 – Differential Bathymetry plotted using ArcGis, in where P1 – vegetated biologs (filled with straw) + Sintemax geotextile from Deflor Bioengineering/Brazil; P2 – rip-rap; P3- rip-rip + bag Gabion; P4- MacMat geotextile from Maccaferri/Brazil + bag Gabion; P5- rip-rap + Gabion mattress; P6 – Gabion mattress + MacMat geotextile from Maccaferri/Brasil; P7 – rip rap; P8- geotextil P550 from North American Green/USA; P9 - geotextil C350 from North American Green/USA.

According to this differential bathymetry the treatments with less soil deposition in front of them were as follows: P6, P8, P9, and P5. Table 2 shows the summary of the best treatment performance according to differential bathymetry and matrix of performance.

Table 2. *Comparison of Treatments Using Matrix Performance and Differential Bathymetry*

	Treatments
Performance Matrix	P3 followed by P5, P6, P4 and P10
Differential Bathymetry	P6, P8, P9, and P5

By superimposing these results, we can conclude that for the studied site conditions, treatements P6 and P5 performed the best – both are armored techniques (P6 -Gabion mattress associated with geotextile, and P5 – rip rap with Gabion mattress). In conclusion, it is important to have armored techniques associated with vegetation to control streambank erosion.

Conclusions

Results presented here for the study area, indicated that:

1. It was not possible to differentiate among the following types of bank erosion – aerial, fluvial, mass failure and cantilever failure, and how much each one contributed to the overall bank retreat process. However, from pictures, it was clear that a cantilever beam was formed, and the toe was totally eroded, before the slope came down in slip failure.
2. Soil fertility studies show that the studied soils have low fertility for K and that all other essential macro nutrients (P, Ca, Mg, Al, H+Al, organic matter) responsible for plant growth were in normal range. Soil pH was 6.6, slightly acid.
3. Atterbert Limits results show that the studied soils are non-plastic and the granulometric analysis classify the soil as sandy-clayey silt.
4. Guelph field permeability indicates that the studied soils have permeability around 10-^{4} cm/s and are erosion prone. Soil erodibility measured according to Wishchmeir and Smith (1978) was about 0.41 (average erodibility). Maximum values that soil erodibility can reach in RUSLE equation is 1.
5. Turbidity results could not be analyzed as absolute values, as they cannot distinguish between the turbidity generated by waves impact with the upstream turbidity.
6. Treatments P6 and P5 performed the best – both are armored techniques (P6 -Gabion mattress associated with geotextile, and P5 – rip rap with Gabion mattress), whereas vegetated biologs (independent of the filled materials used) and crib walls had the worst performance.

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