DESIGN OF FASCINES FOR RIVERBANK PROTECTION IN ALPINE RIVERS: INSIGHT FROM FLUME EXPERIMENTS

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Abstract

We present the results of flume experiments specifically designed to investigate the conditions required for successful bank protection using fascines, considered in the early and critical stage of their installation (no developed root system), in the alpine context. A total of 145 runs were performed with erodible banks, considering different combinations of protection design (no protection, rip-raps, twigs), bed mobility (with or without bedload), discharge (from low to exceptional floods), and bend curvature radius. None of the runs showed any direct fascine grabbing by the flow observed; all destruction was the consequence of bank scouring, erosion and collapse around the structure. In all cases, most destructive effects resulted from water recirculation inside the bank. Thus, we conclude that all measures aiming to reduce water circulations during the first stage of the fascine construction and development are recommended. This include large bend curvature radii (when possible), fining of the filling material, use of antiscouring twigs, optimisation of the programming of the works with consideration of the hydrology (shape of hydrographs) and regular survey of the structure. Our experiments show that anti-scouring twigs have a real protective effect by modifying the local hydraulics and promoting sediment deposition at the bank toe.

Keywords

River bioengineering; Bank protection; Fascine; Bedload

Highlights

- 145 flume runs were performed for studying the stability of fascines.
- In all cases main driver for dramatic collapse was water infiltration inside the bank.
- Water infiltration increases with the river bend curvature.
- Anti-scouring twigs can drastically reduce these effects by modifying the local hydraulics.

1 Introduction

Bank erosion is a natural process participating in river morphodynamics and related ecosystems. It is a geomorphic process that supplies sediments to the river system [*Klavon et al.*, 2017], promotes riparian vegetation succession [*Piegay et al.*, 2005] and creates dynamic habitats for aquatic and riparian plants and animals [*Florsheim et al.*, 2008]. In recognition of this important role, regulatory texts were adapted (e.g. European Union Water Framework Directive) and river managers now seek to preserve bank erosion within a defined erodible corridor as much as possible [*Piegay et al.*, 2005]. However, despite this evolution in restauration policy and practices, the protection of key assets still requires locally limiting bank erosion [*Peeters et al.*, 2018] and the use of soil bioengineering techniques appears to be an appropriate option. The objective of these techniques (fascines, brush mattresses, brush layers, wattles, cuttings and plantings, and seedlings [*Zeh*, 2007]) is to use the natural properties (resistance, resilience, stiffness) of living native species to mimic naturally stable banks consolidated by vegetation; the aim is to fulfil erosion control functions as well as to recover the riverbank's ecological functions [*Li and Eddleman*, 2002; *Cavaillé et al.*, 2018]. This paper presents the results of new experiments investigating resistance of one of the most commonly used of these techniques, fascines, to protect the bank toe, particularly in the alpine context. Live fascines for riverbank protection are long bundles of live woody vegetation buried at the bottom of the streambank in shallow trenches placed parallel to the flow of the stream (Figure 1). The plant bundles sprout and develop a root mass that will hold the soil in place and protect the streambank from erosion.

Figure 1: Fascines (a) in the field (courtesy of P. Belleudy) and (b) in the flume (example of full protection: fascine + riprap toe)

Many bank protection strategies have been developed by acting either directly on the bank to increase its stability or indirectly by deflecting the flow coming from upstream [*Henderson*, 1986]. Direct methods include hard (i.e. civil engineering) and soft methods (i.e. nature-based). Hard engineering methods such as riprap, stone masonry, sheet piling, concrete slabs or gabion (stone) baskets have been used for many decades. These methods are effective against erosion, but they have a very strong footprint on the river ecosystem given that they cover the bank for a very long time and prevent the development of plants and habitats [*Cavaillé et al.*, 2015]. This is particularly true in steep slopes of alpine rivers where application of standard methods can lead to substantial oversizing [*Recking and Pitlick*, 2013]. Bioengineering techniques take advantage of the natural properties of plants to stabilise the bank with the combined effects of roots and canopy cover [*Gyssels et al.*, 2005]. These actually very old techniques [*Evette et al.*, 2009; *Anstead et al.*, 2012] present many advantages: they are low-cost treatment [*Watson et al.*, 1997], they have a small carbon footprint compared to riprap [*Von Der Thannen et al.*, 2017], they support biodiversity and ecological functions in the riparian aquatic and terrestrial habitats created [*Anstead and Boar*, 2010; *Cavaillé et al.*, 2013; *Evette et al.*, 2013; *Cavaillé et al.*, 2018], they can increase the resilience of riverbanks against the effects of climate change [*Anstead et al.*, 2012; *Lavaine et al.*, 2015], and overall, they can resist very aggressive flow conditions: for instance, fascines were observed to resist shear stress up to 250 N/m² [*Lachat*, 1994; *Gerstgraser*, 2000]. These qualities make them an ideal candidate for the restoration of low-cost rivers in remote areas [*Tamrakar*, 2010; *Dhital et al.*, 2013; *Tamrakar et al.*, 2014; *Dhital and Tang*, 2015] or in highly urbanized areas where green solutions are welcome [*Ng et al.*, 2011; *Zhang and Chan*, 2012; *Zhu and Zhang*, 2015].

Despite the high level of interest, design criteria for soil bioengineering methods have long been lacking [*Shields et al.*, 1995]. There have been attempts to publish guidelines during the last few years [*Florineth*, 2007; *The City of Calgary*, 2012; *Evette et al.*, 2013; *Baird et al.*, 2015] based on feedback from field projects. Information consists essentially in observation of the structures' evolution a few years after their construction, considering the type of flow encountered and whether the structure remained intact or failed. Unfortunately, despite a growing effort to valorise post-project data [*Batier*, 2004; *Leblois et al.*, 2016; *Peeters et al.*, 2018], in the case of structure destruction we have almost no information on the mechanisms that resulted in the structure's failure, because we still crudely lack in-situ evaluation of project performance over time [*Buchanan et al.*, 2014; *Pinto et al.*, 2016].

The most questionable aspect of soil bioengineering techniques is probably not the capacity of plants to resist flow, given that specific experiments have demonstrated that vegetation resistance to grabbing was five to ten times higher than the strength exerted by flooding conditions [*Vollsinger et al.*, 2011]. When plants are grabbed from the bank, it is usually more the consequence of local bank scouring around the root system [*Evette et al.*, 2013]. Processes leading to bank erosion have been largely described in the literature [*Henderson*, 1986; *Papanicolaou et al.*, 2007; *Hassan and Pasche*, 2010] and basically comprise mass wasting (geotechnical instabilities), fluvial erosion, or a combination of the two. Fluvial erosion is a surface process consisting in grain detachment and entrainment by the shear stress exerted by the flow. Its intensity depends on the bed's cohesion and can be increased locally (scouring) by plant stem-induced turbulence. Geotechnical failures occur when gravitational forces acting on the bank material exceed the strength of the resisting forces, causing downward displacement of the soil mass. The process is amplified in case of undermining and toe erosion resulting from internal erosion (infiltration and entrainment of fine layers of erodible sediments), or local scouring when the downstream flow velocity is combined with helical velocities in river bends [*Hassan and Pasche*, 2010]. Excess pore water pressure in cohesive material is also an aggravating factor [*Julian and Torres*, 2006].

Ensuring the success of a bank protection with soil bioengineering techniques requires accounting for all these erosion processes. This is particularly true during the early stages of vegetation establishment, as water erosion rates decrease exponentially with increasing root mass [*Gyssels et al.*, 2005]: as long as the root system is under development (usually the first 2 years), the bank is highly vulnerable [*Henderson*, 1986; *Watson et al.*, 1997; *Anstead and Boar*, 2010] and it is recommended to assist the structure to resist erosion, for instance by solidifying the toe of the bank with protections allied with bank grading [*Thorne*, 1990; *Shields et al.*, 1995; *Peeters et al.*, 2018]. However, riverbank stabilisation structures are often designed to address only fluvial erosion, and feedback concerning internal processes (mass wasting) are still missing [*Florsheim et al.*, 2008]. There is a need today to investigate in greater detail how the dynamics of bank erosion is affected in presence of a soil bioengineering protection, and to better understand which design accelerates or moderates these types of erosion.

This paper presents the results of new flume experiments specifically designed to test the resistance of fascines, considering the standard design criteria, and also to test alternative and promising practices for toe protection.

1 Material and methods

1.1 Overview

The experiments were conducted in a 6-m-long, 1.25-m-wide tilting flume at Irstea Grenoble. The slope was set at 2% so that it was representative of energetic rivers (typical for alpine rivers), and also because using such a steep slope made it possible to accelerate the erosion processes and cover a large set of experiments, including experiments with bedload transport.

Because it was not possible to test all types of protection, we chose to focus on the most popular one: fascines for bank toe protection. In all experiments particular attention was paid to the degree of connectivity between the erodible bank and the flow (Figure 2). This connectivity was considered both by the degree of contact of the fascine bundle with the non-erodible bed and with the presence or absence of rip-rap protections.

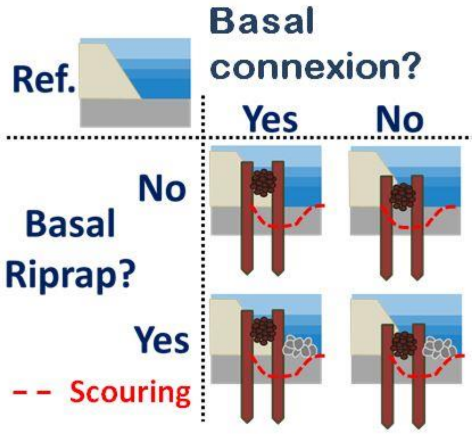

Figure 2: Tested configuration of different connection and protection scenarios between the erodible bed and the flow. Grey material represents the bed, a relatively coarse mixture, fixed (set 1) or mobile (set 2). The beige material behind the fascine represents highly erodible fine sand. The red dashed line represents scouring in the second set of experiments

1.2 Scaling

When scaling an experiment, the main objective is to match the dimensionless parameters prevailing in the field (see El Kadi Abderrezzak et al. [2013] for a full and comprehensive presentation of similarity laws in flume experiments). In practice, this is difficult or even impossible without distorting the model and the sediment density, and as a consequence, experiments are usually performed after relaxing some parameters. At least two scaling criteria, the Froude Fr and the Shields τ^* numbers, must be satisfied for the study of bank erosions [*Healey*, 1997]:

$$Fr = \frac{U}{\sqrt{gd}} \tag{1}$$

$$\tau^* = \frac{\tau}{g(\rho_s - \rho)D} \tag{2}$$

Where $\tau = \rho g H S$ is the bed shear stress, S is the slope, d is the section averaged water depth, U is the section average velocity, ρ_s is the sediment density, ρ is the water density, D is the grain diameter and g is the acceleration of gravity. It is usually considered that for a straight channel $\tau_{bank} \approx K\tau$ with $K \approx 0.75$ (actually $0.5<K<1$ depends on the channel geometry [*Julian and Torres*, 2006; *Muhammad et al.*, 2016; *Klavon et al.*, 2017]). The hydraulics is also satisfied through the relative depth d/D. Other parameters such as the Reynolds number Re or the particular Reynolds numbers Re* can be relaxed without any consequence on the scaling assuming the flow is fully turbulent and rough (which is always the case on steep slopes).

In this study we considered a "*generic Froude-scale model*", which means that we did not try to reproduce a particular river but rather to be representative of a general case. In order to match typical mountain streams, the bed sinuosity was designed with respect to a realistic width (W) to bend curvature radii (R_c) ratio of approximately $W/R_c = 5$ deduced from aerial observation of 9 rivers reach having a similar slope (Arve, Guiers, Vif, Isère, Néphaz, Ainan, Le Gelon, Adour, Ardèche, Adour). In combination with the flume dimensions (width 1.25m), this bend curvature ratio imposed us a scale ratio λ of approximately 1/10-1/20. Because we built an undistorted model, this ratio must be satisfied for all geometric quantities between reality and the model. The resulting mains characteristics for the flow and sediments are recalled in the following table; they will be discussed in the next parts.

Table 1: Correspondence between the generic model and typical field case according to the geometric length scale λ

Parameter	Flume	Field (λ=1/10)	Field (λ=1/15)	Field (λ=1/20)
Slope	2%	2%	2%	2%
Bank height	0.07 m	0.7 m	1.05 m	1.4 m
Width	0.25 – 0.4 m	2.5 – 4 m	4 – 6 m	5 – 8 m
Curvature radii *Rc*	1.5 m	15 m	22.5 m	30 m
W/R_c	4-6	4-6	4-6	4-6
Fascines height	~ 4 cm	~ 40 cm	~ 60 cm	~ _80 cm
Fascines length	~ 20 cm	~ 2 m	~ 3 m	~ 4 m
Bed D_{50} / D_{84} / D_{95}	0. 3 / 0.8 / 2 cm	3 / 8 / 20 cm	4.5 / 12 / 30 cm	6 / 16 / 40 cm
Erodible bank	0.01-1 mm	0.1 – 10 mm	0.15 – 15 mm	0.2 – 20 mm
Bank full R/D_{84}	8.75	8.75	8.75	8.75
Froude Fr	0.85 – 1.4	0.85 -1.4	0.85 -1.4	0.85 -1.4
Shieds number τ^*	0.034 – 0.06	0.034 – 0.06	0.034 – 0.06	0.034 – 0.06

The bed grain size curve was built with respect to the shape of natural grain size curves using a model presented in Recking [2013]. The scaling problem is particularly inextricable for living materials, because we lack similarity laws for reducing in the flume the complex interactions between the plant roots and the soils, which depends on the species considered, its age, and the soil cohesion. This is why we chose to focus on the very crucial early stage of the bank protection evolution, which led us to design experiments reflecting the worst conditions: no root system in very erodible noncohesive materials. Indeed, soil bioengineering works are implemented during the dormant season and do not show any roots before the following spring, and their mechanical resistance increases over time [*Pinto et al.*, 2016].

In our experiments fascines were reproduced with real willow branches collected in the nearby Drac River. Whereas the geometry of the different elements constituting the fascines was correctly downscaled, we cannot guarantee that it was the case regarding the mechanical resistance of the branches of the fascine. This lack of mechanical similitude is assumed acceptable because according to our field observations, flows at prototype scale in this kind of rivers do not destroy fascine by mechanical breakage, but rather by local scouring around the structure.

The scaling of bank collapse in undistorted Froude model must satisfy a same angle of internal friction ϕ for the bank material between the field and the model [*El Kadi Abderrezzak et al.*, 2013]. Here it was the case as the erodible bank was built with noncohesive fine sands ($0.01<D<1$mm, with $D84=0.7$mm). Coarse gravels (2-3 cm), painted in blue in Figure 1, were also used to simulate riprap at the toe or at the upstream or downstream connections and anchoring of the fascine in the riverbank flume. To finish, surrogates are often used to simulate in a more or less realistic manner some of the components of the problem studied [*Maike et al.*, 2016]. Here we used nylon threads to simulate the use of anti-scouring twigs (*Figure 3*), a promising and soft solution sometimes encountered in the field [*Peeters et al.*, 2018]. The difficulty of course is to ensure a realistic stiffness of the surrogate. This is why we used several thickness (0.4–1.4 mm in diameter) allowing a different posture in the flow (from rigid to very flexible).

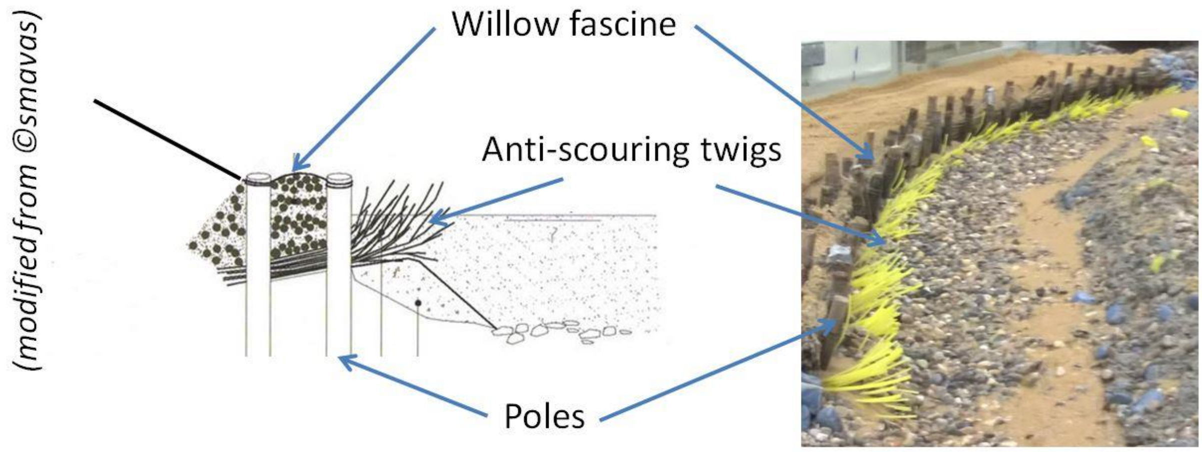

Figure 3: Toe protection with twigs: profile sketch for construction and small-scale model

1.3 Measurement techniques

The water was recirculated directly from the pump and the water discharge was remotely controlled by a computer through a pump speed controller. The bed topography was measured by photogrammetry. High-quality pictures of the flume (~30 images) were taken before and after each run from above to be later used in photogrammetry software (Agisfost Photoscan). The overlap of the images was quite high, since most points of the flume were covered by at least nine pictures taken from different positions (seven images minimum for all points). Control points were used to scale the images. Their X, Y, Z positions were measured with millimetre accuracy by a total station. The classical procedure to perform photogrammetry by Structure-from-Motion was applied [*Westoby et al.*, 2012], namely (i) ground control point localisation on images, (ii) back calculation of camera alignments and (iii) construction of a dense point cloud with millimetre accuracy. As a complement to this image survey, we also measured, manually and for each run, the flow depth (with a point gauge) and changes in channel width at several control sections (*Figure 4*).

Figure 4: Channel width and channel depth measurement (point gauge), ground control point targets can be seen on the right-hand side of the picture.

Large-Scale Particle Image Velocimetry (LSPIV) was used to compute surface velocity fields. The technique proved to be robust in highly varied contexts [*Fujita et al.*, 1998; *Nord et al.*, 2009]. The Fudaa LSPIV software was used (https://forge.irstea.fr/projects/fudaa-lspiv). This free software has shown satisfying performance in small-scale model measurements with low submersion and relatively steep slopes [*Nord et al.*, 2009]. The procedure used was the same as in [*Piton et al.*, 2018]: for each measurement we first dyed water with white TiO_2 powder, and then we seeded the flow with crushed charcoal powder, which created clear advection patterns easily captured by the cameras (Figure 5).

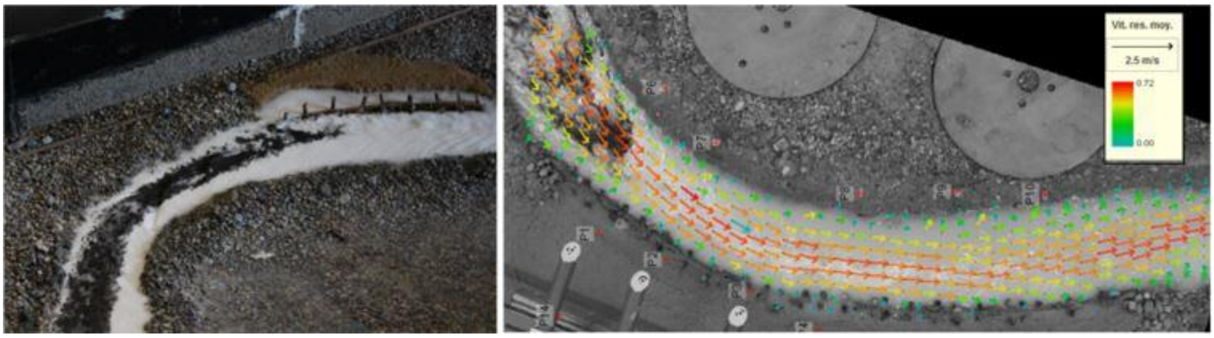

Figure 5: Example of flow seeding and velocity field measured with LSPIV (Large-Scale Particle Image Velocimetry)

1.4 Runs

Two sets of experiments were considered, for a total of 145 runs (+12 additional preliminary tests not presented here [Perez, 2016]). The first set of experiments (136 runs) explored a wide range of flow and design conditions in order to isolate the most sensitive design criteria. The objective was to repeat experiments as much as possible in order to describe the response of the bank-fascine system to changing flow conditions and construction details. This is why this first set of experiments was conducted without sediment transport and without bed general scouring; the channel bottom was partly fixed by powdering low concentrated cement at its surface to prevent large morphodynamic changes (clogged bed). This allowed us to focus only on the structure design and banks resistance to the changing flow condition. Among the criteria tested, we considered the bend curvature radius [Watson et al., 1997], the nature of the toe protection [Anstead and Boar, 2010], its quality (e.g., the connection between two subsequent bundles), or the applied shear stress [Evette et al., 2013]. We designed a trapezoidal channel (base = 15 cm, top = 25 cm, height = 7 cm) meandering with different curvature radii Rc decreasing from infinity (no curvature) to Rc=2 m, Rc=1.2 m and finally Rc=0.5 m (Figure 4). For this first set of experiments, we tested different discharges in order to gradually load the three main zones of a bank: the toe zone (from the bed to the middle of the fascines), the bank (from the middle to the top of the fascine) and overbank zones. These discharges correspond to low (Q=0.9 l/s), medium (Q=1.7 l/s), moderate (Q=2.5 l/s) floods, respectively. One additional discharge (Q=3.6 l/s) was used to simulate exceptional floods inundating the whole valley floor. The main hydraulic parameters are summarised in Table 2.

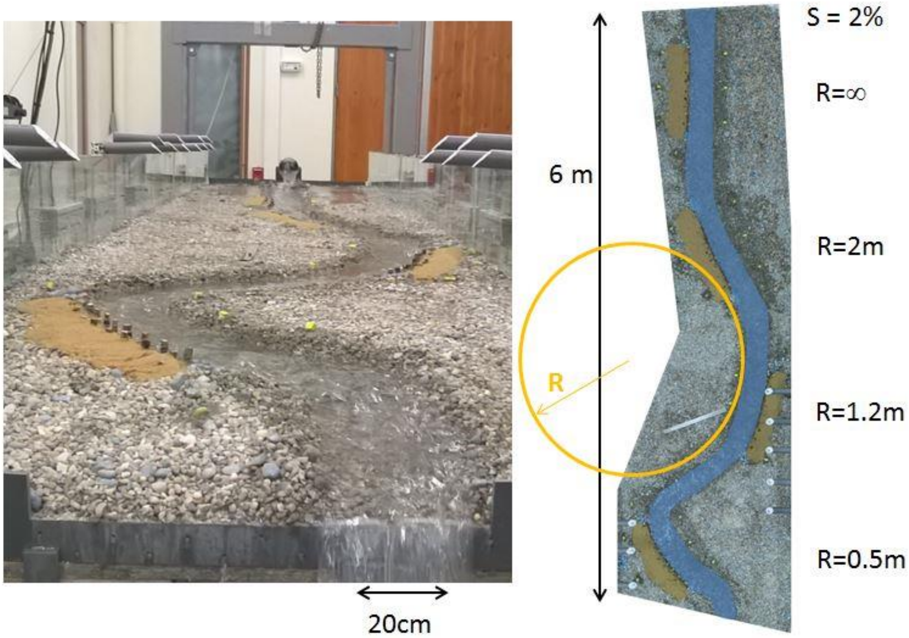

Figure 6: Set-up for the first set of experiments with a fixed flume bed and four curvature radii

Table 2: Main hydraulic parameters measured for the first set of experiments

Hydraulic conditions	Low	Med.	High	Excep.
Q - Discharge (l/s)	0.89	1.68	2.5	3.6
R - Hydraulic radius (mm)	17.6	21.9	22.8	26.0
V - Velocity (m/s) (R=∞, R=2)	0.56	0.76	0.84	0.71
V - Velocity (m/s) (R=1.2, R=0.5)	0.45	0.58	0.61	0.67
τ^* **- Shields par. (riprap D_{84}=10 mm)**	0.034	0.039	0.044	0.060
τ^* **- Shields par. (bank D_{84}=0.7mm)**	0.48	0.55	0.62	0.86
Fr = V/(gd)$^{0.5}$ - (R=∞, R=2)	1.12	1.38	1.41	1.01
Fr = V/(gd)$^{0.5}$ - (R=1.2, R=0.5)	0.86	0.97	0.91	0.96

The second set of experiments (9 runs) aimed to study in detail the destruction induced by compound bank and bed erosion processes. The same material mixture as in the first set was used, but the bed was not fixed, allowing local scouring, and sediment was fed at the flume entrance. The channel was larger but still trapezoidal (base width = 25 cm, bankful width =35–40 cm, height = 7 cm) and only one bend was considered with *Rc* = 1.5 m (Figure 7), allowing detailed measurements. For this second set of experiments one discharge of 2.8 l/s (medium flow) was used considering the results of the first set of experiments. The bed was fed with sediments at the flume entrance with a feeder composed of a hopper associated with a conveyor belt whose velocity allowed setting the solid discharge. Sediment was fed intermittently (at a rate of 35 g/s) in order to maintain the bed level, measured with a point gauge, in a quasi-constant value just upstream of the fascine. Namely, the objective was not to achieve a reach-scale alluvial equilibrium, which requires very long experiments, but to maintain stable boundary conditions for the flows in the vicinity of the structure and an efficient transfer downstream of the injected material (no deposition). The hydraulics parameters measured were U≈0.6 m/s, Fr≈0.7 and τ^*≈0.055 for the bed median diameter, i.e. the bed material was mobile. Nylon threads to simulate the use of anti-scouring twigs were only tested in the second set of experiments.

Figure 7: Set-up for the second set of experiments with a mobile flume bed and one curvature radius; the lateral bars attached to the walls support the targets used by photogrammetry

2 Results

2.1 Elementary failure modes

The first set of experiments (136 runs) allowed us to identify five main pathologies (Figure 8):

- Toe erosion leading to piping and local bank collapse (Figure 8a);
- Top surface erosion caused by overbank flow for the highest discharges (Figure 8b);
- Fascine by-pass due to absence or collapse of the upstream anchoring protection (Figure 8c);
- Fascine by-pass due to absence or collapse of the downstream anchoring protection (processes starting downstream are rapid because they lead to backward-propagating erosion, Figure 8d);
- Local erosion at fascine discontinuity (Figure 8e).

The flow conditions and bank protection structures promoting each of these pathologies are detailed in the next sections.

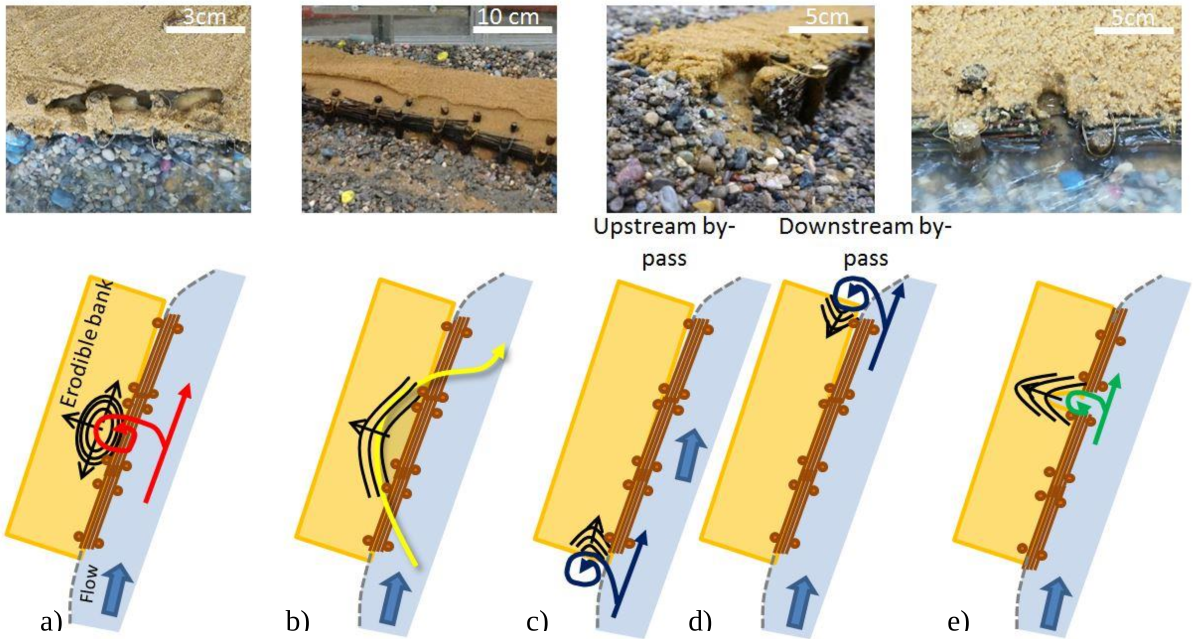

Figure 8: Five main failure modes observed during the first set of experiments: a) toe erosion, b) upper bank surface erosion, c) fascine upstream by-pass, d) fascine downstream by-pass and e) fascine bundle discontinuity

These failure modes started independently but could occur simultaneously in the same experiment, and the highest destruction rates were observed when "compound erosion" occurred, i.e. (upstream or downstream) by-pass erosion combined with local bank collapse caused by toe erosion.

2.2 Full failure by compound erosion

The different steps of compound erosion are synthesised in Figure 9: as long as the two failure modes were disconnected, the erosion kinetics was low. Once the by-pass erosion connected to the bank collapse, the flow coming from upstream could circulate behind the structure and exit at the next erosion point, loaded with bank material. The structure failure rate and bank erosion very rapidly increased during that stage. Finally, once the structure was totally by-passed, the kinetics was low again with progressive enlargement of the bank erosion and the structure could be considered as totally ruined.

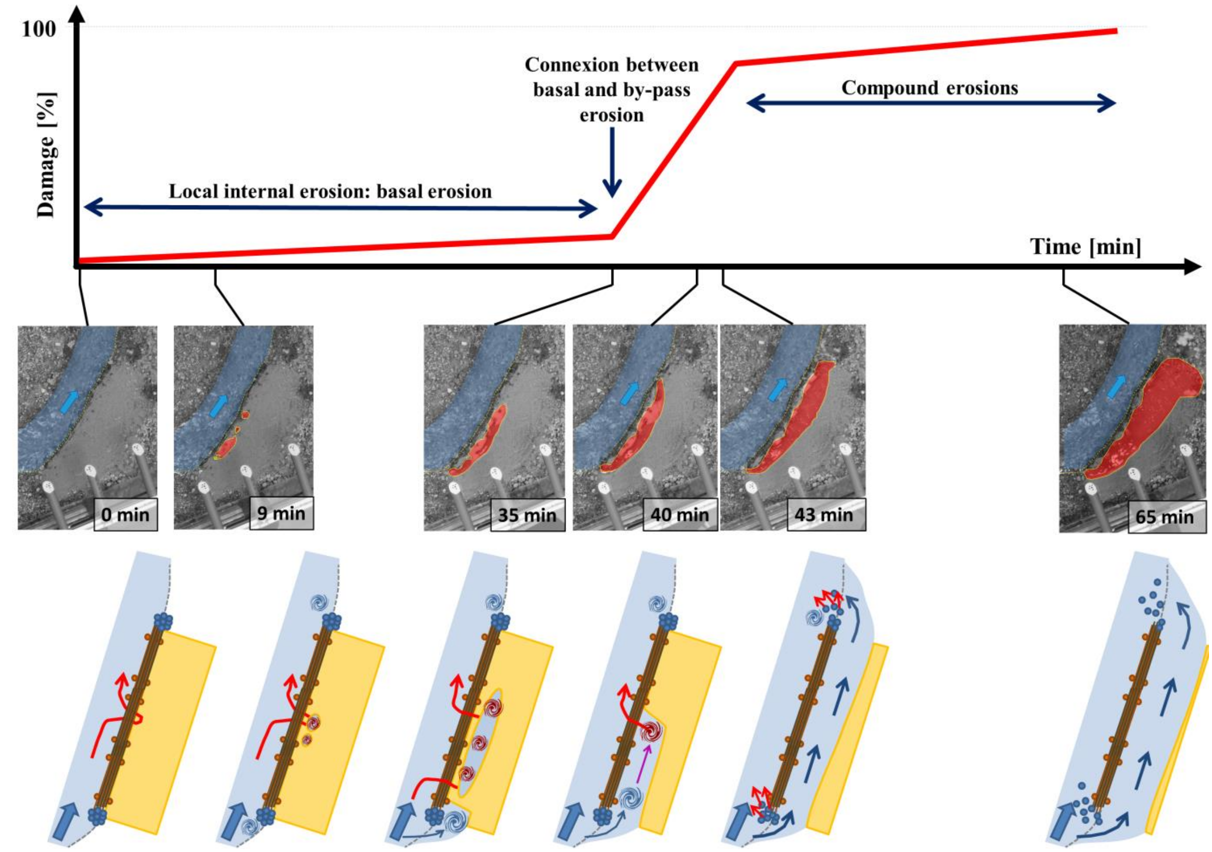

Figure 9: Main steps involved in full failure of the structure over time. Flume aerial pictures (in red: extent of bank erosion) and synthesis sketches. Local erosion creates weaker points and local damage. Damage rate sharply increases when by-pass erosion connects with existing points, enabling the flow to pass behind the protection, get loaded with bank material and extend further.

2.3 Efficacy of protection against failure modes

The degree of structure destruction, which matches the water path near or inside the bank, was summarised with a colour code in Table 3:

- Green indicates an absence of disorder (for the fascine structure and the bank);
- yellow indicates weak and local scouring, i.e. local fragility without flow behind the structure;
- orange means substantial scouring behind the erosion, allowing flow behind the structure;
- red means nearly total destruction, where the structure is still in place but useless because totally by-passed by the flow.

Visual inspection of Table 3 allows one to draw several conclusions:

- Fascines can be very efficient in protecting the bank when correctly designed (bundles correctly connected with no longitudinal discontinuity) and protected against scouring (see runs a and h);
- The erodibility of the basement of the structure is determinant for the general stability
- Setting a basal protection, with riprap protecting the erodible material below the fascine, strongly reinforces the structure's resistance (compare runs a versus e; h versus k);
- Sharp bends, i.e. low curvature radius, are more prone to scouring and structure damage: damage is minimum when the flow is parallel to the structure and maximum when the flow is frontal;

- All situations promoting flow circulation inside the bank aggravate internal erosion: this is the case when upstream ripraps are removed as well as when the flow is frontal to the structure, i.e. in sharp bends.

Table 3: Structure disorders (white: no test; green: no disorder; yellow: weak and local disorder; orange: well developed disorder (piping and local bank collapse); red: quasi-destruction) for different flow conditions: low flow (L), moderate flow (M), high flow (H), exceptional flow (E)

Run #	Riprap protections*			R=∞ (Rc/W=∞)				R=2 m (Rc/W=8)				R=1.2 m (Rc/W=4.8)				R=0.5 m (Rc/W=2)			
	Up.	Basal	Down.	L	M	H	E	L	M	H	E	L	M	H	E	L	M	H	E
Reference: no fascine																			
0																			
Basal connection (between fascine and fixed bed)																			
a	X	X	X																
b		X	X																
c	X	X																	
d		X																	
e	X		X																
f																			
g	X	X**	X																
Basal disconnection (presence of erodible material between fascine and fixed bed)																			
h	X	X	X																
i		X	X																
j	X	X																	
k	X		X																
l			X																
m	X																		

* Riprap protections were added upstream of the fascine (Up.), along its entire length at its base (basal) and downstream of the fascine (Down.).

** Test #g was performed with unconnected fascines showing an ill-constructed structure; see e.g., #Figure 8e

2.4 Scouring on mobile bed with sediment transport

The experiments with a mobile bed confirmed an acceleration of the toe erosion and fascine destruction compared to the first set of experiments. A movie given as supplementary material presents this scouring dynamics. Figure 10 presents the result of two repeated runs performed without rip-rap, but with the fascine bundles applied directly on the coarse (mobile) bed (similar to run #f, high flow, i.e. code “H” and R=1.2 in Table 3). The first observation is that the ruin of the structure is total after a 30-min experiment. This scour-deposition mapping, obtained by a diachronic analysis of DEMs measured before and after the run, indicates several centimeters of scouring below the fascine and large deposition of sand (coming from upstream and from the eroded bank) downstream of the bend. Fascine stability is highly vulnerable to toe erosion, suggesting that all surface protection without appropriate toe protection is useless in scouring-prone river bends and must be restricted to streams and brooks with marginal scouring activity.

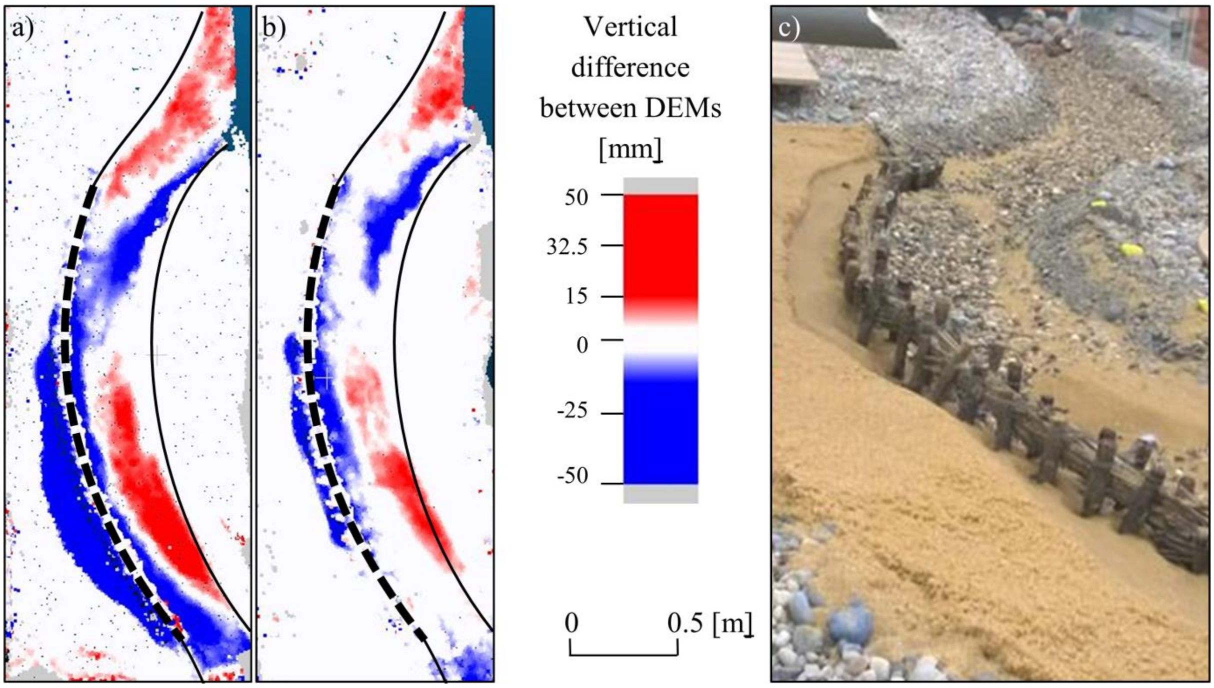

Figure 10: Diachronic analysis of bed topography evolution for two repeated runs with a mobile bed (a and b). Erosion (in blue) reached several centimetres below the fascine while deposition (in red) can be observed outside the bend as shown in (c), a photo of the final state of another run.

2.5 Riprap and anti-scouring twigs: two options for basal scouring protection

Riprap is sometimes used to protect bank toes under fascines [*Sotir and Fischenich*, 2001] as a “falling apron” [*Ciria/Cur/Cetmef*, 2007]. The first set of experiments demonstrated that they are effective in protecting toe and fascine heads (runs a and h in Table 3), obviously when supplied in a sufficient amount to rearrange and remain stable even when scouring is fully developed. Feedback from the field has proven that, when supplied in insufficient amounts, it is insufficient when the bed is highly mobile (an example in a braided morphology on the Buëch River is shown in Figure 11). However, river managers often prefer to use only bank soil bioengineering techniques that are more environmentally friendly and require lighter machinery and less expensive material: riprap typically costs 10–50 €/ton [*Ciria/Cur/Cetmef*, 2007], and several tons are required at the toe of each meter of fascine.

Figure 11: Fascine protected by one row of large riprap, destroyed on the Buëch River after a 10-year return period flood involving local scouring of about 1 m. (picture courtesy of G. Piton).

To seek another option than expensive riprap, anti-scouring twigs were tested in the flume in the mobile bed configuration. Anti-scouring twigs are willow branches, a few centimeters thick, which are anchored below the fascine inside the bank and protrude horizontally in the main flow over 1 m or more (Figure 3). In our experiments two-thirds of the twig lengths were anchored in the bank and one-third protruded in the flow. The erosion extension was measured with and without twigs over time. The results, plotted in Figure 12, clearly show a reduction of the scouring development below the fascines when twigs are present. We tested two kinds of twig called "twigs1" (mixture 0.7–1.4 mm) which was stiff and "twigs2" (0.4 mm), which was very flexible. Both twigs had a positive impact against scouring, but the thicker twigs were more efficient.

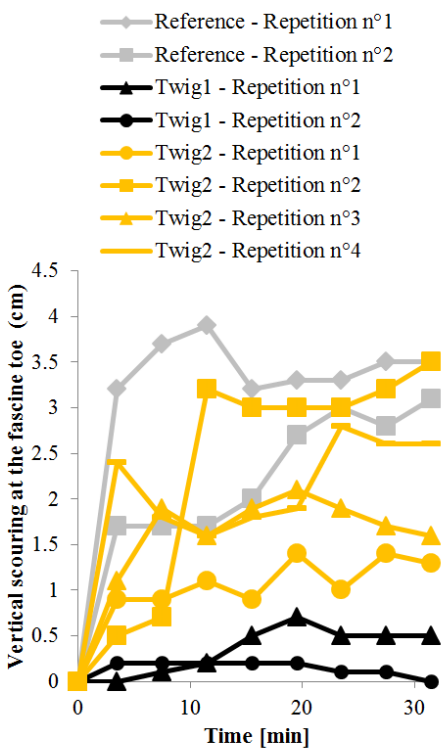

Figure 12: Scouring depth below the fascine with and without twigs (twigs 1 = 0.7–1.4 mm and twigs 2 = 0.4 mm).

An analysis of the final bed after the runs indicates that the presence of twigs generates accumulation of gravel against the fascines (Figure 13). These accumulations prevent toe erosion. Averaging the flow velocity measured by LSPIV, considering the flow immediately in contact with the fascine, explains this bed evolution in that the ratios between the velocities measured in presence of twigs and velocities in the referent experiment (no protection) clearly indicate a reduction of velocity in presence of twigs (Figure 14). This reduced velocity promotes gravel deposition.

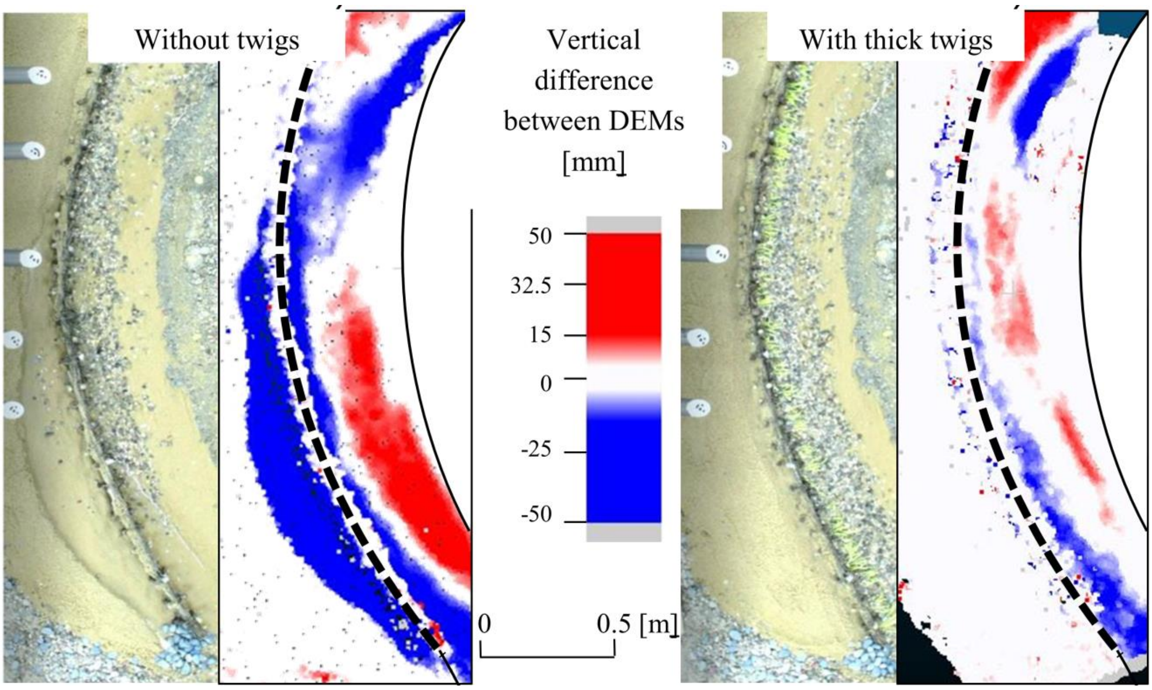

Figure 13: Diachronic analysis of bed topography changes for two runs with and without twigs. Erosion (in blue) is substantially reduced in presence of twigs.

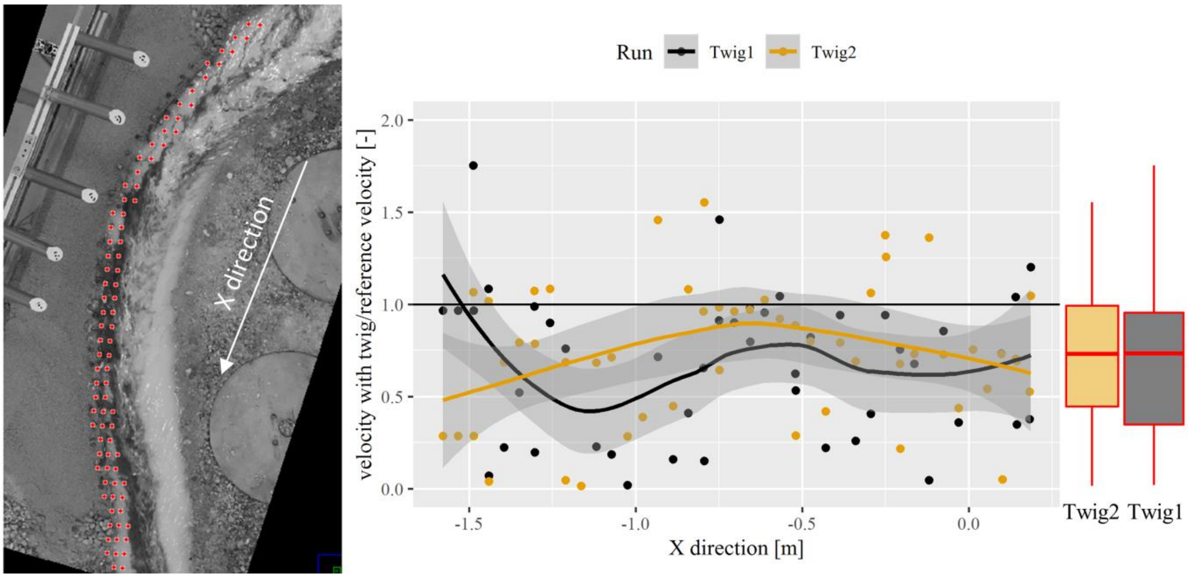

Figure 14: Velocity ratio between the twig experiments and the referent experiment with no protection. Thick stiff twigs (twig1) reduce velocity more than thin twigs (twig2)

3 Discussion

Our experiments have shown (Table 3) that fascine destruction increases when the bends are sharper, i.e. when the R_c/W ratio decreases from infinite (no destruction) to 2 (total collapse). This result is consistent with *Watson et al.* [1997], who found that a R_c/W value of 2 could be a lower limit for willow post soil bioengineering structures. Note that the bend curvature was also observed to be critical for other soil bioengineering structures such as combs [*Peeters et al.*, 2018], which suggests that the explanation driving this process should be sought elsewhere.

The R_c/W effect could reflect the intensity of internal bank flows. In our experiments the permeable flume bed exchanged water along the entire channel length, from upstream to downstream; however, this exchange was maximum in case of overbank flow, and also when the bend curvature was high. Indeed, flow exchanges depend on the pressure difference between the channel and the bank. When channel flows are parallel to the bank, this pressure difference is approximately the water level difference. When the flow is not parallel to the bank, a dynamic pressure is added, which is proportional to the square of the flow velocity component normal to this bank ($P \approx \rho ACU_n^2$ where A is the surface of exposure to the flow and C is a drag coefficient). In addition, for very curved bends (flow nearly perpendicular to the bank) we observed a head loss (i.e. energy dissipation) responsible for a local high water level reaching the top of the protection, directly feeding the permeable bank. These water inputs were very concentrated at the upstream part of the bank, percolated inside the bank, before being returned to the main channel downstream, entraining particles and progressively leading to piping and bank collapse.

This explanation by water recirculation is consistent with *Julian and Torres* [2006] who found that not only the maximum peak discharge, but also the variability of peak discharge (all discharge) explained bank erosion. This is not very surprising because water recession is faster in the channel than in the banks, which creates a positive pressure gradient from the bank to the channel. A fast flood (rapid hydrograph rising and recession) would create larger pressure gradients than long and slow floods, and a succession of floods cumulate these periods of high-pressure gradient (contrary to long and infrequent floods). As a consequence, the succession of discharges increases water circulation and particle entrainment from the bank to the channel. This discharge variability should be accounted for through seasonal consideration in a project definition.

This erosion process should logically be reduced when banks are clogged with fine materials. For instance *Peeters et al.* [2018] concluded in their study that the main cause of degradation was inappropriate back filling of structures with granular materials. This highlights the importance of the quality of the bank material [*Wallick et al.*, 2006] and local materials may sometimes be inappropriate, which would mean bringing materials from other sites. The natural concentration of flows with fine sediments should also be accounted for in a project: highly concentrated flows will infiltrate not only water in the bank, but also silt and clay particles [*Harvey et al.*, 2012].

Anti-scouring twigs seem to be a promising solution for reinforcing bank protection against erosion in soil bioengineering techniques. They have a direct surface protective action, like riprap, by covering the fascine toe as a protective carpet, when bent by the flow. Overall, however, they have indirect effects through modification of the local hydraulics, damping turbulence at the fascine toe and displacing scouring towards the centre of the channel, thus promoting gravel deposition against the fascine and bank toe. Used alone or in association with indirect protection (such as stream barbs) redirecting flow coming from upstream [*Jamieson et al.*, 2013], anti-scouring twigs offer promising perspectives against scouring even in erodible beds. New experiments are needed to optimise this technique and to determine up to which level of vertical scouring they remain an option and above which level of scouring threat, heavier options such as riprap remain necessary. First, our experiments suggest that anti-scouring twigs' efficiency is related to their rigidity. Whereas they must be flexible enough not to break during high flows, Figure 12 suggests that they must be rigid enough to increase flow resistance effectively. In future work, specific analysis accounting for the mechanistic properties of willows should help to optimise the sizing of anti-scouring twigs, with consideration of the river hydraulics and bed material. A second aspect which should be investigated is the anti-scouring twigs' efficacy under various bedload transport intensity conditions, as our experiments showed that the best protection was partly due to bedload deposition against the bank. Anti-scouring twigs generally disappear after a few years and their mechanical action is replaced by the development of the live fascine root system.

To finish, the conclusion drawn from these flume experiments still needs to be compared to direct field observations. Unfortunately, documented soil bioengineering structures (design, materials used, construction and eventually destruction dates, associated hydrology) are very scarce and field post-project surveys over long periods are clearly needed [*Buchanan et al.*, 2014].

4 Conclusion

This paper presents the results of a series of experiments aiming to provide a better understanding of the mechanisms leading to the failure of bank protection structures made with fascines, considered in the early stage of implementation (without any resprouting stems or root).

It was clearly shown that fascines can be very efficient for protecting a highly erodible banks and that the flow shear stress alone cannot explain fascine destruction. All destructions resulted from scouring of the erodible bank. Scours could remain a local phenomenon, but could also evolve very quickly to large bank collapse when several erosion locations connect and combine. This erosion process is considerably reduced when fascines are coupled with riprap (upstream, downstream, and toe protection).

The most relevant external factor contributing to this scouring effect is the possibility of the flow to penetrate and circulate inside the bank, behind the protection structure, a situation promoted when the bend curvature is sharp. As a consequence, we conclude that all measures to reduce the flow of water in the bank should be favored when designing a structure:

- the bend curvatures radii must be as large as possible; special attention must be paid when the curvature is strong.
- the hydrological regime must be accounted for when programming the construction as the structure must have enough time to consolidate (roots development, soil compaction, infiltration of fines) before the fascine experience successive hydrographs recessions.
- when local material are used for filling the fascine, it must be adequately compacted and one must ensure that they contain enough fine for reducing the water recirculation; one could expect that watershed naturally producing high concentration of fines should be prone to a rapid stabilisation of the structure.

- Anti-scouring twigs deviates the flows in the immediate vicinity of the bank, reinforcing protection against erosion. They are easy and low-cost solution which should systematically be implemented, at least during the early stage of the fascine development.
- monthly inspections are advisable during the first growing season [*Henderson*, 1986]

Of course, in addition of these recommendations, the design of fascines must overall respect the state-of-the-art technique. Many documents, tools and guidelines were proposed to assist practitioners in these different steps [*Gray and Sotir*, 1996; *Schiechtl and Stern*, 1996; *Evette et al.*, 2013; *Pinto et al.*, 2018] including sediment transport estimate (https://en.bedloadweb.com/), morphodynamics and stability of the reach [*Wohl et al.*, 2015] or rip-raps design ([*Ciria/Cur/Cetmef*, 2007], p. 1012).

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