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Experimental investigation on the erosion of vegetated soils by flume tests

Gragnano C.G.,[1*] Domeneghetti A.,[2] Gottardi G.,[3] Guerrero M.,[4] and Toth E.[5]

[1]Research Fellow, Department of Civil, Chemical, Environmental and Material Engineering DICAM, University of Bologna, Viale del Risorgimento 2 – 40123 – Bologna, Italy; e-mail: carmine.gragnano2@unibo.it. Corresponding author.
[2]Senior Assistant Professor, Department of Civil, Chemical, Environmental and Material Engineering DICAM, University of Bologna, Viale del Risorgimento 2 – 40123 – Bologna, Italy; e-mail: alessio.domeneghetti@unibo.it
[3]Full Professor, Department of Civil, Chemical, Environmental and Material Engineering DICAM, University of Bologna, Viale del Risorgimento 2 – 40123 – Bologna, Italy; e-mail: guido.gottardi2@unibo.it
[4]Junior Assistant Professor, Department of Civil, Chemical, Environmental and Material Engineering DICAM, University of Bologna, Viale del Risorgimento 2 – 40123 – Bologna, Italy; e-mail: massimo.guerrero@unibo.it
[3]Associate Professor, Department of Civil, Chemical, Environmental and Material Engineering DICAM, University of Bologna, Viale del Risorgimento 2 – 40123 – Bologna, Italy; e-mail: elena.toth@unibo.it

ABSTRACT

The impact of planting deep-rooted vegetation on riverbank slopes is currently considered as a useful measure for reducing river flooding occurrence, mitigating the erosive action of water flow and increasing soil resistance, thus limiting the risk of local and shallow instability that may progressively lead to levees and river embankments collapse. An important insight into the effect of vegetation cover on soil erosion can derive from physically-based models and laboratory tests, where measurements of erosion and sediment transport rate are typically performed in experimental flumes, under controlled conditions (i.e. of flow velocity and depth). The main goal of this contribution is to discuss the performance of a testing procedure, purposely developed to simulate erosion on vegetated soils in a laboratory flume, investigating the performance of herbaceous deep rooting plants. Even in this preparatory phase, the designed method is shown to be useful in testing the effect of this nature-based solution. The work presents the execution of a series of experiments, the relevant observations and preliminary findings.

INTRODUCTION

River water stage and velocity fluctuations cause soil erosion in artificial and natural retaining water infrastructures. The cyclic nature of this kind of external action may produce important reductions in riverside slope stability, demanding for significant maintenance and frequent improvement strategies. In this situation, the presence of a vegetation cover may contribute to constrain the fluvial surface erosion by dissipating the stream power, which eventually produces shear stress on soil surface, as shown by previous experiences on the use of vegetation in naturalistic engineering (Pollen, 2007; Chirico et al., 2013; Zhu et al., 2018). Regarding stream flow to vegetation reciprocal influence, the produced resistance to flow was tested under controlled conditions in laboratory setups for long stalk plants, i.e. comparable to the water depth, and short grass (Järvelä, 2002; Ahmad et al., 2018). As a matter of fact, aiming to assess the performance of vegetation linings, such as turf enforcement mat, Pan et al. (2018) recently performed full scale experiments with large hydraulic flume and an extended ensemble of vegetation patches, while erodibility parameters were derived by McNichol et al. (2017) comparing site and laboratory experiences for root-permeated soils. Generally speaking, due to the complex experimental set-up and the significant number of variables involved, there is still a general need for defining and validating testing procedures and consistency of results, in order to fully understand the effectiveness of different vegetation covers to mitigate the superficial erosion. A set of laboratory experiments were so designed and implemented, in order to gain information on the modification of both hydraulic and erosive processes in a controlled environment. The experimental activities are developed on the soil collected from a real embankment of the river Panaro, a tributary of the Po river in Northern Italy, as part of the activities of the European Horizon2020 Project OPERANDUM: the project will include the implementation, on a reach of the riverbank in the downstream part of the river, of a vegetation cover with herbaceous deep-rooted plants, in order to mitigate the flooding risk. Such risk is principally related to soil erosion on the internal toe of riverbank and on outer slope, consequently to overtopping events, both possibly triggering local or global collapse mechanisms. In this contribution, the principal focus is on the design and preparation of the laboratory activities, with a preliminary discussion on the first experimental findings and observations recently gathered. The presented experimental approach encompasses both the investigation of vegetation resistance to flow, which determines the flood water level, and the erosion rate, that is paramount for the levee stability.

IDENTIFICATION OF TEST CONFIGURATIONS

The experimental activities are referred to the case of a real embankment of the river Panaro. The river Panaro is a tributary of the Po river and flows for its greatest part in the province of Modena (north Italy), with a basin covering a surface of 1775 km^2, 45% of which in mountain environment. The risk of flooding occurrence at the site scale is principally related to soil erosion on the internal toe of riverbank and on outer slope, consequently to overtopping events, both possibly triggering local or global collapse mechanisms. In order to get a better insight on the interactions of the flow field with the vegetation and on the triggering of soil erosion processes, a series of laboratory flume tests was performed in different soil surface conditions, i.e.:

0. Smooth, compacted and non-vegetated surface;
1. Soil vegetated with standard herbaceous plants adopted by the Interregional Agency of the Po River (AIPO) that manages and maintains the riverbank;
2. Soil vegetated with deep-rooted herbaceous plants, which are expected to provide an increase of erosivity resistance respect to standard vegetation.

Case 0 was mainly designed and performed as trial experiment, or β-test, with the main aim to gain confidence with the measuring system and to analyze the hydraulic and shear stress state conditions over the soil when there is no interference from the vegetation. Cases 1 and 2, on which the present contribution principally focuses on, have the two main objectives of i) understanding the impact of the presence of vegetation on the flow and ii) getting information on the erosivity resistance of each system of soil-vegetation under known hydraulic flow conditions.

PRELIMINARY CHARACTERIZATION OF THE RIVERBANK SOIL

Soil samples were collected from the riverbank where the vegetation cover will be successively tested in the real-world case study. Soil classification tests, like particle size distribution, Atterberg's limits, specific gravity, organic content and free calcium carbonate concentration were firstly executed on different samples taken at shallow depths (within 0.6 m depth from the river berm). The soil resulted a mixture of inorganic silt ($\approx$35 to 45%) and very fine sand ($\approx$30 to 35%) with clay ($\approx$20 to 36%), characterized by low plasticity, a $CaCO_3$ content of about 10%, an organic matter of $\approx$2% in weight and a specific gravity of 2.71. Main laboratory results are still presented in Figure 1. Unsaturated soil behavior was preliminary investigated trough the execution of evaporation tests, following the procedure suggested by Schelle et al. (2013) for extending the measuring range up to about 300 kPa of suction. The test was executed on an undisturbed soil sampled at 0.5 m depth from the berm and characterized by a void ratio of about 0.589, unit weight equal to 20.1 kN/m^3 and a gravimetric water content of 22.6% (measured subsequently to a high-water event occurred in May, 2019). The widely-adopted van Genuchten model (van Genuchten, 1980) was considered to fit the laboratory data, obtaining values of soil retention properties α and n respectively equal to 31.0 kPa and 1.183, while a value of 1.0E-08 m/sec was obtained for the saturated hydraulic conductivity.

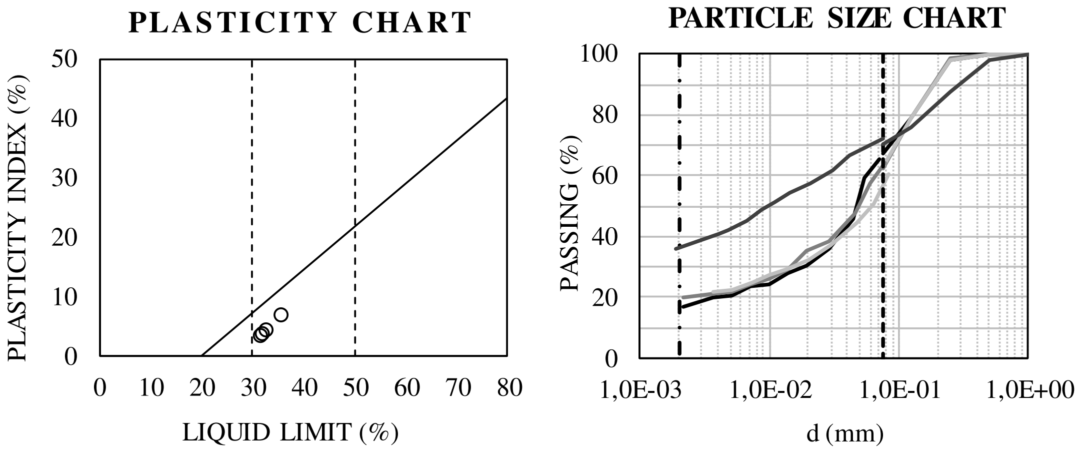

Figure 1. Casagrande plasticity chart (left) and particle size distribution curves (right) obtained from soil samples taken within 0.6 m depth from river berm.

PREPARATION OF LABORATORY SOIL SAMPLES

The volumes of the soil samples to be vegetated and then inserted in the flume were chosen to allow the growth of a relevant rooting system, keeping into account the characteristics of the flume channel. To this aim, metal caissons for soil storage and plant growing were specifically designed and then custom-made, as sketched in Figure 2. For each caisson, the base is 60x45 cm (L_1xL_2); the four sides are closed through 40 cm and 30 cm height metallic slabs on the L_1 (flow direction) and L_2 sides, respectively; thus, an open height of 10 cm was realized to allow sediment flux in the longitudinal direction, allowing for a maximum of 10 cm-deep soil erosion. The soil volume overall involved in each test was approximately equal to 0.324 m^3 with a potential eroded volume of about 0.081 m^3 for the three caissons. Another feature of the caissons is the open bottom drainage, obtained through a perforated metallic base. In the experimental setup and tests, three caissons are placed inside the flume channel (total length 1.8 m) and in contact each to the other along sides L_2, with first caissons having a horizontal plate to direct the water flux upon soil surface.

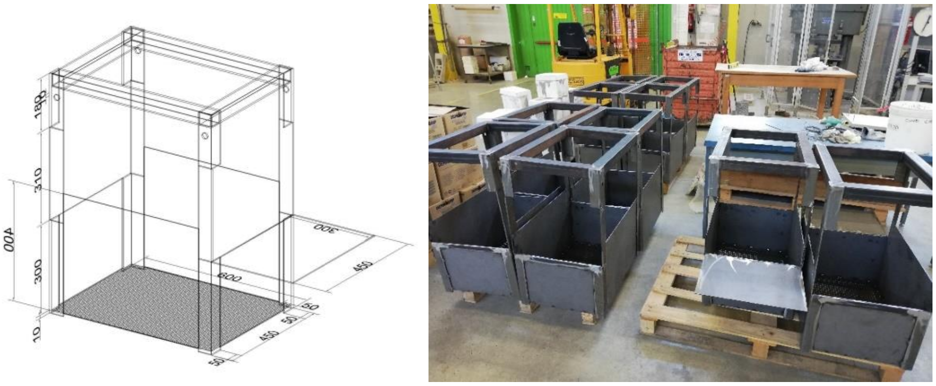

Figure 2. 3D sketch of the metallic caissons and picture of the finished elements.

A volume of about 1.5 m^3 of remoulded soil was then taken from from a reach of the riverbank close to the study section through a machine excavator. The soil used was first selected separating the silt-clay layers, representative for the berm units, from the gravel, rocks and organic (large roots and branches) parts, not representative at the laboratory scale. The natural water content of the whole amount of collected soil was found to be variable in the wide range of 6.5 to 40.2%, while the organic matter was found variable in the range 1.9 to 4.4%. A target value of water content approximately equal to about 25% was so considered, in order to be both suitably workable and representative of site conditions. Compaction of the soil in the metallic caissons was performed following a moist tamping compacting technique, aiming to place controlled quantities of soil weight up to prescribed height, until the caissons were filled. On average, for the caissons were obtained values of the unit weight equal to 18.9 kN/m^3, with a gravimetric water content of 25.6%, a saturation degree equal to 84% and a void ration of 0.636 at the end of the compaction. In a last stage of activity (August to beginning of September 2019) the soil surfaces were scratched for a few centimeters in order to plant two different types of seeds; in Case 1, appropriate amount of fertilizers was added for improving the plant growth, while this was not the case for Case 2, due to the fact that the seeds were provided already mixed with fertilizing substances. An amount of 75 g of seeds on the top surface (0.27 kg/m^2) were planted for Case 1, while a double quantity of the seeds and fertilizer mixture was planted for Case 2 (being equally balanced in terms of seeds and fertilizer tablets), following the suggestions of each provider. The last three caissons filled with not-vegetated soil

(Case 0) were prepared immediately before the test execution (November 2019) following the same specifications stated before. Following the seeding, a more diffused plant growth was observed in Case 1 respect to Case 2; this evidence persists for the whole duration of the experiment and is depicted in Figure 3, where plant growth in Cases 1 and 2 was compared one month from the seeding. At the time of experiments (i.e. around three months from the plants seeding), the vegetation of Case 1 was characterized by significant plants density on the soil surface, thus with limited exposure of nude soil to flow erosion and shallow roots; on the opposite, vegetation of Case 2 was characterized by limited density but higher rooted depths. Thus, Cases 1 and 2 depicted very different situations in terms of water-vegetation-soil interaction, as deep-rooted vegetation offered a limited hydraulic resistance to flow when compared to traditional grass, whatever the flume slope and corresponding discharge.

Figure 3. Plant growth 1 month from the seeding for Cases 1 (left) and 2 (right).

LABORATORY TESTING AND MONITORING SYSTEM

The experimental flume channel (Figure 4) has a rectangular section of 0.5 m x 0.7 m (width x height), it is 16 meters long and the side walls are made of glass, thus making visible the experiments. The two sets of tests were designed to be performed with a flume slope of about 0.3% and 8.5% respectively. The duration of the test was chosen in order to have a sufficient amount of time to allow the measurements for three different steps of steady-states with increasing discharge (15, 50 and 80 l/sec with a flume slope of 0.3%, 50, 80 and 100 l/sec with a flume slope of 8.5%), every one of which lasted for about 30 minutes, with the aim to cover a wide range of hydraulic resistance to flow (i.e. from few units to hundreds of Pascal). In case of higher bed slope each test included two runs of the different steady-states conditions, with 2 hours in between, which may represent a flood and dry conditions sequence, although no complete drying was achieved between the two runs.

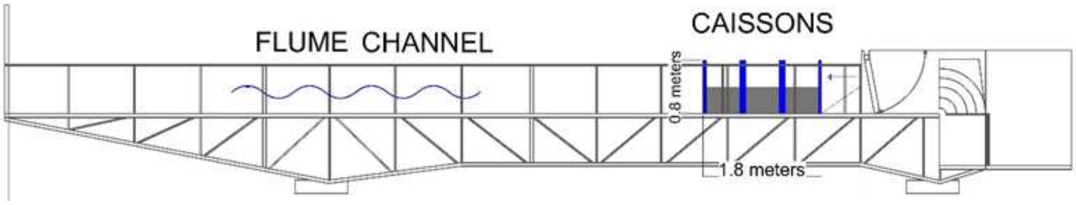

Figure 4. Sketch of the experimental setup in the flume channel.

Non-intrusive techniques such as ultrasonic and image acquisition methods were applied to evaluate the resistance to the flow and shear stress at bottom, at the same time not interfering with the simulated process. Ultrasound Velocity Profilers (UVP) were adopted to measure the water velocity profile in different sections of the channel, upstream and at the end of the caisson series. Specifically, four 1 MHz probes were placed upstream of the first caisson, thus providing information about the entry velocity pattern; three of these were installed with a 75° slope respect to the horizontal plane and placed perpendicularly to the mean flow direction with 0.125 m spacing; the fourth one was installed in vertical position and aligned with the flume axis at 3 cm distance from the others, overall enabling the two-dimensional profiling. Two additional UPVs were installed in the last caisson, placed at different vertical depths during the various experiments (depending on water depth), representing the outflow conditions. Other information on the flow velocity can be achieved from data gathered through the Particle Track Velocimetry (PTV), based on the analysis of series of pictures captured at high resolution and speed. The camera was placed above the middle caisson to monitor the experiments. During the hydraulic tests, spherical polystyrene floaters (2-cm diameter) were used for the seeding of water surface. These are made of expanded polystyrene having 0.025 g/cm^3 density. The volume and weight of such a spherical floater are equal to about 4 cm^3 and 0.1 g, respectively. The latter corresponds to a small water volume of 0.1 cm^3, meaning a small draught of the spherical floater into water giving rise to the thrust of Archimedes that balances its weight. In other words, the coupling between water surface and spherical balls is in the order of few millimeters. Thus, the tracers were mostly floating and their volume into water was very small. This limited the tracers' disturbance to streamflow. At the same time, the large portion of tracers emerging from water facilitated their detection in the images sequence, i.e., pixel intensity noise filtering and 2-cm diameter shape detection were applied to locate tracers at each image. This enabled the assessment of the surface water velocity field using PTV technique, tracking the movement of artificial seeding using a looking-down camera with acquisition up to 80 fps. The recording area was covered by a black cloth to avoid ambient light noise, and the light was instead controlled by two LED spotlights. Finally, the gaging and volumetric metering of eroded soil were performed. The eroded volume was quite limited and, due the particularly fine-grained texture of the material, it tended to be suspended in the water rather than transported as bed load sediment, thus resulting difficult to collect. An estimate of the bed-load was attempted through a trapping box (which weight is measured through load cells), placed just downstream of the last caisson, beyond a connection plate with a dissipation section aimed at directing the eroded material to the box (Figures 5, left, and 6). However, only little quantities of sediments could be collected in this box. In addition, the gaging and volumetric metering of eroded soil were performed by means of surveys of the changes in the soil surface levels, through both visual imaging and direct measures, i.e. measuring the distance from a horizontal reference at prescribed points over a grid (Figure 5, right).

OBSERVATIONS AND PRELIMINARY FINDINGS

Considering all testing conditions, the experiments were conducted under a water flux in the flume channel varying approximately from 15 l/sec (at the beginning of the tests) to 100 l/sec (at the final stage of the tests); the values of the Froude and Reynolds numbers varied from 0.3 to 2.3 and from 2.0E+04 to 15.6E+04, respectively, with a mean water velocity measured at few centimeters from the soil surface varying from 0.21 to 2.54 m/sec, thus in a wide range of hydraulic flow conditions.

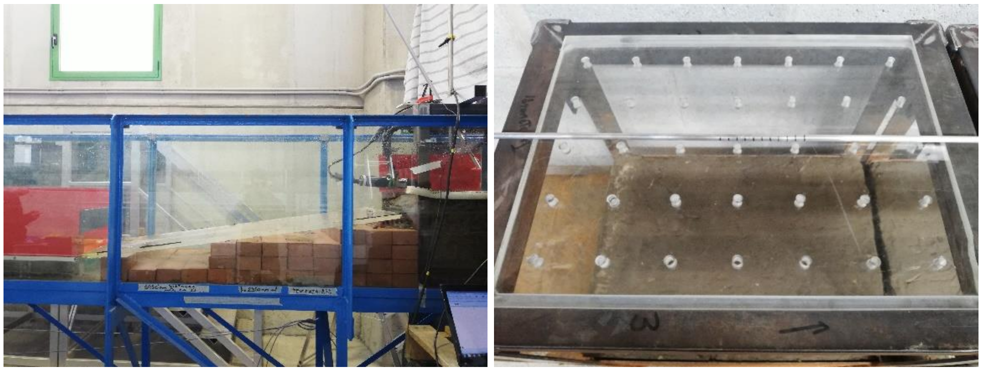

Figure 5. Details of the box for bed-load eroded soil collection, dissipation section (left) and datum for surface measurement (right).

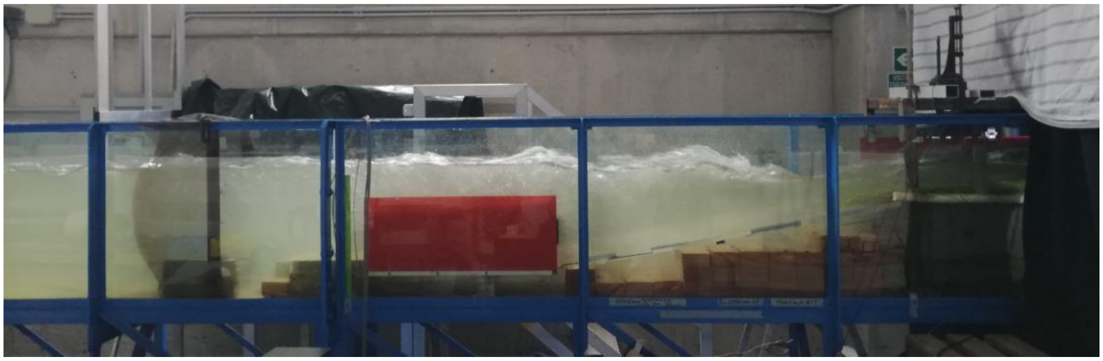

Figure 6. Ending section of the flume channel for Case 1 and 8.5% bed slope.

Comparing bare to vegetated soils, it was observed that the presence of vegetation produced both a reduction in the surface erosion rate and resistance increase: the more plants were diffused, the less was the erosion rate measured. Partial and local states of failure (measuring about 3-4 cm in scour) were obtained only during the erosion test at 8.5% bed slope for Case 2, with an eroded volume of about 0.008 m^3 considering the measures of the soil surface levels for the whole set of caissons. On the other hand, erosion processes were not clearly seen for Case 1, which seems to indicate that the resistance to erosion mainly depends on the plant density: the higher density of plants in Case 1 (with 40/dm^2 stalks prior the test) produced a much higher erosion resistance than in Case 2 (with 0.7/dm^2 stalks prior the test). Root depth seemed here to have a minor influence on the erosion rate; in this respect, herbaceous species in Case 2 evidenced root system up to 15 cm depth, while this depth was limited to few centimeters (less than 5) for plants in Case 1. The conditions of the two types of vegetation may be, however, very different on site, where the plants grow in a natural environment and for a longer period. It should be also considered that the regularity and compaction of the soil surface in the caissons were probably different from the actual conditions of the riverbanks. In fact, the site discharge peaks can last for days during high water events and frequent wetting-drying cycles might generate irregularities at the soil surface and, subsequently, weak areas, cracks and fissures. The dataset collected during the whole series of tests is still under investigation, while further research activities, including interpretation of the monitoring data and extensive soil-vegetation characterization, will be also carried out.

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