Riverbank fascines mostly fail due to scouring: Consistent evidence from field and flume observations

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Received: 24 January 2024 | Revised: 12 July 2024 | Accepted: 15 July 2024

DOI: 10.1002/rra.4356

RESEARCH ARTICLE

WILEY

Riverbank fascines mostly fail due to scouring: Consistent evidence from field and flume observations

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Abstract

The willow fascine soil bioengineering technique is commonly used worldwide in river restoration projects to stabilize riverbanks, thanks to high theoretical shear stress resistance and adaptable configuration. Fascines are composed of bundles of living branches fixed between stakes. When positioned in meanders at bank toe, they are subjected to strong hydraulic constraints. Here, we present the field back-analysis of 470 willow fascines alongside experiments in a small-scale model (scale 1:25). We describe the dynamics of failure in various situations. The field analysis revealed that 78% of fascines present no signs of bank instability. No fascines were pulled out, and they rarely showed signs of destruction once vegetation had established. Flume experiments confirmed that the main mechanical process of failure is erosion at fascine toe and extremities (9% and 3% of occurrence in the field, respectively). The dynamics of failure occur through: (i) erosion at the fascine toe, removing materials under the bundle; (ii) bank sediments, sliding underneath the fascine; (iii) scouring, leaving stakes exposed to falling into the river. Based on these observations, the fascine toe should be protected sufficiently deeply against undermining to keep sediments in place while vegetation is established. Bank slopes should be reduced as far as possible to decrease scouring. Finally, the mean shear stress values used as reference when designing bioengineering techniques do not capture the local and continuous scouring processes leading to failure. Thus, bend curvature, degradation, grain sizes, and level of fascine implementation should be considered when adapting design.

KEYWORDS
erosion control, fascine, meanders, scouring, shear stress, small-scale modelling, soil and water bioengineering, SWBE

1 | INTRODUCTION

The mobility of rivers is necessary to maintain their good biogeomorphic functioning; consequently, soil and water bioengineering techniques (SWBE) should only be installed for bank stabilization purposes when the cause of the destabilization cannot be eliminated and the elements to be protected cannot be relocated (Bonin et al., 2013; Pinto et al., 2019).

TABLE 1 Shear stress levels resisted by fascines according to the structure's age, adapted from Leblois et al. (2016).

Time since completion	< 1 year	1–2 years	3–4 years	>9 year	No date
Fascine at bank toe	20[b]; 60[f]; 50[a]; 141[a]	50[b]; 60[b]; 116[a]; 172[a]; 240[c]	80[f]; >300[g]	98[a]	100–150[e]; 150–200[d]

Note: Values corresponding to structure failures are underlined. Letters in brackets link to the original references from which the values are derived.
[a]Leblois et al. (2016).
[b]Venti et al. (2003).
[c]Gerstgraser (2000).
[d]Gerstgraser (Gerstgraser, 1998a; Gerstgraser, 1998b).
[e]Florineth and Molon (2004).
[f]Schiechtl and Stern (1996).
[g]Lachat et al. (1994).

Riparian vegetation by structuring floodplains plays a key role in restored rivers (Andreoli et al., 2020). As a tool, willow fascines are prevalent in river restoration designs (Anstead & Boar, 2010). They are an ancient soil and water bioengineering technique (SWBE), which was already used by Roman and Chinese populations in the last century BC to limit riverbank erosion (Mai et al., 2022; Evette et al., 2009). Willow fascines are composed of one or more bundles of living branches, secured by wooden stakes (Lachat et al., 1994). These living structures are an effective method of stabilizing riverbanks; through anchorage, they provide protection as soon as they are installed. The technique is generally combined with another SWBE to stabilize the middle and top of the bank (Adam et al., 2008; Bonin et al., 2013; Peeters et al., 2020; Schiechtl & Stern, 1997). Fascines can also be used in the form of drains, in multiple layers or rows, to stabilize any type of slope (Didier et al., 2023a). They are relatively lost-cost, easy to implement, and are used all over the world, as attested by guidelines and field back-analysis available in many languages (Mai et al., 2022; Sangalli, 2019; Sotir & Fischenich, 2001; Yochum & Reynolds, 2020; Zeh, 2007). The willow fascine is the technique most frequently used to protect riverbank toes in France, accounting for 26% of 1233 SWBE inventoried (Jaymond et al., 2023). Because of this prevalence, the present study focuses on willow fascines implemented at the bank toe, for stabilization purposes.

According to the literature, fascines offer a high theoretical mechanical resistance (Table 1), close to that of riprap based on the shear stress that some structures have withstood: 140 N/m^2 at completion and 300 N/m^2 3 years after completion when the vegetation has grown. Theoretical SWBE resistance increases with vegetation growth and therefore with time (Pinto et al., 2016). In rivers, shear stress values are computed according to Equation (1) assuming a uniform flow.

$$\tau = \rho \cdot g \cdot R \cdot i, \tag{1}$$

with τ: fluid shear stress (N/m^2), ρ, water density = 1000 kg/m^3; g, acceleration of gravity = 9.81 m/s^2; R, hydraulic radius (m) = (cross-sectional area)/(wetted perimeter); and i, river slope. Shear stress is the pressure applied by the moving fluid to the bank and bed of the river, driving sediment transport (Shields, 1936). In guidelines, shear stress resistance values are presented as evidence of how well a SWBE stabilizes the bank, generally based on flood events that SWBE have resisted.

Bank erosion is a natural process occurring when driving forces are greater than resisting forces (Thorne, 1982). Erosion processes are classified as "terrestrial" or "fluvial" (Chassiot et al., 2020). Terrestrial processes are sometimes slow and require preparatory steps (freeze–thaw, desiccation, infiltration) but can also be rapid and result from breakup (landslide, rockfall, runoff). Non-protected banks of rivers flowing through alluvial deposits typically erode in a three-phase cycle initiated by fluvial erosion (Thorne & Tovey, 1981): (i) erosion of weakly cohesive materials at bank toe, eventually leading to undercutting; (ii) failure of the overlying cohesive materials; (iii) entrainment by the river of sediments that have fallen at bank toe. The relative importance of the preparatory terrestrial processes do not explicitly enter into this description of failure and were not evaluated for this study.

To date, only Recking et al. (2019) have used a small-scale model to analyze the processes that can affect the stability of fascines installed at bank toe. They described four processes that can lead to the loss of the fascine's stabilizing functionality, all of which involve erosion: (i) at the toe and under the fascine; (ii) of the bank above the fascine; (iii) at the upstream and downstream ends of the fascine; (iv) around a point of discontinuity in the fascine. Their results also highlight the dramatic acceleration of the erosive processes and consequent damage when several types of erosion are combined, allowing the river flow to circulate freely within and/or behind the structure. However, their exploratory study was performed on a narrow river channel with low banks and, due to the limited size of the flume, was unable to reproduce a rigorous similitude among channel width, grain size, water discharge, and fascines. The results obtained must be confirmed using a wider channel, allowing the system studied to be tested under more representative scaling with respect to comparable field sites.

The aim of the present study was to describe the succession of processes involved in the temporal dynamics of the failure of riverbanks implemented with fascines, especially prior to vegetation establishment when the fascine is at its weakest. We applied a dual approach: empirical with in situ observations, and experimental with a small-scale model. Field data were used both to design the small-scale model with consistent and representative geometry and flow conditions, and to cross-check the consistency of the flume results thanks to field back-analysis of actual structures. Indeed, the field study

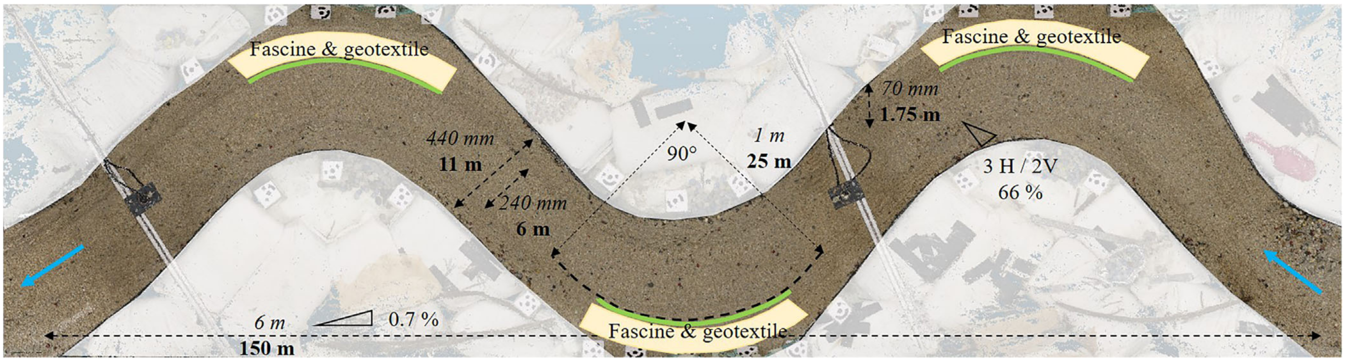

FIGURE 1 Top view of the 1:25 scale model, showing the outer banks of the three meanders implemented with fascines and geotextile and the main geometric characteristics. Values in italics are at model (1:25) scale, and values in bold are the corresponding values at field (1:1) scale. Unformatted values are similar at both scales. 3H/2V defines the bank slope and is the width over height ratio of a slope seen in a vertical section; H stands for horizontal and V for vertical. [Color figure can be viewed at wileyonlinelibrary.com]

provided a real, but time-limited insight into the condition of the fascines at the time of the inspection. As field observations are generally not possible during floods due to turbidity and for safety reasons, the small-scale model is a good complement. It provided the opportunity to observe the dynamics of failure and to test two configurations (with and without geotextile) and study differences in responses faced with similar flood events. Based on our understanding of the destabilization dynamics of riverbanks where fascines are installed, we discuss the significance of the use of shear stress values as the main criterion for SWBE design and the uncertainties hidden behind the values presented in the literature. We also provide guidance on additional check-points that would help ensure the success of fascines in riverbank stabilization.

2 | METHOD

2.1 | Field back-analysis

The fascines studied were extracted from the GeniVeg database (https://genibiodiv.inrae.fr/en/database-of-french-constructions/) (Jaymond et al., 2023). They are distributed throughout France. The study encompassed a total of 470 bank toe fascines, with data acquired either from reports, single field visits, or exchanges with river managers. Sites are not monitored over time. Among the environmental and morphological data acquired for the GeniVeg database (Jaymond et al., 2023), the following information was collected where possible: condition of the structure and pictures, slope of the riverbed, slope of the bank, orientation, and shading. This present study, describing the destabilization processes affecting banks implemented with fascines relies on field observations, pictures analysis, and other descriptions of the condition of the fascines.

Observations of failures were analyzed and classified between various processes contributing to the destabilization of banks fitted with fascines (Leblois et al., 2022): poor vegetation recovery, erosion of various types, and structural failures.

2.2 | Small-scale model

The second part of the study was based on a 1:25 scale model (Figure 1). Small-scale modelling makes it possible to repeat selected hydraulic events on two fascine configurations and to continuously observe the dynamics of degradation of these structures. The 1:25 scale is the largest compatible with the capacity of the laboratory pumps and the size of the channel while limiting scale effects (Heller, 2011). As it is impossible to control the scaling of soil cohesion, no clay was included in the sediment and no vegetation was grown in the small-scale model. The modelled fascine was reinforced with a three-dimensional mat placed on the bank and filled with soil to limit surface erosion. This structure reproduced a fascine topped with a coir mat recently implemented in the field. The fascine is most fragile just after installation, when willow roots and aerial vegetation systems have not yet developed to anchor and protect the soil. If the fascine does not show signs of destabilization at this stage, we can assume that it will also withstand conditions later as its strength increases.

In the small-scale model, the river meanders studied were derived from 25 sites across France (Table 2), where SWBE are positioned in the outer bank of meanders and show signs of bank destabilization. Thus, the model was intended to be representative of the geomorphological and hydrological processes at play in gravel-bed rivers present in plains and foothills.

The width of the river (W), the sediment sizes D50 and D84 (sediment sizes for which 50% and 84% of the sediments are smaller, respectively), and the two-year return flood peak flow (Q2) were directly scaled by geometric and Froude similitudes based on the median values for the 25 reference sites. To have enough space in the channel to create relatively closed meanders with an arc angle of at least 90° (Williams, 1986), and to ensure scour processes, the radius of curvature to width ratio (R/W) was set at 4. These rather sharp bends correspond to the 25% quantile of the reference sites, where scouring is expected. If R/W = 4, from the scaled W, R = 1 m on the small-scale model. The experimental setup, presented in

TABLE 2 Hydromorphological characteristics of the 25 reference field sites and the small-scale model: River width at mean flow (W), radius of curvature (R), radius of curvature to width ratio (R/W), riverbed slope (i), sediment sizes for which 50 and 84% of the sediments are smaller (D50 and D84, respectively), and two-year return flood peak flow (Q2).

Parameter (units)	W (m)	R (m)	R/W (–)	*i* (%)	D50 (mm)	D84 (mm)	Q2 (m^3/s)	*d* (m)	*v* (m/s)	τ (N/m^2)
25 Reference sites: 25%–75% quantiles	5–10	21–63	4–10	0.5–1.1	22–45	49–80	9–55	0.8–1.5	2.5–3.2	53–98
25 Reference sites: median	6.5	37	7	0.7	31	61	25	1.2	2.9	74
Small-scale model (1:25 scale)	0.26	1	4	0.7	1.2	2.4	0.008	0.05	0.6	1.8

Note: Water depth (d), flow velocity (v), and shear stress (τ) at Q2 computed using the friction law developed in Recking et al. (2016).

TABLE 3 Flow conditions at Q2 between the reference site (from the median values) and the small-scale model: Froude number (Fr), Reynolds number (Re), granular Reynold's number for D84 (Re^*_{84}), and transport stage ratio (τ^*/τ_{cr}^*).

Scale	Fr (–)	Re (–)	Re^*_{84} (–)	τ^*/τ_{cr}^* (–)
Reference site from medians	0.9	$3.4 \cdot 10^6$	$1.5 \cdot 10^4$	2.2
Small-scale model (1:25 scale)	0.9	$2.7 \cdot 10^4$	122	2.2

TABLE 4 Dimensions of the willow fascine at 1:1, field scale developed according to SWBE guidelines, and at 1:25 model scale based on geometric similitude.

Parameter (material)	Reference (m) (1:1 scale)	Small-scale model (mm) (1:25 scale)
Stake diameter (woody)	0.08–0.15	3–6
Stake length (woody)	2	80
Branch diameter (herbaceous)	20–60 (mm)	0.8–2.4
Branch length (herbaceous)	2–3	80–120
Bundle diameter	0.3–0.4	12–16
Bundle length	2–5	80–200
Longitudinal space between stakes	0.8–1	32–40
Steel wire diameter (iron)	2–3 (mm)	0.01
Geotextile hole size (cotton)	20–40 (mm)	1

Figure 1, includes three successive meanders with these characteristics, implemented with same bank layout.

Shear stress values of the 25 reference sites for a Q2 are in the lower range of values found in the literature for fascines implemented less than 2 years previously (Tables 1 and 2). The expected velocities in the small-scale model configuration are in the range of the scaled velocities of the 25 reference sites (Table 2).

The hydrograph applied to each test was similar, with a flood peak corresponding to a 2-year return periodic flood, often corresponding to bank-full conditions. Moreover, Q2 is a relatively common flooding pattern, which newly implemented fascines should be able to withstand. Peak flows for the 25 reference sites were taken from the Shyreg database (Arnaud et al., 2014). By Froude scaling, the flood in the channel lasted 2 h 32 min in steps of 0.0005 m^3/s. The rising time lasted 22 min 30 s, the flood peak 9 min 30 s, and the decreasing limb 2 h 00 min. At field scale, this would correspond to a flood lasting 12 h 30 min. This hydrograph duration was chosen as a trade-off between a realistic flood duration and a manageable experimental timeframe during which bank destabilization could occur.

The model was built applying the Froude similitude, with conservation of the transport stage ratio (Table 3). Like for the reference sites, the Froude number (Fr) in the flume at Q2 was close to the critical regime (Peakall et al., 1996) and remained sub-critical throughout all tests. Despite the scaling, the flow remained turbulent (Reynolds number Re » 1000). The granular Reynold's number for D84 (Re^*_{84}) remained above 70, guaranteeing a minimal effect of viscous forces during small-scale model experiments (Peakall et al., 1996). The transport stage ratio (τ^*/τ_{cr}^*) is greater than two ensuring efficient morphological adjustments. No sediments were continuously injected during runs. A two-meter-long straight channel at the upper part of the flume supplied sediment during the experiment. The small-scale model was rebuilt similarly before each test using a frame to level out the sediments.

Bank slope was set at 66% (the ratio of 3 horizontal distances to 2 vertical distances—3H/2V), which is the maximum slope recommended in SWBE guidelines (Bonin et al., 2013; Peeters et al., 2020). The bank height was 70 mm (Figure 1), corresponding to 1.75 m at scale, slightly higher than the estimated 50 mm water depth at flood peak (Table 3).

Fascines and geotextile, sized according to SWBE guidelines (Didier et al., 2023a; Lachat et al., 1994; Peeters et al., 2020), were geometrically scaled at 1:25 for the small-scale model (Table 4). To ensure that observations were robust and results reproducible, each run was performed with three identical fascines placed on the outer bank of the three meanders (Figure 1). The fascines were made of two rows of stakes with a prefabricated bundle placed between them and fixed in place with a thin steel wire (Figure 2). The middle of the fascine bundle was set at mean flow level (Schiechtl & Stern, 1997), 0.0005 m^3/s in the flume, corresponding to a depth of 5 mm above the riverbed. Tests were carried out with and without geotextile (see §III).

3 | RESULTS

3.1 | Field back-analysis of fascine failures

Field observations showed that of the 470 fascines studied, 103 (22%) presented signs of degradation or bank erosion. The

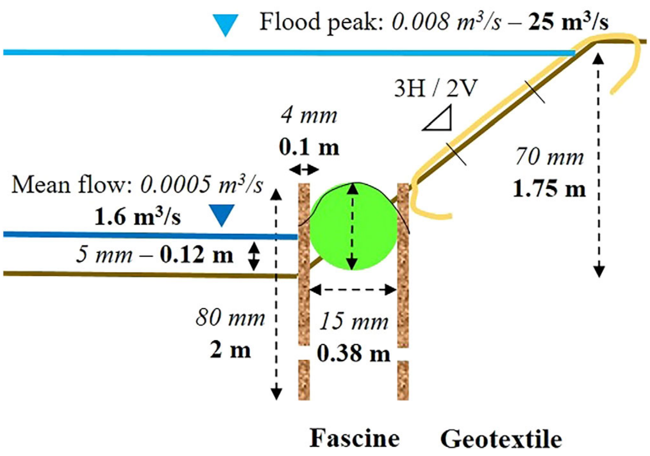

FIGURE 2 Transverse profile of the fascine with geotextile installed at bank toe on the outer bank of meanders of the 1:25 scale model. Values in italics are at 1:25 scale, and values in bold are the corresponding values at field scale (1:1). Unformatted values are similar at both scales. 3H/2V defines the bank slope and is the width over height ratio of a slope seen in vertical section; H stands for horizontal and V for vertical. [Color figure can be viewed at wileyonlinelibrary.com]

various types of fascine damage or bank destabilization with their percentage of occurrence are summarized in Figure 3. Note that a single fascine may be affected by several types of degradation.

The most serious fascine damage leading to possible bank failure was observed in cases of poor vegetation recovery; this was the case for 13% of all the fascines studied (Figure 3a). For another 9%, total destruction of the structure was observed; the details of the failure process are unclear (Figure 3b). However, no pulled out of willows or stakes were observed. Signs of structural destruction were observed mainly on fascines with a lack of vegetation growth. The most significant mechanical process leading to destabilization of riverbanks with fascines was erosion, representing 17% of cases (Figure 3c–f). Erosion at the fascine toe, sometimes leading to an overhanging bank was the most prevalent erosion process, affecting 9% of sites (Figure 3c).

A lack of data meant that no analysis of statistical significance was possible between the environmental and geomorphologic parameters collected and the success or failure of the fascines. Further data collection must be conducted to obtain convincing results. No data were available on past flood events and the corresponding conditions of the fascines. Therefore, no new shear stress values were computed for field sites.

3.2 | Fascine destabilization processes in the small-scale model

Unless specified, quantitative results are presented at 1:1 field scale.

The water depth measured on the outer bank of meanders at flood peak is equivalent to bank-full, 140% of the computed value from Table 2. The corresponding velocity is 2 m/s, and shear stress is 120 N/m^2, respectively, 0.4 m/s and 4.8 N/m^2 at 1:25 scale. Due to a higher than computationally expected water depth measured, the velocity and shear stress values are, respectively, lower and higher than their computed cognates.

Overviews and detailed views of the fascine, with and without geotextile, before and after a run are presented in Figures 4 and 5. Without the geotextile, the bank did not hold, the river flooded the top of the fascine. During the run, the bank was levelled to fascine elevation, and a maximum of 0.5 m of scour was observed at the fascine toe. With geotextile, the bank held better, but erosion was nevertheless observed at the extremities of fascines: -0.40 ± 0.22 m^3/m^2. Erosion also occurred in the center of the bank: -0.36 ± 0.04 m^3/m^2, as shown in Figure 5 by the staples protruding 10 mm (1:25 scale) above the geotextile. Before the run, staples were completely buried. The contribution of the erosion at fascine extremities is slightly higher in magnitude than that occurring below the geotextile at the bend apex. With geotextile cover, scouring at the fascine toe was deep (>1.25 m) and led to the removal of sediments from under the fascine, to the point where one stake fell into the river.

Thus, with a fascine at bank toe and without geotextile, bank erosion is of high magnitude: -1.02 ± 0.18 m^3/m^2, leading to a reduction in bank slope associated with shallow scour at the toe: -0.05 ± 0.03 m^3/m^2. With geotextile, overall bank erosion is of lower magnitude: -0.38 ± 0.11 m^3/m^2, bank slope remains stable but deeper scouring occurs at the toe: -0.16 ± 0.05 m^3/m^2 (Figures 4 and 5).

The dynamics leading to the failure of the banks with fascines and surface cover, as presented in Figures 4 and 5, involve three successive processes (Figure 6). (i) Erosion at fascine toe with removal of materials from under the bundle, creating a scour hole. (ii) As the bank material is no longer held by the toe of the bank, it slides under the fascine into the scour hole, from where it is transported by the river flow. If the volume eroded becomes significant, the riverbed migrates laterally, outflanking the fascine, which becomes isolated in the watercourse, as illustrated in Figure 3b. (iii) Finally, if the scour hole is deep enough, the stakes lose their anchorage and fall into the river.

4 | DISCUSSION

This article describes the dynamic erosion of riverbanks protected with toe fascine, presenting the parameters leading to fascine failure and deducing elements to improve fascine designs. Although lateral mobility is essential in river restoration, using fascines gives the opportunity to stabilize riverbanks and shape of restauration projects if assets or areas vulnerable to bank erosion remain in or nearby the restored reach. When implemented, such fascine must therefore be efficient.

Fascines are widely used SWBE as they offer high theoretical shear stress resistance and have various possible configurations (Didier et al., 2023b). However, in the field, fascines have been observed to fail to stabilize banks in 22% of situations. This percentage is higher than for other SWBE (Leblois et al., 2022), probably because of the larger range of application of fascines, and their

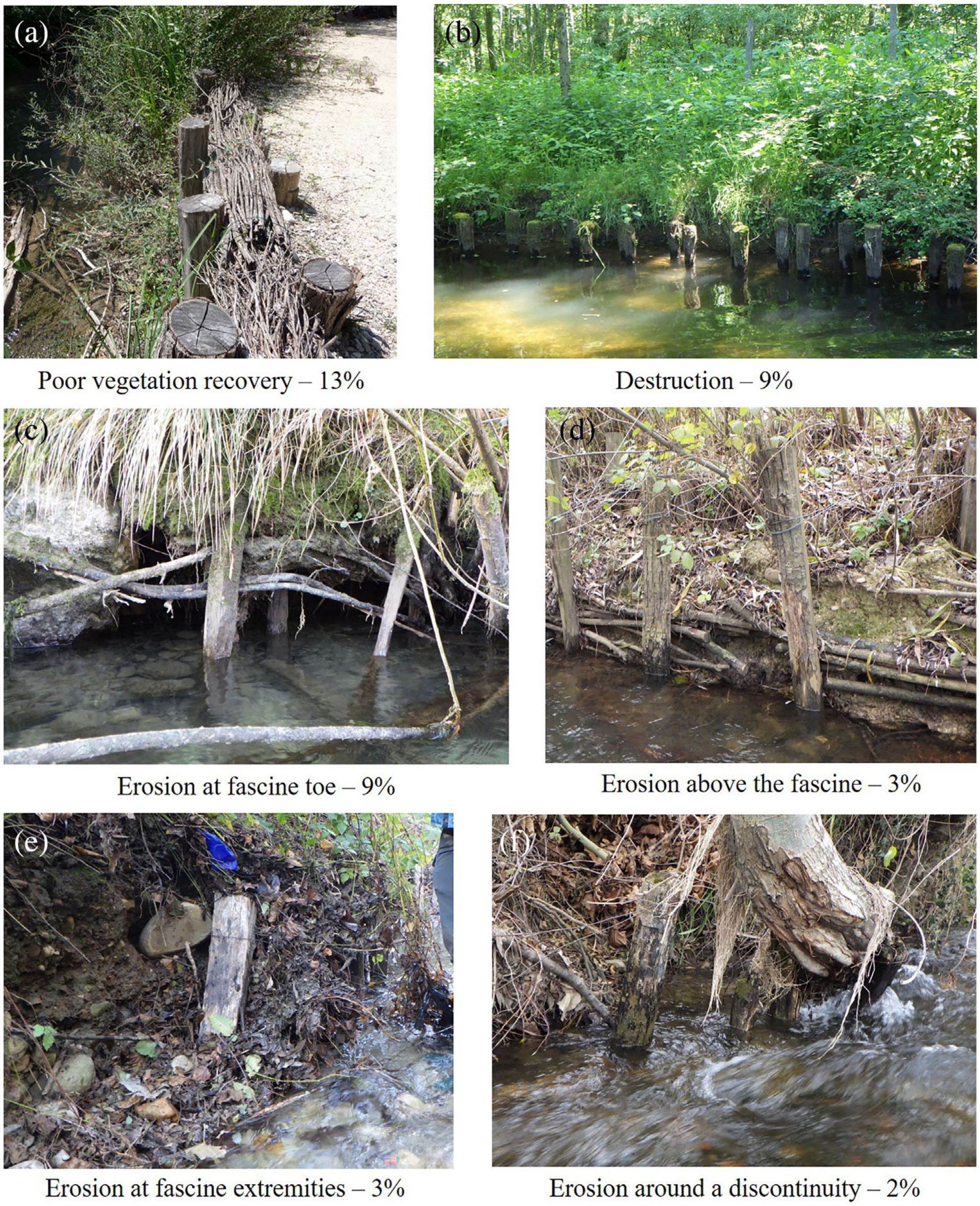

FIGURE 3 Photographic report and percentage of occurrence of each type of process leading to destabilization encountered in the field. The percentage of failure was calculated for a total of 470 fascines, among which 103 were degraded or presented signs of bank destabilization. A single fascine can be subject to multiple processes. [Color figure can be viewed at wileyonlinelibrary.com]

theoretical high resistance to shear stress compared with other techniques (Evette et al., 2018; Leblois et al., 2016; Peeters et al., 2018). In comparison, willow spiling, tree revetment, and brush layers present respective failure frequencies of 18%, 10%, and 8%. A better understanding of the dynamics of destabilization should help increase the confidence in such techniques and reduce failure frequency. The main outcomes are summarized in Figure 7.

The four erosion processes observed around fascines in the field (Figure 3c–f)—(i) at fascine toe; (ii) above the fascine; (iii) at fascine extremities; and (iv) around discontinuities—are almost the same as those observed by Recking et al. (2019) and in the small-scale model used here. Only the erosion around discontinuities was not observed in the flume because the fascines consisted of a single tied bundle of small intertwining branches, that is, with no discontinuities. In Recking et al. (2019), erosion processes were highlighted by performing multiple tests in a model with very short fascines installed on banks composed of fine sand, which is highly erodible in the hydraulic conditions applied. The small-scale model used here implemented a poorly-sorted granulometry with a fascine covering the entire meander.

Recking et al. (2019) observed a dramatic acceleration in damage once the water could circulate from one erosion to another. This effect was probably enhanced by the fine grain size of the sand used to build their bank as no such effect was observed here (in the model or in the field). Similar field features, that is, relatively fine, non-cohesive bank material contrasting with the channel bed material, would probably be more prone to similar dramatic and rapid failure of outflanked fascines.

The effect of surface erosion of the bank above the fascine would be reduced in the presence of vegetation. The problem of the temporary absence of vegetation just after installation can be tackled by

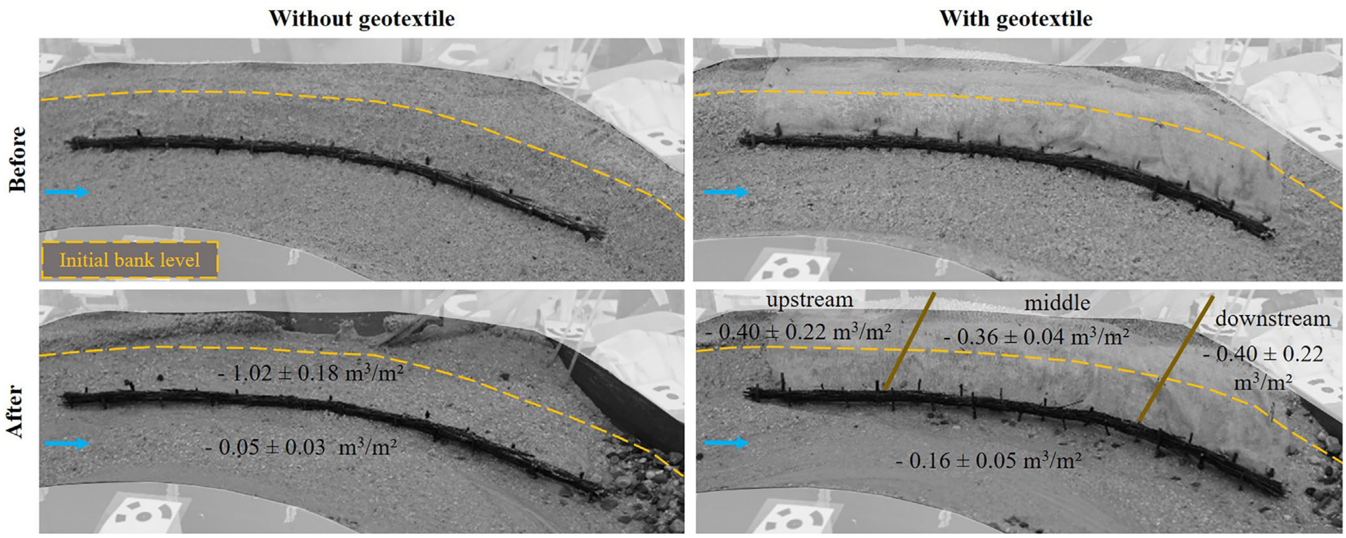

FIGURE 4 Overview of the stabilized riverbanks from pictures taken before and after passage of a Q2 flood on the 1:25 scale model. The outer bank of meanders was implemented with fascines at bank toe and with or without geotextile. The values shown represent the amount of sediments eroded during the flood from the bank and from the bed transposed at 1:1 (field) scale. [Color figure can be viewed at wileyonlinelibrary.com]

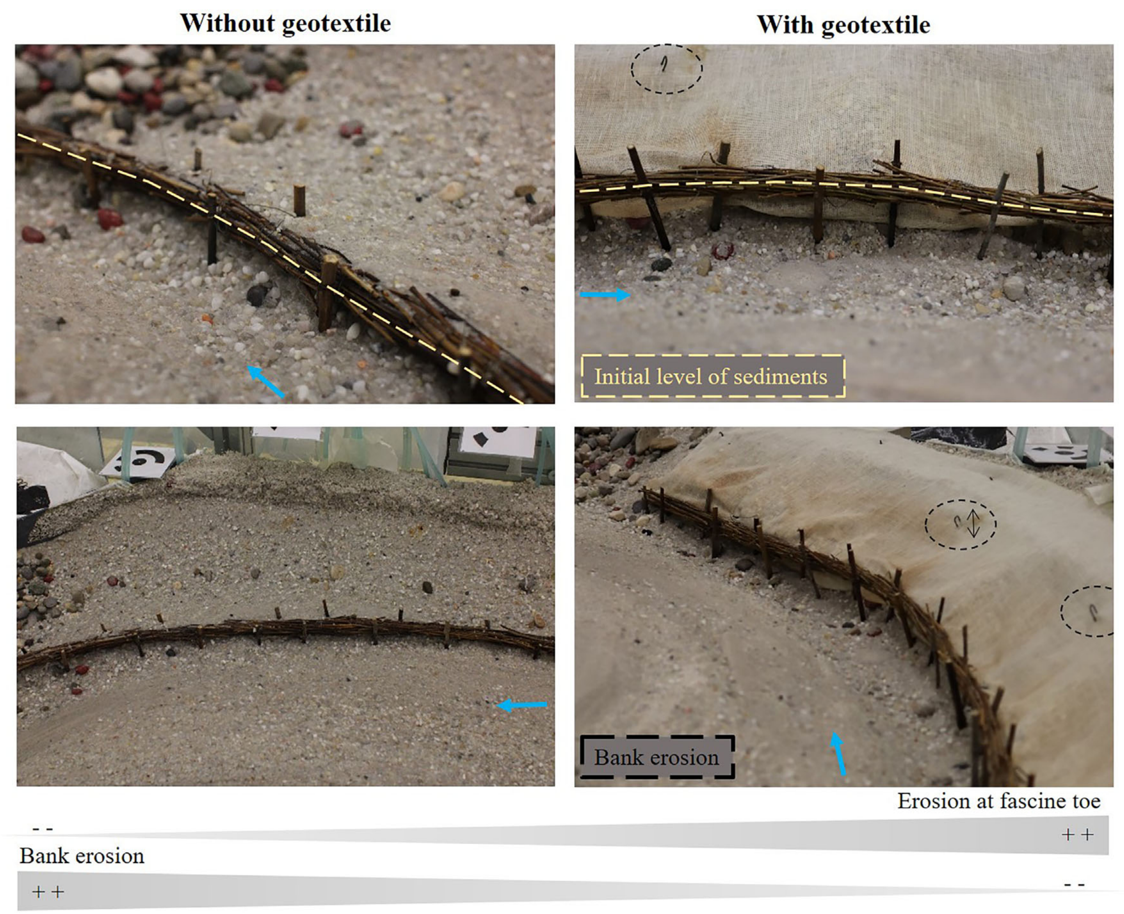

FIGURE 5 Erosion processes from detailed pictures taken after passage of a Q2 flood on the 1:25 scale model. Fascines were implemented on the outer banks of meanders at bank toe and with or without geotextile. The yellow dashed lines show the initial level of sediments. The black dashed lines highlight staples protruding above bank level after flooding, revealing bank erosion. [Color figure can be viewed at wileyonlinelibrary.com]

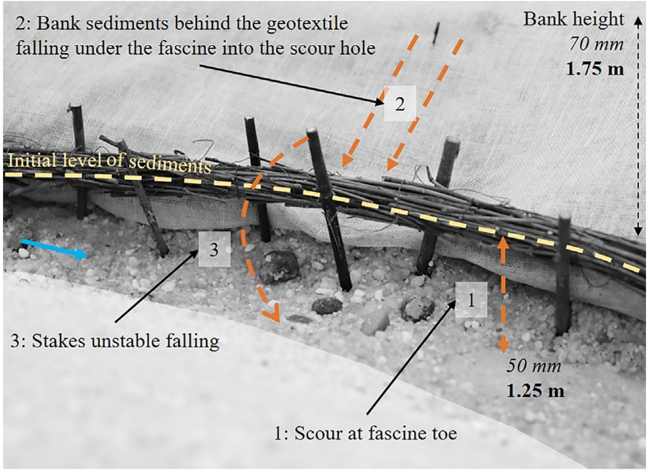

FIGURE 6 Three-step dynamics of the degradation processes of a fascine implemented at bank toe with geotextile protection in the middle and on top of the bank. Observations from the 1:25 small-scale model. Values in italics are at 1:25 scale, and values in bold are the corresponding values at 1:1, field, scale. [Color figure can be viewed at wileyonlinelibrary.com]

adding a layer of geotextile. Finally, according to our quantitative analysis, two types of erosion contribute significantly to destabilization: erosion at bank toe and erosion at the extremities of the fascine.

Therefore, it is essential to stabilize bank toe erosion below the fascine resulting from general incision or secondary currents in meanders (Figures 2 and 6). This weaker area is located below the green line, defined as the level at which shrub vegetation can grow. Consequently, the possible SWBE solutions involving living plants are limited. However, the fascine can be positioned at the lowest possible level for vegetation recovery, by looking at the level where the surrounding vegetation has taken hold. Moreover, depending on the context of the riverbank, alternatives to riprap can be implemented to limit erosion at bank toe, such as placing one or two dead bundles below the fascine or using large wood with stumps to cover the scour hole (Baird et al., 2015; Didier et al., 2023a; ÖWAV, 2021; Yochum & Reynolds, 2020). The use of stumps placed perpendicular to the flow has been shown to provide direct protection, more complexity, and therefore habitats and to increase the roughness of the bed in the scour hole, leading to a dissipation of kinetic energy (Brooks et al., 2006; Chen et al., 2011; Järvelä, 2004; USBR and USACE, 2015).

Civil engineering studies suggest that another means to reduce bank toe erosion is to reduce the bank slope (Blanchet & Morin, 1990). The presence of the fascine, and above all of the geotextile, strongly damps lateral erosion of the bank, accentuating the depth of the scour hole (Figures 4 and 5). Conversely, in a channel without geotextile, when bank erosion is strong, bank slope will be reduced, and scouring is minimal. Although fascines create roughness and anchorage on the bank, and although banks with fascine and geotextile are more flexible than banks with riprap, the erosive power of the flow dissipates to the bottom of the channel bed if it cannot dissipate laterally. As a result, the depth of the scour hole varies with the slope of the bank: the steeper the bank, the deeper the scour hole.

The three steps dynamic of failure proposed from the results obtained with the small-scale model (Figure 6) are consistent with field observations and with the results reported by Edmaier et al. (2011). These authors described how sediments around pioneer vegetation are first eroded and then, at a certain depth of erosion, how the vegetation can be uprooted or toppled.

The dynamics of failure are reminiscent of the bank erosion dynamics described by Thorne and Tovey (1981). The main limit and the major difference between the small-scale model study presented here and the description by Thorne and Tovey (1981) relates to soil cohesion, which was absent in the banks of the small-scale model. If the addition of cohesion could be scaled, it would mimic the field conditions, where clays, silts, and root systems combine to reduce continuous fluvial erosion, potentially leading to mass failure if toe erosion continues to occur (Chassiot et al., 2020; Couper, 2003; Thorne & Tovey, 1981). In the field, cohesion leads to very deep undercutting of the bank where fascines are implemented (Figure 3c). The fascine therefore plays its role of maintaining the bank despite scouring, with the stabilization process reinforced by soil cohesion.

The soil stabilizing functions played by plants through their root and aerial systems is well established (Gasser et al., 2020; Ghestem et al., 2011, 2014; Gray & Sotir, 1996; Simon & Collison, 2002) and applies strongly to riverbanks. Vegetation recovery following installation of SWBE is essential to enhance long-term stability, and rapid cover is preferable. However, in the field, vegetation recovery is not achieved in 13% of sites visited (Figure 3a). It remains unknown if the vegetation failed to grow, and therefore, the structure eventually failed, or if the removal of soil through bank toe erosion made it impossible for the vegetation to take hold. Whatever the case, it is very important: (1) to monitor plant recovery closely during the 3 years following construction, and to consider replanting if necessary. (2) To go back to the field and stabilize the toe of the riverbank to maintain bank material in place. (3) To ensure soil material and conditions that are adapted to plant growth. (4) To consider seasonality of the plants selected for planting and to comply with classical precautions during implementation (Didier et al., 2024; Peeters et al., 2020; Schiechtl & Stern, 1997).

The shear stress values presented in Table 1 vary from one fascine to the next and do not always increase with time since completion, as they depend on the flood events experienced. The literature holds little information on these values, making it impossible to completely understand their significance: where was the fascine placed in relation to bank height, was it in a meander, what type of fascine was used (number of stacks, sizes of bundles), was vegetation already established, in some cases how long has it been since completion, what was the bank slope, were other SWBE installed on the bank, what was the return time for the event, what was the duration of the flood peak, what were the bank and bed grain sizes, did the fascine suffer minor damage, and has the shear stress value been calculated for the bank or the bed? Gerstgraser (2000) previously

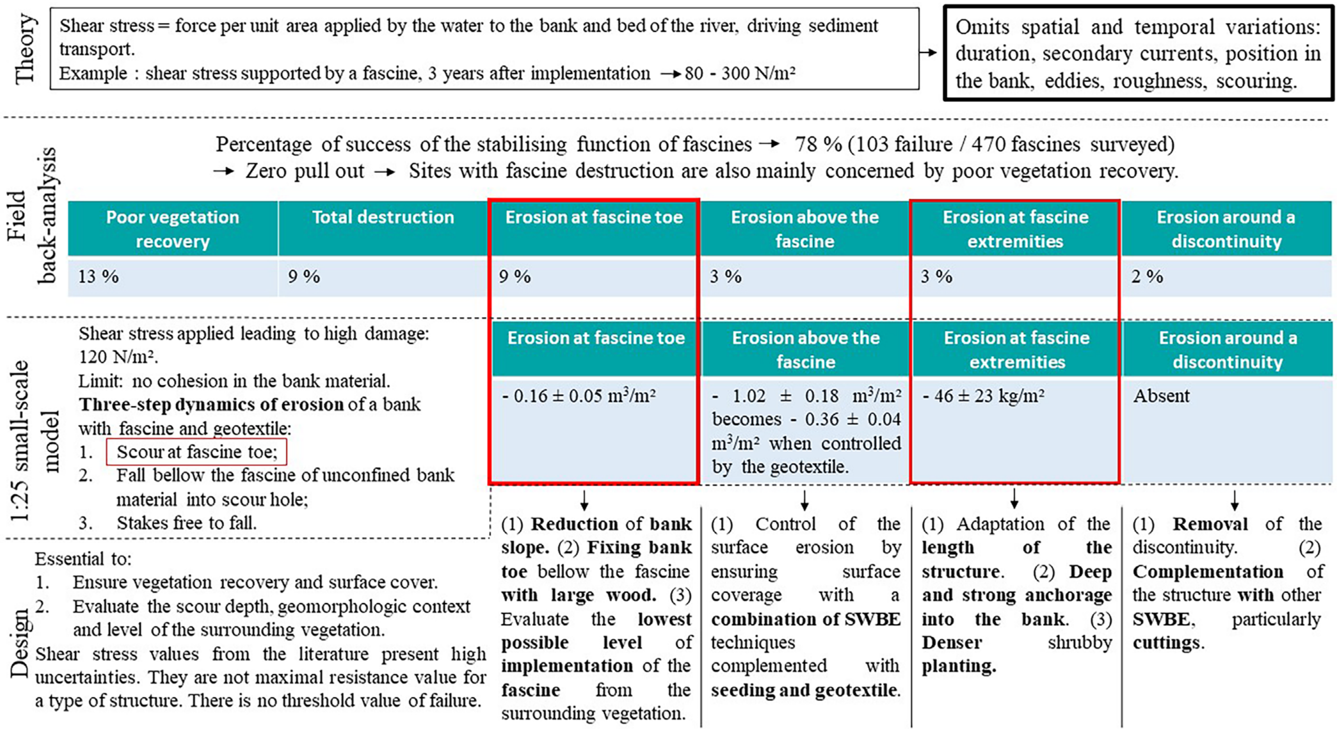

FIGURE 7 Fascines for riverbank stabilization in all their states, summary. SWBE—Soil and Water BioEngineering techniques. [Color figure can be viewed at wileyonlinelibrary.com]

highlighted the lack of knowledge around how the values were established leading to significant uncertainty. Without this information it is impossible to understand why one fascine failed at 50 N/m^2 at completion, whereas another resisted 141 N/m^2 (Table 1). In addition, the values reported are not always maximal nor minimal resistance limits, making them even more difficult to interpret.

One major type of contextual information missing from the literature is the spatial variability of shear stress. Within engineering projects, when designing a structure, shear stress is defined at reach-scale, at least for reported values (Table 1). Therefore, the values do not reflect the strong local spatial and temporal variations that may exist, particularly in bends where real shear stress constraints applied in the banks can be, for example, two-fold larger than those computed from Equation (1) (Papanicolaou et al., 2007). This discrepancy reduces the confidence in the published values compared with locally estimated values from 2D models when designing a new project.

The shear stress values of the 25 reference sites used to develop the flume setup and the shear stress exerted by the fluid on the bed at bank-full level in the flume are in the range of values that fascines installed less than 2 years ago could withstand without damage, according to the literature (Table 1). However, the banks implemented with fascine and geotextile showed strong signs of destabilization in the flume as shown by the amount of sediments eroded from the entire bank during the flood event (Figure 4). Therefore, having a shear stress value in the range of the literature value is not enough to guarantee that the fascine will stand. Fascine stability also relies on scouring intensity, which is not directly taken into account when only shear stress values are considered.

Florineth and Molon (2004) reported from Vollsinger et al. (2000) that the force required to pull out willows aged between 2 and 5 years is five to ten times greater than the shear stress values to be withstood by SWBE according to guidelines (Table 1). As examples, Tanaka et al. (2012) showed that the force required to pull out a *Salix babylonica* with a heart-root system is between 5 and 40 kN/m^2 for a 7 to 17 cm trunk diameter at breast height. To pull out *Juglans ailanthifolia* with a plate-root system and trunks of 7 to 15 cm diameter at breast height, the force required is 3 to 12 kN/m^2. These values are one order of magnitude greater than the values presented in Table 1. Field observation of fascines confirmed the absence of pull-out events. From the dynamics of failure, therefore, fascines appear to be much more destabilized by erosion around the structures than by direct pull-out. The results presented here explain this order of magnitude difference between the resistance to pull-out and the shear stress values which led to failure of some SWBE structures (Table 1) (Evette et al., 2018). It also highlights that the process is relatively continuous over time, meaning that there is no clear threshold shear stress value that can be readily established which fascines could not withstand.

Nevertheless, shear stress values still offer a gradient in the choice of the SWBE to implement. However, considering the small number of values available in the literature, for some techniques, measurements could be made where the structure would withstand larger flood events than previously reported. Moreover, how should shear stress values be compared between a fascine placed at bank toe and a brush layer positioned in the middle of the bank? The choice of the technique will be guided by the morphological and environmental context of the bank to be stabilized: lower part, middle part, bank slope, and exposure. In addition, the surrounding vegetation gives insights into the vegetation types suitable for the area. These criteria will give a clearer picture than shear stress values alone.

5 | CONCLUSIONS

Data from the small-scale model, validated by the field feedback, indicate that sediment transport below the fascine and at fascine extremities are the leading cause of fascine failure. Nevertheless, in 78% of the 470 fascines surveyed, engineers and river managers found solutions to achieve the objective of stabilizing the bank, which is promising for river restoration.

To increase fascines' capacity to stabilize riverbanks, designers should focus on: (1) Reducing bank slope as much as possible. (2) Evaluating the scour depth or possible aggradation or degradation of the bed, to adequately adapt any necessary bank toe protection to be installed below the fascine and the depth of anchorage of the fascine. (3) Identifying the greenline, to determine the lowest possible where the fascine can be implemented on the bank to ensure good, rapid vegetation recovery and ensure adequate toe protection. (4) Ensuring surface cover of the whole bank immediately after completion and at least up to Q2 level. (5) Ensuring vegetation recovery with appropriate soils and to reduce the potential for erosion that would wash out the soil material in contact with plants.

Shear stress values cannot be understood as absolute values of maximal resistance capacities. With the knowledge that failure results from progressive erosion and undermining processes which leave fascines free to fall due to a lack of contact with the soil, it becomes clear that there are no precise threshold values at which a SWBE will fail. Because of the lack of information on how the values in the literature were acquired and the high spatial variability of shear stress, the uncertainty is too great for them to be used as the most influential parameter for SWBE design.

Thus, although shear stress values can help determine a range of techniques applicable for a project, structure design must above all be guided by a general and local understanding of the hydraulic, morphodynamic, ecological, and landscaping contexts, using shear stress values as just one parameter among several.

Consequently, for new shear stress values to be added to the literature, details should be provided on the geomorphologic and environmental contexts, the specificities of the related flood event and the precise design of the structure. Values can be taken from 2D or 3D hydraulic models, which give a better idea of how shear stress distributes spatially.

To take these conclusions a step further, it would be interesting to test various fascine configurations in small-scale models, for example, varying the slope of the bank and the protection systems below the fascine or the type of anchorage used at the extremities. Although not quantitatively scalable, it would also be interesting to add cohesion in the bank material.

ACKNOWLEDGEMENTS

The team would like to thank the OFB (the French Biodiversity Agency) and INRAE's AQUA department (National Research Institute for Agriculture, Food and the Environment) for funding this project, and Suez Consulting for funding Solange Leblois' thesis. We would also like to thank all the people who were involved in the field visits, helped with the installation, and ensured the smooth running of the canal: Christian Eymond-Gris, Hervé Bellot, Firmin Fontaine, Marie Didier, and Emma Schmitt.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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REFERENCES

Adam, P., Debiais, N., Gerber, F., & Lachat, B. (2008). *Le génie végétal: Un manuel technique au service de l'aménagement et de la restauration des milieux aquatiques*. La Documentation française.

Andreoli, A., Chiaradia, E. A., Cislaghi, A., Bischetti, G. B., & Comiti, F. (2020). Roots reinforcement by riparian trees in restored rivers. *Geomorphology*, *370*, 107389. https://doi.org/10.1016/j.geomorph.2020.107389

Anstead, L., & Boar, R. R. (2010). Willow spiling: Review of streambank stabilisation projects in the UK. *Freshwater Reviews*, *3*(1), 33–47. https://doi.org/10.1608/FRJ-3.1.2

Arnaud, P., Aubert, Y., Organde, D., Cantet, P., Fouchier, C., & Folton, N. (2014). Estimation de l'aléa hydrométéorologique par une méthode par simulation: La méthode SHYREG: présentation—performances—bases de données. *La Houille Blanche*, *2*, 20–26. https://doi.org/10.1051/lhb/2014012

Baird, D. C., Fotherby, L., Klumpp, C. C., & Sculock, S. M. (2015). *Bank Stabilization Design Guidelines*. Report No.: SRH-2015-25. U.S. Department of the Interior Bureau of Reclamation Technical Service Center.

Blanchet, C., & Morin, E. (1990). Les affouillements et la protection des berges dans les coudes des rivières à fond mobile-rapport de synthèse de la Sogreah. *Rapport Technique Notice STC. ER. VN*, *90*(2), 139.

Bonin, L., Evette, A., Frossard, P. A., Prunier, P., Roman, D., & Vale, N. (2013). Génie végétal en rivière de montagne. Connaissances et retours d'expériences sur l'utilisation d'espèces et de techniques végétales: Végétalisation de berges et ouvrages bois. ⟨hal-02598614⟩.

Brooks, A., Abbe, T., Cohen, T., Marsh, N., Mika, S., Boulton, A., Broderick, T., Borg, D., & Rutherfurd, I. (2006). *Design guideline for the reintroduction of wood into Australian streams*. Land & Water Australia, Canberra. http://lwa.gov.au/products/px061171

Chassiot, L., Lajeunesse, P., & Bernier, J. F. (2020). Riverbank erosion in cold environments: Review and outlook. *Earth-Science Reviews*, *207*, 103231. https://doi.org/10.1016/j.earscirev.2020.103231

Chen, S.-C., Kuo, Y.-M., & Li, Y.-H. (2011). Flow characteristics within different configurations of submerged flexible vegetation. *Journal of*

Hydrology, *398*(1–2), 124–134. https://doi.org/10.1016/j.jhydrol.2010.12.018

Couper, P. (2003). Effects of silt–clay content on the susceptibility of river banks to subaerial erosion. *Geomorphology*, *56*(1–2), 95–108. https://doi.org/10.1016/S0169-555X(03)00048-5

Didier, M., Evette, A., Pires, M., Rousset, J., Prunier, P., Frossard, P.-A., Martin, L., & Vivier, A. (2024). Le bouturage pour le génie végétal en berges de cours d'eau, Guide technique, OFB-INRAE: 152 p. https://genibiodiv.inrae.fr/le-bouturage-et-les-especes/

Didier, M., Evette, A., Schmitt, E., Leblois, S., Jaymond, D., Evette, J.-B., Mira, E., Raymond, P., Frossard, P.-A., & Vivier, A. (2023a). Les fascines de Ligneux en génie végétal, Guide technique, OFB-INRAE: 74 p. https://genibiodiv.inrae.fr/wp-content/uploads/Les_fascines_de_ligneux_INRAE_OFB.pdf

Didier, M., Evette, A., Schmitt, E., Leblois, S., Jaymond, D., Evette, J.-B., Mira, E., Raymond, P., Frossard, P.-A., & Vivier, A. (2023b). Les Fascines De Ligneux. *Sciences Eaux et Territoires*, *43*(octobre), 57–65. https://doi.org/10.20870/Revue-SET.2023.43.7707

Edmaier, K., Burlando, P., & Perona, P. (2011). Mechanisms of vegetation uprooting by flow in alluvial non-cohesive sediment. *Hydrology and Earth System Sciences*, *15*(5), 1615–1627.

Evette, A., Labonne, S., Rey, F., Liebault, F., Jancke, O., & Girel, J. (2009). History of bioengineering techniques for erosion control in Rivers in Western Europe. *Environmental Management*, *43*(6), 972–984. https://doi.org/10.1007/s00267-009-9275-y

Evette, A., Recking, A., Piton, G., Rauch, H. P., Frossard, P. A., & Jaymond, D. (2018). The limits of mechanical resistance in bioengineering for riverbank protection. *IALCCE-2018*, *6th international symposium on life-cycle civil engineering*. *Ghent*, *Belgium*: 1–6.

Florineth, F., & Molon M. (2004). Dispensa di ingegneria naturalistica. Università di Bodenkultur, Istituto di ingegneria Naturalistica e Costruzione del Paesaggio, Vienna, Austria.

Gasser, E., Perona, P., Dorren, L., Phillips, C., Hübl, J., & Schwarz, M. (2020). A new framework to model hydraulic Bank erosion considering the effects of roots. *Water*, *12*(3), 893. https://doi.org/10.3390/w12030893

Gerstgraser, C. (1998a). Uferstabilisierungen mit Pflanzen: Was halten sie aus? *Österreichische Wasser-Und Abfallwirtschaft*, *50*(7–8), 180–187.

Gerstgraser, C. (1998b). *Ingenieurbiologische Bauweisen an Fliessgewässern*—Grundlagen zu Bau, Belastbarkeiten und Wirkungsweisen. Diss, Univ. f Bodenkultur Wien.

Gerstgraser, C. (2000). Uferstabilisierung mit Lebendverbau. *Wasser Und Boden*, *52*(5), 50–55.

Ghestem, M., Sidle, R. C., & Stokes, A. (2011). The influence of plant root systems on subsurface flow: Implications for slope stability. *Bioscience*, *61*(11), 869–879. https://doi.org/10.1525/bio.2011.61.11.6

Ghestem, M., Veylon, G., Bernard, A., Vanel, Q., & Stokes, A. (2014). Influence of plant root system morphology and architectural traits on soil shear resistance. *Plant and Soil*, *377*(1), 43–61.

Gray, D. H., & Sotir, R. B. (1996). *Biotechnical and soil bioengineering slope stabilization: A practical guide for erosion control*. John Wiley et Sons.

Heller, V. (2011). Scale effects in physical hydraulic engineering models. *Journal of Hydraulic Research*, *49*(3), 293–306. https://doi.org/10.1080/00221686.2011.578914

Jaymond, D., Evette, A., Bray, F., Leblois, S., Jung, D., Vivier, A., & Dorget, C. (2023). BD GeniVeg: Une base de données française sur les ouvrages de protection de berges en génie végétal. *Sciences Eaux et Territoires*, *42*, 35–39. https://doi.org/10.20870/Revue-SET.2023.42.7298

Järvelä, J. (2004). *Flow resistance in environmental channels: Focus on vegetation*. Helsinki University of Technology.

Lachat, B., Adam, P., Frossard, P. A., & Marcaud, R. (1994). Guide de protection des berges des cours d'eau en techniques végétales. Ministère de l'environnement.

Leblois, S., Evette, A., Favier, G., & Recking, A. (2016). Amélioration des méthodes de dimensionnement des ouvrages de génie végétal en berges de cours d'eau par une approche empirique. *Sciences Eaux et Territoires*, *27*, 7. https://doi.org/10.14758/SET-REVUE.2016.HS.05

Leblois, S., Evette, A., Jaymond, D., Piton, G., & Recking, A. (2022). Processus et causes de défaillance du génie végétal pour la stabilisation des berges de rivière: retour d'expérience sur un large jeu de données issues de la BD GeniVeg. *Géomorphologie: Relief*, *Processus*, *Environnement*, *28*(2), 105–120. https://doi.org/10.4000/geomorphologie.16954f

Mai, B., Liu, N., Liu, J., Liu, D., Li, J., Wang, J., Chen, A., Cao, J., & Li, Y. (2022). Analysis and appraisal of fascine in Shahe ancient bridge ruins, Xi'an, Shaanxi, China. *Heritage Science*, *10*(1), 24. https://doi.org/10.1186/s40494-022-00659-9

Papanicolaou, A. N., Elhakeem, M., & Hilldale, R. (2007). Secondary current effects on cohesive river bank erosion. *Water Resources Research*, *43*, W12418. https://doi.org/10.1029/2006WR005763

Peakall, J., Ashworth, P., & Best, J. (1996). Physical modelling in fluvial geomorphology: Principles, applications and unresolved issues. *The Scientific Nature of Geomorphology: Proceedings of the 27th Binghamton Symposium in Geomorphology*, 221–253.

Peeters, A., Houbrechts, G., Hallot, E., Campenhout, J. V., Verniers, G., & Petit, F. (2018). Efficacité et résistance de techniques de protection de berges en génie végétal. *Géomorphologie: Relief*, *Processus*, *Environnement* [En ligne], *24*(2). https://doi.org/10.4000/geomorphologie.11927

Peeters, A., Verniers, G., Houbrechts, G., Hallot, E., & Petit, F. (2020). Protections de berges en génie végétal: Conception, application, suivi et recommandations. Direction des Cours d'Eau non navigables (SPW—DGO3—DDRCB—DCENN). http://hdl.handle.net/2268/248736

Pinto, A., Fernandes, L. F. S., & Maia, R. (2016). Monitoring methodology of interventions for riverbanks stabilization: Assessment of technical solutions performance. *Water Resources Management*, *30*(14), 5281–5298. https://doi.org/10.1007/s11269-016-1486-4

Pinto, A., Fernandes, L. F. S., & Maia, R. (2019). A method for selecting suitable technical solutions to support sustainable riverbank stabilisation. *Area*, *51*(2), 285–298. https://doi.org/10.1111/area.12488

Recking, A., Piton, G., Montabonnet, L., Posi, S., & Evette, A. (2019). Design of fascines for riverbank protection in alpine rivers: Insight from flume experiments. *Ecological Engineering*, *138*, 323–333. https://doi.org/10.1016/j.ecoleng.2019.07.019

Recking, A., Piton, G., Vazquez-Tarrio, D., & Parker, G. (2016). Quantifying the morphological print of bedload transport. *Earth Surface Processes and Landforms*, *41*(6), 809–822. https://doi.org/10.1002/esp.3869

Sangalli, P. (2019). Bioingenieria fluvial. Manual técnico para el ámbito cantábrico—Proyecto H2O Gurea.

Schiechtl, H. M., & Stern, R. (1996). *Ground bioengineering techniques. For slope protection and erosion control*. Blackwell.

Schiechtl, H. M., & Stern, R. (1997). Water bioengineering techniques for watercourse bank and shoreline protection. ISBN: 0-632-04066-1.

Shields, A. (1936). *Anwendung der Aehnlichkeitsmechanik und der Turbulenzforschung auf die Geschiebebewegung* (PhD Thesis Technical). University Berlin.

Simon, A., & Collison, A. J. C. (2002). Quantifying the mechanical and hydrologic effects of riparian vegetation on streambank stability. *Earth Surface Processes and Landforms*, *27*(5), 527–546. https://doi.org/10.1002/esp.325

Sotir, R. B., & Fischenich, C. (2001). Live and inert fascine streambank erosion control. Army engineer waterways experiment station Vicksburg MS Hydraulics Lab.

Tanaka, N., Samarakoon, M. B., & Yagisawa, J. (2012). Effects of root architecture, physical tree characteristics, and soil shear strength on maximum resistive bending moment for overturning Salix babylonica and Juglans ailanthifolia. *Landscape and Ecological Engineering*, *8*(1), 69–79. https://doi.org/10.1007/s11355-011-0151-6

Thorne, C. R. (1982). Processes and mechanisms of river bank erosion. In R. D. Hey, J. C. Bathurst, & C. R. Thorne (Eds.), *Gravel-bed Rivers: Fluvial processes, engineering and management* (pp. 227–271). Wiley.

Thorne, C. R., & Tovey, N. K. (1981). Stability of composite river banks. *Earth Surface Processes and Landforms*, *6*(5), 469–484. https://doi.org/10.1002/esp.3290060507

US Bureau of Reclamation, US Army Corps of Engineers. (2015). National Large Wood Manual: Assessment, planning, design, and maintenance of large wood in fluvial ecosystems: Restoring process, function, and structure. https://www.usbr.gov/research/projects/download_product.cfm?id=1481

Venti, F., Bazzurro, F., Palmeri, F., Uffreduzzi, T., Venanzoni, R., & Gibelli, G. (2003). Manuale tecnico di Ingegneria Naturalistica della Provincia di Terni D. Applicabilita delle tecniche, limiti e soluzioni. 432 p.

Vollsinger, S., Doppler, F., & Florineth, F. (2000). Ermittlung des Stabilitätsverhaltens von Ufergehölzen im Zusammenhang mit Erosionsprozessen an Wildbächen. Studie im Auftrag des Bundesministerium für Land-und Forstwirtschaft, 107 p. Eigenverlag Universität für Bodenkultur Wien. Institut für Ingenieurbiologie und Landschaftsbau.

Williams, G. P. (1986). River meanders and channel size. *Journal of Hydrology*, *88*(1), 147–164. https://doi.org/10.1016/0022-1694(86)90202-7

Yochum, S. E., & Reynolds, L. V. (2020). Guidance for stream restoration. 125.

Zeh, H. (2007). Ingenieurbiologie: Handbuch Bautypen. Génie biologique: Manuel de construction. Ingegneria naturalistica: Quaderno delle opere tipo. Soil bioengineering: Construction type manuel. Ingeniería biológica: Manual tecnico. Schweizerischer Verein für Ingenieurbiologie & European Federation for Soil Bioengineering, Éds. vdf Hochschulverlag AG an der ETH.

ÖWAV. (2021). Holz in und an Fließgewässern—Wildholzmanagement. *Österreichischen Wasser- und Abfallwirtschaftsverbandes (ÖWAV).* [online] https://www.oewav.at/Publikationen?current=410953etmode=form

How to cite this article: Leblois, S., Piton, G., Recking, A., Jaymond, D., Buffet, A., & Evette, A. (2024). Riverbank fascines mostly fail due to scouring: Consistent evidence from field and flume observations. *River Research and Applications*, 1–12. https://doi.org/10.1002/rra.4356