



Original Research

Flow-induced vegetation uprooting in a meandering bend: Experimental investigation

Donatella Termini*, Alice Di Leonardo

^a Department of Engineering, University of Palermo, Viale delle Scienze, Palermo, 90128, Italy

ARTICLE INFO

Article history:

Received 26 April 2021

Received in revised form

24 October 2021

Accepted 28 October 2021

Available online 3 November 2021

Keywords:

Physical experiment

River bend

Resistance

Flow disturbance

Vegetation

Uprooting

ABSTRACT

Vegetation uprooting is a complex process which depends on many interrelated factors. In this paper, attention is focused on the flow-induced uprooting in river bends, where the flow characteristics vary as effected by the channel's curvature and its continuous changing in the downstream direction. Results are presented by an experimental work done in a high-amplitude meandering flume with mature herbaceous vegetation on the bed. In the first part of the paper, the variation along the bend of the geometrical (length, thickness, and radical architecture) and the mechanical (resistance force) characteristics of the roots are analyzed. In the second part of the paper, the transition from the condition of vegetation distributed on the bed to the condition of vegetation uprooted by the flow is experimentally examined. The results show that the flow-induced uprooting varies along the bend depending on the roots' geometrical and mechanical characteristics which are, in turn, influenced by the variation of the water surface elevation along the bend itself. It has been found that lower values of the resistance force occur at the apex section where the roots are characterized by higher values of length and lower values of thickness and have radical apparatuses characterized by limited encumbrance, a high number of roots, and low bushyness. The flow-induced uprooting especially develops close to the outer bank along the channel reach between the bend entrance and the apex section, where the root resistance force and the water surface slope tend to decrease in value.

© 2021 International Research and Training Centre on Erosion and Sedimentation/the World Association for Sedimentation and Erosion Research. Published by Elsevier B.V. All rights reserved.

1. Introduction

Several studies (De Serio et al., 2018; Gran & Paola, 2001; Gurnell et al., 2012; Mossa et al., 2017; Tal & Paola, 2010; Termini, 2021) have demonstrated that the presence of vegetation strongly affects a river's morphological evolution and plays a fundamental role in the ecosystem. But, the vegetation growth and distribution on riverbeds strongly depend on the rooting efficiency (Crouzy et al., 2014). On one hand, the roots guarantee the vegetation is anchored to the soil (Corembliet et al., 2007; Ennos, 1990; Mickovski et al., 2009; Murray et al., 2008), on the other hand they influence the soil's shear strength, cohesion and aeration, and the biological activity in the soil by providing nutrients (Bertin et al., 2003; Waisel et al., 2002). Thus, the understanding of flow-induced uprooting dynamics is extremely important for river and floodplain restoration (Bertoldi et al., 2014).

Several different factors could influence the vegetation uprooting: flooding events (i.e., the frequency, duration, and magnitude of floods), which could cause either vegetation damage or its anchoring reduction because of the sediment ablation (Edmaier et al., 2011; Perona et al., 2012); the soil characteristics (i.e., the soil typology and composition) and the roots' characteristics (i.e., the roots' diameter, length, number, and radical architecture), which could strongly affect the vegetation anchoring and the resistance to uprooting (Ennos, 1993).

The difficulties in analyzing uprooting dynamics at the field scale have limited field investigations so that laboratory studies have especially been done to analyze how different factors could affect the uprooting process. Sand-Jensen (2008) analyzed the drag action as a function of velocity-biomass interaction establishing that drag increases with water velocity and plant biomass. Hussner et al. (2009) investigated the role of the water depth on uprooting and verified that the water depth increases contributing to improve the delivery of nutrition to the roots, favoring the plant resistance (see also Edmaier et al., 2015). Perona et al. (2012) investigated the effect of flooding disturbance on the uprooting dynamics highlighting that it operates as a selective

* Corresponding author. Department of Engineering, University of Palermo, Palermo, Italy.

E-mail address: donatella.termini@unipa.it (D. Termini).

mechanism of the plants depending on the ratio between the flood duration and the plant's age. Other researchers (Edmaier et al., 2011; Gregory, 2006; Konrad, 2012; Pasquale & Perona, 2014; Polvi et al., 2014), focused their attention on the effects of soil and roots' characteristics on the uprooting mechanism. These studies verified that the roots' characteristics can be considered as the result of a balance between the vegetation's growth rate and its potential anchorage which also depends on the plant's age. In particular, according to Edmaier et al. (2011, see also Edmaier et al., 2015), two types of flow-induced uprooting processes occur: Type I, which is essentially without sediment ablation and mainly occurs during the early vegetation growth stages; Type II, which occurs with sediment ablation and is relevant especially with vegetation at the mature stage. Some other researchers (Bailey et al., 2002; Ennos, 1990; Karrenberg et al., 2003; Liu et al., 2011; Pollen, 2007; Schwarz et al., 2011) investigated, by means of static pull-out tests along the vertical direction, either the role of roots' branching or the role of different vegetation species on the roots' anchorage strength.

The aforementioned studies allowed for the better understanding of the influence of some important factors on the uprooting mechanism, but much work is needed to explore how the combination of different factors and their variation in time and/or in space could influence uprooting dynamics.

This last aspect is especially important in river bends where the spatial variation of the flow and the vegetation characteristics could be significant (Nepf, 2012; Termini, 2009, 2016; Termini & Piraino, 2011). To the authors' knowledge, none of the previous studies investigated this aspect and considered the complex structure of the flow within river bends.

In the current study, the aim is to contribute to filling the aforementioned gap, with the aid of data collected in a meandering laboratory flume. The flow-induced uprooting of mature vegetation present on the bed is experimentally investigated. The laboratory scale experiments allowed some significant factors involved in the process and their variation in space and in time to be controlled. The specific objectives of the current study are: 1) to verify how the channel's curvature and its spatial variation could affect the geometrical and the mechanical characteristics of the roots; and 2) to gain some insight on the flow-induced uprooting along the bend for increasing values of water discharge.

2. Materials and methods

2.1. Experimental apparatus and procedure

The laboratory flume follows the sine-generated curve with a deflection angle at the inflection section of 110° . The channel's cross

section is rectangular with a width of 0.50 m and a length of the channel axis equal to 28 m. The channel's sidewalls are composed of transparent plexiglass strips. The flume is equipped with a recirculating system (Fig. 1a) which allows the flow at the upstream inflow channel to be conveyed through a submersible pump (type Flygt 3085-183) located in the downstream tank. The bed, whose topography was obtained at the end of a mobile-bed run, is composed of quartz sand covered by dense (concentration of 200 stems/dm²), real, herbaceous mature vegetation (Fig. 1b). In the current study, attention is focused on five sections (the inflection sections 1 and 5, the bend entrance section 2, the apex section 3, and the bend exit section 4) of the central meander wave (see Fig. 1b where the photo-reconstruction of the vegetated bed is shown).

Based on the specific aims of the current study, the study was done in two steps. In the first step, the geometrical and the mechanical characteristics of the roots along the bend were measured and analyzed. To this aim, two squared samples of the vegetated bed were extracted close to the banks of the five considered sections and the radical apparatuses extracted from each sample were examined. Figure 2 shows the samples and the reference system. In the second step, an experimental run was done to analyze the flow-induced uprooting for increasing values of water discharge.

2.2. Identification of the geometrical roots' characteristics: length, thickness, and radical architecture

In order to investigate the variation of the roots' geometrical characteristics along the bend, for each extracted sample, the length and thickness of the roots and the architecture of the radical apparatuses were identified before the experimental run was done. The root's length (L_r) and thickness (S_r) were determined both by using a digital caliper (accuracy of 0.01 mm) and with the help of calibrated images acquired through a high-resolution camera (Nikon-24 Mp). Then, for each sample, the series of the L_r and S_r values were used to determine the corresponding mean root length, $\bar{L}_r$, and mean root thickness, $\bar{S}_r$, respectively.

The architecture of the radical apparatuses was identified by using the open-source code "Gia Roots" (Galkovsky et al., 2012). This code allowed the characterizing parameters of the extracted radical apparatuses to be estimated by using as input the acquired high-resolution images. The parameters obtained as output of the code were grouped in five classes, as schematically shown in Fig. 3: The first class ($k = 1$) identifies the encumbrance of the radical apparatus and includes three parameters (i.e., the network depth, the network width, and the network encumbrance area); the second class ($k = 2$) indicates the dimension of the containment ellipse approximating the radical apparatus and includes three parameters (i.e., the major ellipse axis, the minor ellipse axis, and their ratio);

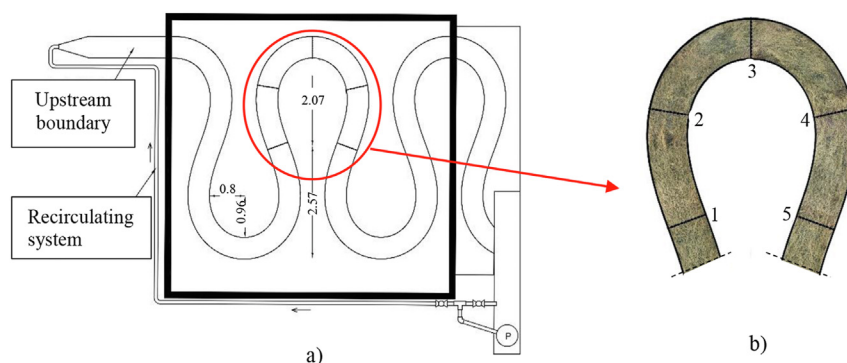


Fig. 1. a) Plan view of the experimental apparatus; and b) photo-reconstruction of the vegetated bed and examined sections.

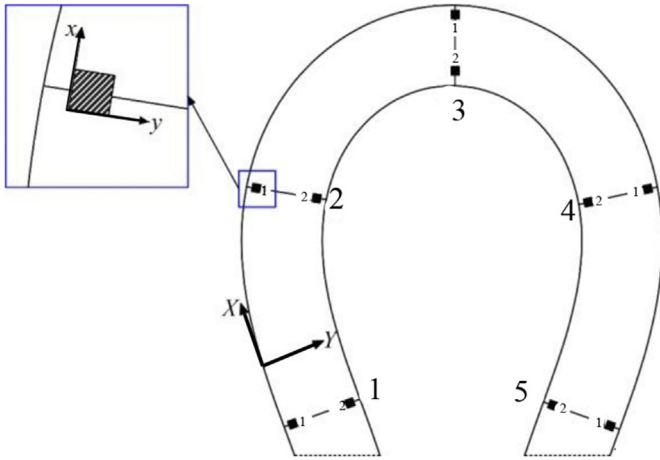


Fig. 2. Plan view of the extracted samples.

the third class ($k = 3$) identifies the number of the roots of the radical apparatus and includes three parameters (i.e., the maximum number of roots, the median number of roots, and the network bushyness); the fourth class ($k = 4$) defines the geometry of the

radical apparatus and includes five parameters (i.e., the network volume, the network transversal surface area, the network perimeter, the network area, and the network length); and the fifth class ($k = 5$) indicates the density of the radical apparatus and includes three parameters (i.e., the network distribution length, the network solidity given by the ratio between the root area and the network encumbrance area, and the specific network depth). Then, the values of the parameters, p_{kj} (i.e., the j -th parameter of the k -th class), estimated for the roots of each sample were used to determine the corresponding mean values, $\bar{p}_{kj}$.

2.3. Identification of the mechanical roots' characteristics

The mechanical characteristics of the roots were determined using a tensile testing machine (Zwick/Roell – see Fig. 4a) located at the Geotechnical Laboratory of the Department of Engineering, University of Palermo, Italy. This machine is equipped with a load cell of 5 kN having a load force resolution of 0.01 N. The roots were clipped by the two clamps of the testing machine at a mutual distance of 10 mm. The tests were done by setting a pretension of 0.03 N and a pulling velocity of 1 mm/min. The system is controlled by a computer which also is used for real time data acquisition and the plotting of the stress σ_T (expressed in N/mm²) against the root's deformation, ε (expressed in percentage with respect to the initial

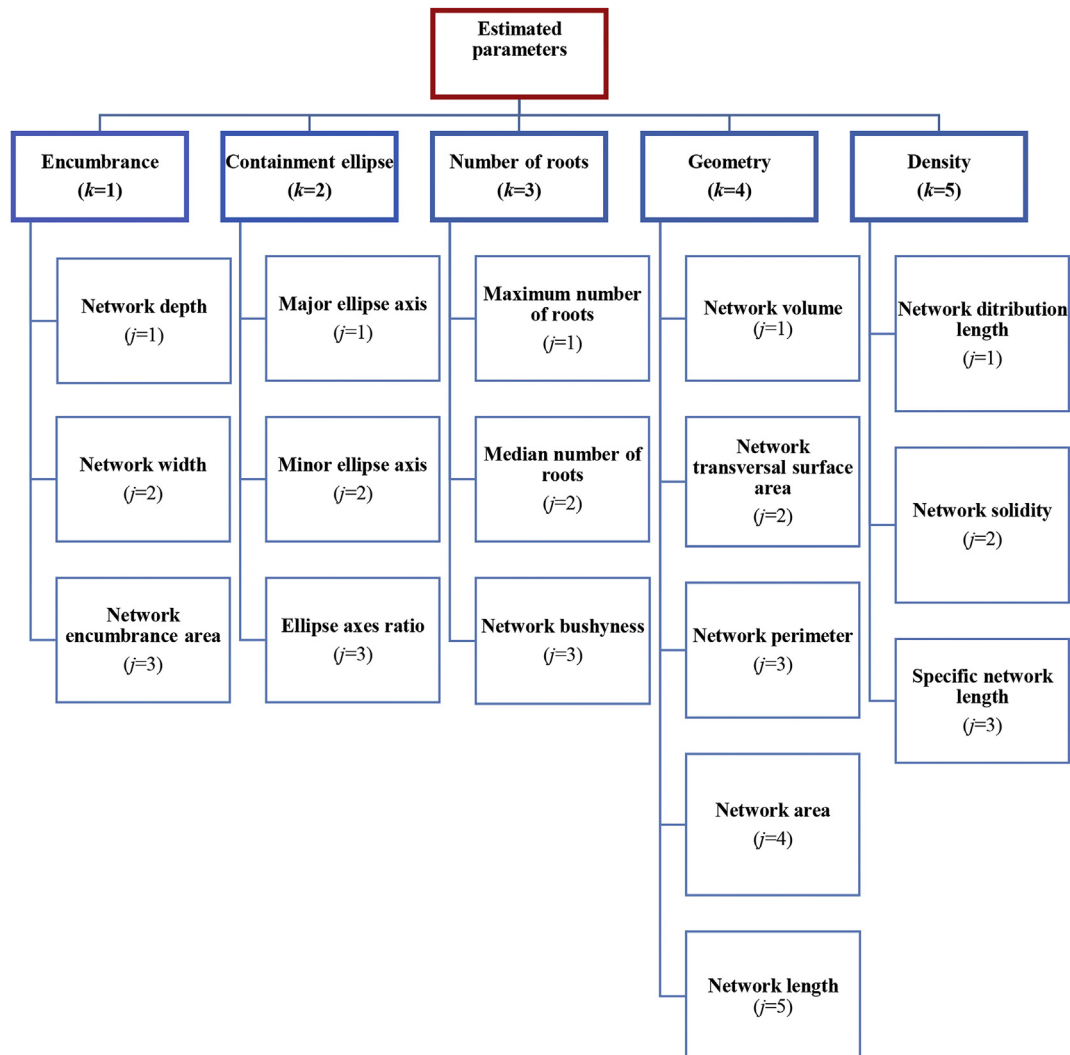


Fig. 3. Classification of the parameters, p_{kj} , estimated by using the “GiA Roots” (Galkovskyi et al., 2012) code.

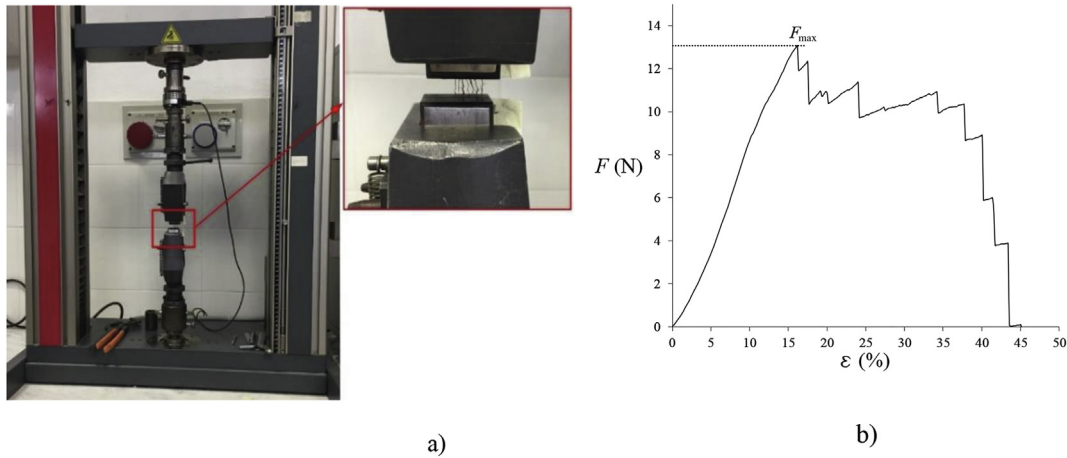


Fig. 4. a) Photo of the testing machine used with clamping of a sample; and b) resistance force, F , against the deformation ε (sample close to the outer bank of section 2).

distance between the two clamps). Thus, by using the values of σ_T , it was possible to determine the corresponding values of the root resistance force, F , as described in previous literature (De Baets et al., 2008; Goodman, 2005). Fig. 4b shows, as an example, the $F - \varepsilon$ curve obtained for the roots extracted close to the outer bank of Section 2. From Fig. 4b, it can be observed that the $F - \varepsilon$ curve shows an initial linear trend which represents the elastic phase. The angular coefficient of such a linear portion allows the Young's elastic modulus, E , to be estimated. After the elastic phase, F assumes an increasing trend until a maximum value, F_{max} , then it decreases showing sudden drops in values at each root break. The ratio $F_{max,m} = F_{max}/n_d$, where n_d indicates the number of drops, has been considered in the following analysis to quantify the resistance force of the examined roots.

2.4. Monitoring the evolution of the flow-induced uprooting

After that the geometrical and the mechanical characteristics of the roots were determined, the evolution of the flow-induced uprooting along the meandering bend was analyzed. To this aim, an experimental run was done in the meandering channel for increasing values of the water discharge. During the run, the water discharge was constantly measured using an instrument Mainstream EH 7000, based on the Doppler effect, located in the inflow straight channel reach. Furthermore, the water depths at the outer bank of the bend were continuously monitored through the transparent channel walls using three cameras (Nikon with a resolution of 24 Mp) opportunely fixed around the channel. A video-camera (Panasonic NG-GS120 with a resolution of 1.7 Mp) also was used to monitor the extension of the eroded vegetated-bed areas at different time. The experimental run was done until no significant uprooting was observed. Before the start of the experiment, the vegetated-bed of the five examined sections was differently colored using spray paints, as shown in Fig. 5. This allowed the location and the number of the roots uprooted during the experiment to be identified, by collecting them on a wire mesh located downstream of the outflow straight reach of the channel.

3. Results

3.1. Variation of the roots' geometrical characteristics (length, thickness, and radical architecture) along the bend

Figure 6 shows the values of the mean roots length, $\bar{L}_r$, normalized by the bent vegetation height kv ($kv = 2.6$ cm – see also in Termini & Di Leonardo, 2018), and of the mean roots thickness, $\bar{S}_r$, normalized by the average blade width of the vegetation stem, d ($d = 3 \times 10^{-3}$ m – see also in Termini & Di Leonardo, 2018), estimated along the bend. It can be observed that, close to the outer bank, the normalized length $\bar{L}_r/kv$ has low values in sections 1 and 2, then it increases until reaching a maximum at the apex section (section 3) and decreases again until reaching the inflection section 5. Close to the inner bank, $\bar{L}_r/kv$ has an increasing trend until reaching the bend entrance (section 2), where the maximum value is obtained, then it decreases reaching a minimum at the apex section (section 3), and it increases again until reaching section 5.

Thus, Fig. 6a suggests that $\bar{L}_r/kv$ assumes along the outer bank a trend opposite to that obtained along the inner bank. The normalized mean thickness $\bar{S}_r/d$ (Fig. 6b) increases close to the outer bank passing from the inflection section upstream to the

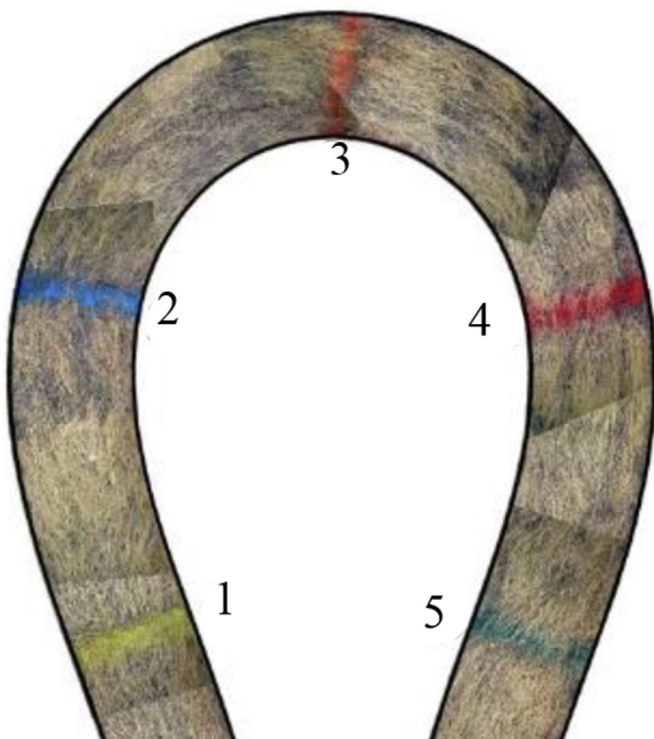


Fig. 5. Bed vegetation and colored sections before the start of the experiment.

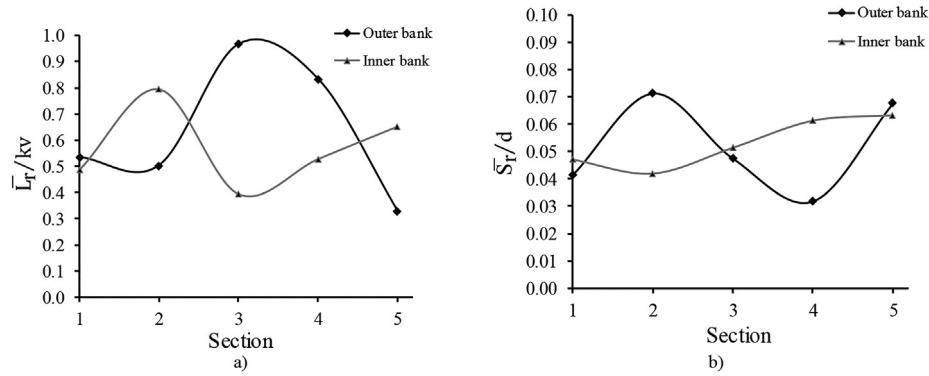


Fig. 6. a) Normalized mean root length, $\bar{L}_r/kv$, along the bend; and b) normalized mean root thickness, $\bar{S}_r/d$, along the bend.

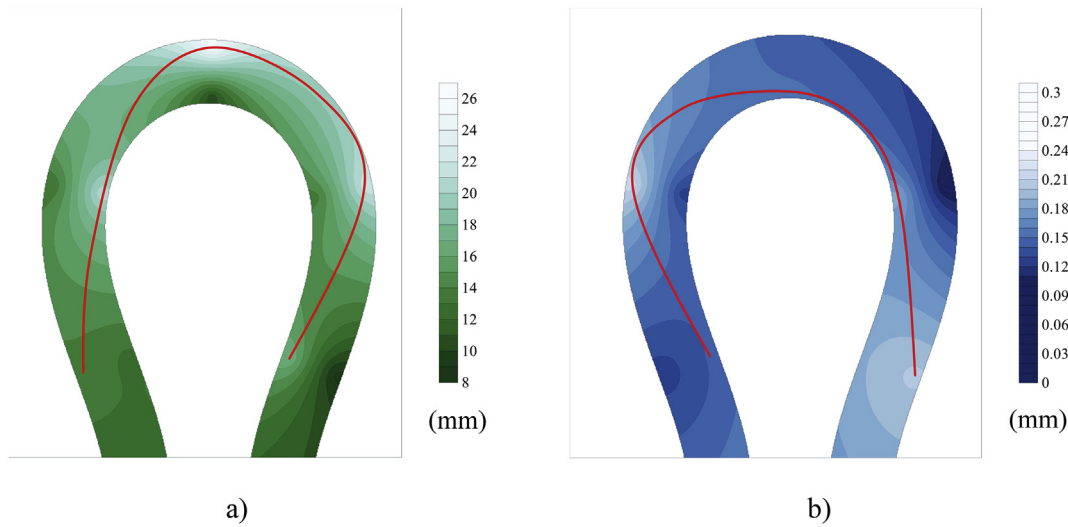


Fig. 7. a) Distribution of $\bar{L}_r$ in the bend; and b) distribution of $\bar{S}_r$ in the bend (the red line connects positions characterized by the highest values $\bar{L}_r$ of and of $\bar{S}_r$).

bend entrance (section 2), where it has a maximum value, then it decreases until reaching a minimum at the bend exit (section 4). Close to the inner bank, $\bar{S}_r/d$ slightly decreases until reaching the bend entrance (section 2) and it increases until the inflection downstream (section 5). Thus, Fig. 6b indicates that $\bar{S}_r/d$ also has, close to the outer bank, a trend opposite to that obtained close to the inner bank. Furthermore, $\bar{L}_r$ and $\bar{S}_r$ have opposite trends along the bend. This behavior also can be observed in Fig. 7 which shows the distributions of $\bar{L}_r$ and $\bar{S}_r$ in the bend. It can be noted that $\bar{L}_r$ has high values where $\bar{S}_r$ has low values, thus, suggesting that the shortest roots are the thickest ones and *vice versa*.

The variation along the bend of the architecture of the radical apparatuses can be analyzed from Fig. 8, which shows the values of the parameters, $\bar{p}_{k,j}$, estimated close to the banks. It can be observed that the parameters of the first class $\bar{p}_{1,j}$ (Fig. 8a), which characterize the encumbrance of the radical apparatuses, have, close to the outer bank, a maximum value at section 2 and a minimum value at section 4; and close to the inner bank, they have a trend opposite to that observed close to the outer bank. This indicates that the radical apparatuses characterized by the highest encumbrance are those close to the outer bank of the bend entrance. The parameters of the second class, $\bar{p}_{2,j}$ (Fig. 8b), which indicate the dimension of the containment ellipse of the radical apparatuses, have the higher values close to the outer bank of section 2 (bend entrance) and close to the inner bank of section 4 (bend exit). Thus, high dimension of the containment ellipse can also be found close to the outer bank of the bend entrance. By inspecting the parameters of

the third class, $\bar{p}_{3,j}$ (Fig. 8c), which identify the number of roots of the radical apparatus, it can be observed that the maximum and the median number of roots have, close to the outer bank of sections 3 and 5 and close to the inner bank of sections 2 and 5, values higher than those obtained close to the outer bank of sections 1 and 4 and to the inner bank of sections 3 and 4. The roots' bushyness has a trend opposite to that of the number of roots. This suggests that the radical apparatuses characterized by a high number of roots and low bushyness are those close to the outer bank of the apex section. The parameters of the fourth class, $\bar{p}_{4,j}$ (Fig. 8d), defining the geometry of the radical network, indicate that the dimensions of the network increase in value close to the outer bank along the channel reach between sections 2 and 3 and close to inner bank of the channel reach between sections 3 and 4. Finally, the parameters of the fifth class, $\bar{p}_{5,j}$ (Fig. 8e), which represent the root density, indicate that high values of the root length distribution and of the network solidity can be found close to the outer bank of section 4 and close to the inner bank of section 2, while the specific length assumes a minimum value close to the outer bank of section 4 and close to the inner bank of the apex section (section 3).

In summary, Figs. 6–8 suggest that, close to the outer bank along the channel reach between the bend entrance and the apex section, the roots are characterized by increasing values of mean length and decreasing values of the mean thickness, and the radical apparatuses are characterized by decreasing values of the network encumbrance and increasing values of the number of roots and of the network geometry.

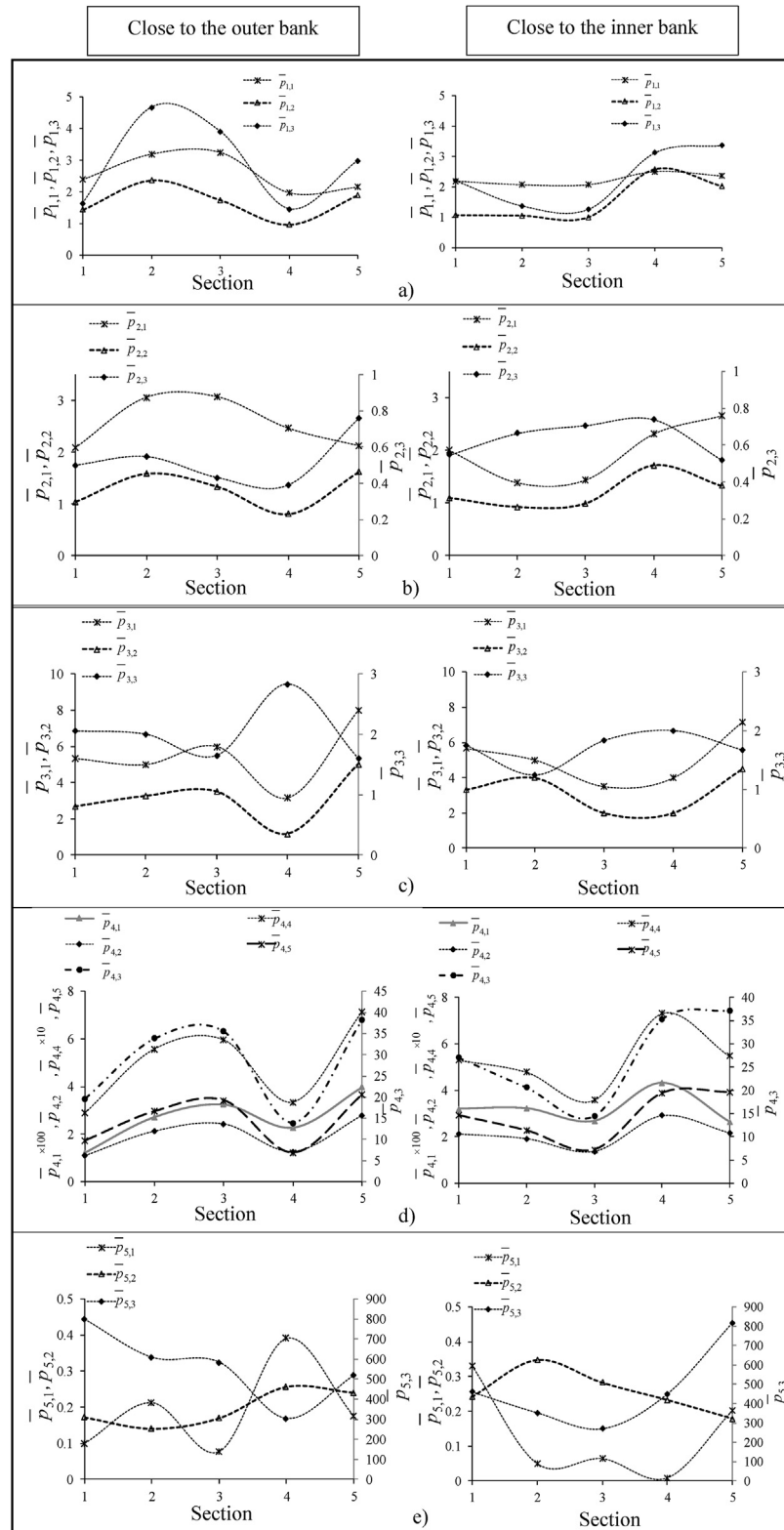


Fig. 8. a) Parameters of first class, $\bar{p}_{1,j}$; b) parameters of second class, $\bar{p}_{2,j}$; c) parameters of third class, $\bar{p}_{3,j}$; d) parameters of forth class, $\bar{p}_{4,j}$; and e) parameters of fifth class, $\bar{p}_{5,j}$.

3.2. Variation along the bend of the roots' mechanical characteristics

In order to analyze the variation of the roots' mechanical characteristics along the bend, Fig. 9 shows the values of $F_{\max,m}$

estimated in the examined sections. It can be observed that, close to the outer bank, $F_{\max,m}$ has a high peak value at the bend entrance (section 2) and a second lower peak at the bend exit (section 4); and close to the inner bank, $F_{\max,m}$ has a peak value at bend exit (section 4).

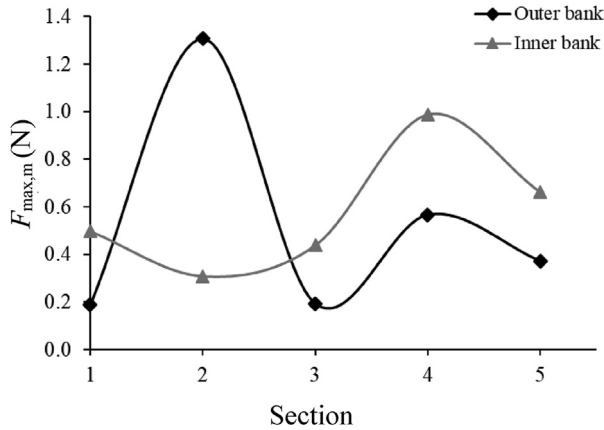


Fig. 9. Variation of $F_{\max,m}$ along the bend.

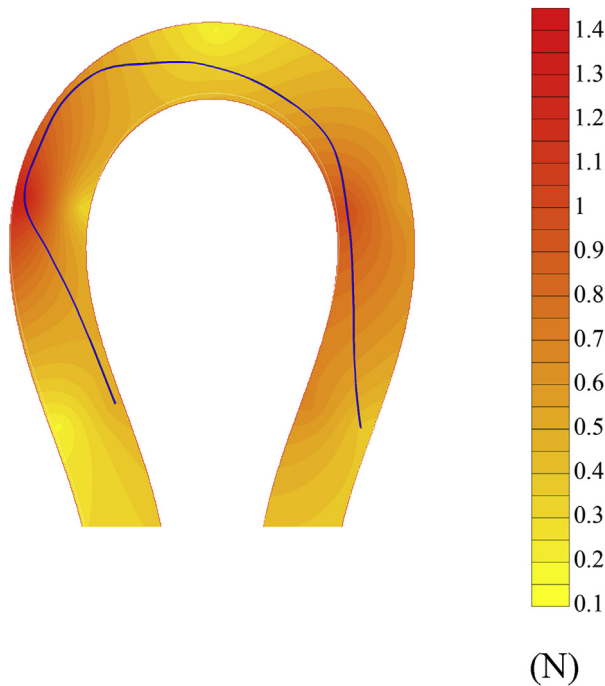


Fig. 10. Distribution of $F_{\max,m}$ in the bend (the blue line connects positions characterized by the highest values of $F_{\max,m}$).

The distribution of $F_{\max,m}$ in the bend, shown in Fig. 10, also clearly indicates that $F_{\max,m}$ increases along the outer bank until reaching a maximum at the bend entrance (section 2), and then it decreases until reaching the apex section (section 3) and increases again until the bend exit; and close to the inner bank, it decreases until reaching a minimum at the bend entrance and then it increases obtaining a maximum value at the bend exit. The comparison between Figs. 7 and 10 indicates that $F_{\max,m}$ has a trend similar to that of $\bar{S}_f$ and opposite to that of $\bar{L}_r$. This confirms that, on average, the roots characterized by high values of the resistance force are those characterized by high values of the mean thickness and low values of the mean length.

In Fig. 11, the values of $F_{\max,m}$ are compared with those of Young's modulus E , estimated along the bend. Figure 11 indicates that the inner bend has a decreasing trend along the channel reach between the bend entrance (section 2) and the apex section (section 3), where it has a minimum value, then it increases reaching a

maximum value at the bend exit (section 4). Furthermore, passing from the inflection section upstream to the bend entrance, E has a trend different to that of $F_{\max,m}$, but downstream of the apex section, they have a similar trend. From Fig. 11, it can also be concluded that, close to the outer bank of the channel reach between the inflection section upstream and the bend entrance, the roots are characterized by increasing values of the resistance force and decreasing values of the elastic modulus; and at the apex section, the roots have the lowest values both of the resistance force and of the elastic modulus.

3.3. Evolution of flow-induced uprooting

The evolution of the flow-induced uprooting process along the bend has been analyzed using both the direct observations and the data collected and the videos recorded during the experimental run.

As it is clear from Section 1, some previous studies (Hussner et al., 2009; Perona et al., 2012; Sand-Jensen, 2008) indicate that the water depth exerts an important role in the uprooting process. Figure 12 shows the values of the water depth, h , measured at the outer bank of the apex section during the experimental run as functions of time and water discharge Q . It can be observed that h increases passing the time T , but for $3,510 \text{ s} < T < 4,110 \text{ s}$ (and, thus, for values of flow discharge varying in the range of $14.21 \text{ l/s} < Q < 20 \text{ l/s}$), h gradually increases until $T > 4,110 \text{ s}$ after which it maintains an almost constant value. Fig. 13 shows the profiles of both the water surface elevation, H , and of the term $\tau = \gamma h S_f$ (where S_f is the downstream water surface slope, $S_f = -dH/ds$, and γ is the specific weight of water) obtained at the outer bank at time $T = 3,510 \text{ s}$. Both terms show a first high peak at the bend entrance (section 2) and a second lower peak at the bend exit (section 4). The trend of the profiles reported in Fig. 13 is in accordance with that of the downstream water surface slope observed by Termini (2009) in the same meandering bend but in the absence of vegetation on the bed. In particular, highlighting the formation of two oscillation damping conditions downstream, Termini (2009) established that as effect of the changing channel curvature, the downstream water surface slope varies along the bend like a damped oscillating system.

By using the videos recorded during the experimental run, the extension and the location of the vegetated-bed areas eroded at different time also were identified. As an example, Fig. 14 shows the maps of the eroded vegetated-bed areas at the time instants $T_1 = 1,620 \text{ s}$, $T_2 = 2,700 \text{ s}$, $T_3 = 3,510 \text{ s}$, and $T_4 = 4,110 \text{ s}$, respectively corresponding to values of the water discharge equal to $Q_1 = 9.7 \text{ l/s}$, $Q_2 = 10.67 \text{ l/s}$, $Q_3 = 14.21 \text{ l/s}$, and $Q_4 = 20 \text{ l/s}$. Figure 14 clearly indicates that the rate of uprooting varies in time, but after time $T_3 = 3,510 \text{ s}$, the eroded vegetated areas do not change a lot. This behavior can be also observed in Fig. 15, which shows the values of the total eroded vegetated-bed area normalized by the total initial area, $E_{s,n}$, at different time. Figure 15 clearly shows that the rate of uprooting follows three evolution phases: For time $T < T_3$, the total eroded vegetated-bed area increases rapidly; then for $T_3 < T < T_4$, it grows gradually; but after the time T_4 it tends to maintain an almost constant value.

Figure 14 also indicates that the extension of the eroded vegetated-bed areas especially increases along the channel reach between the bend entrance (section 2) and the apex section (section 3), extending towards the bend exit (Section 4). As Fig. 10 shows, along the channel reach between Section 2 and Section 3, the resistance force assumes a decreasing trend until reaching a minimum at the apex section (Section 3); then, moving towards the bend exit (Section 4), it has an increasing trend.

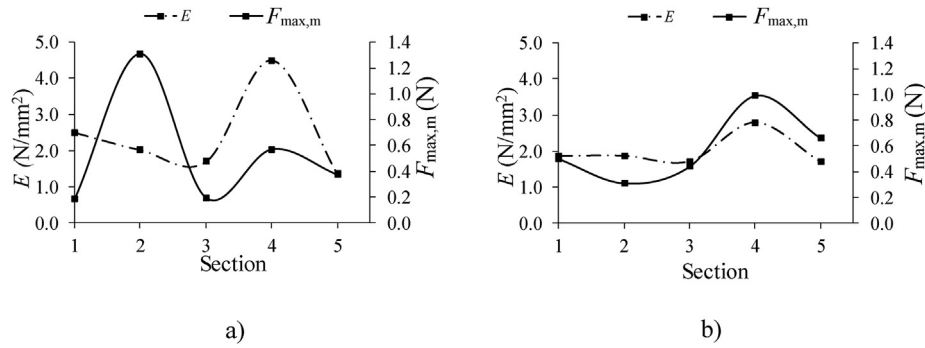


Fig. 11. Comparison between the values $F_{\max,m}$ and the values of the Young's modulus, E , along the bend: a) close to the outer bank; and b) close to the inner bank.

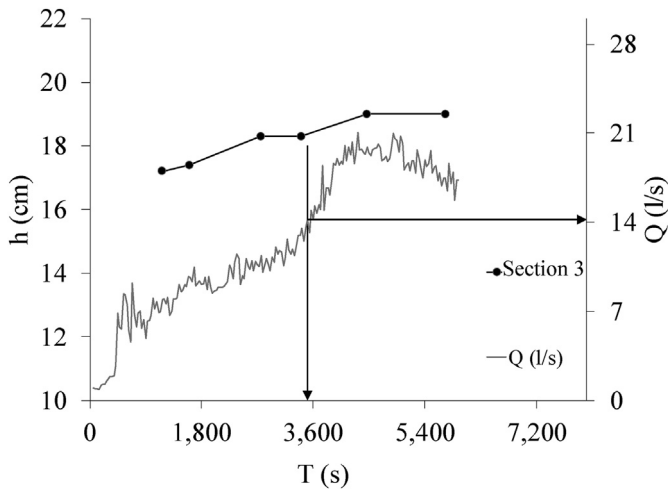


Fig. 12. Variation in time of the water depth, h , at the outer bank of the apex section and the flow discharge, Q .

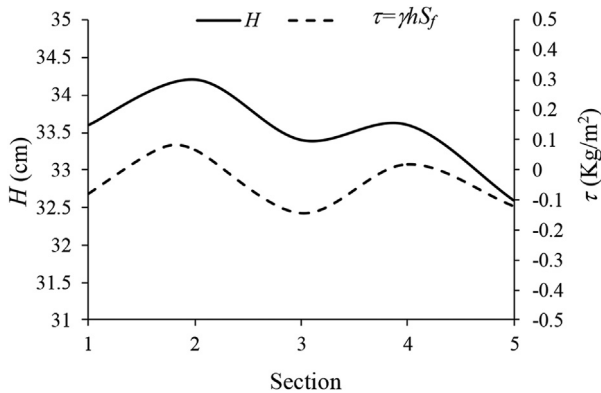


Fig. 13. Values of H and of τ along the outer bank of the bend at time $T = 3,510$ s.

The evolution of the uprooting has also been analyzed by evaluating the number of the roots eroded during the experimental run. To this aim, the colored uprooted stems collected at different time in the wire mesh downstream in the flume have been used. Figure 16a shows that the total number of the uprooted colored stems, n_{st} , has an increasing trend passing from the inflection section to the apex section, where it has the maximum value, then it decreases until reaching the bend exit. This confirms

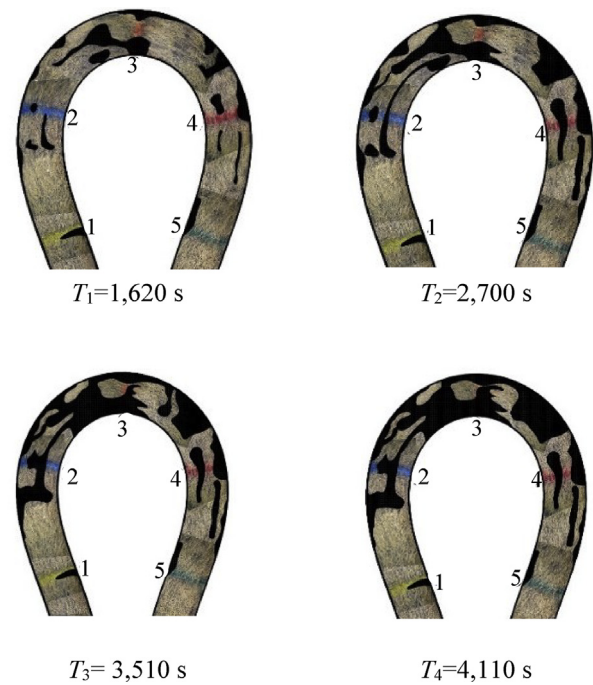


Fig. 14. Vegetated-bed eroded areas at different time.

that the erosion process especially occurs along the channel reach between the bend entrance (section 2) and the apex section (section 3). Figure 16b shows the percentage, $P_{n_{st,k}}$, of the total number of the colored stems uprooted at different times from the

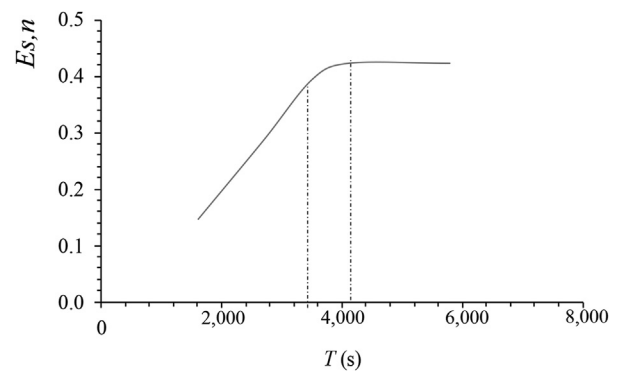


Fig. 15. Total extension of the normalized eroded vegetated area, $E_{s,n}$, over time.

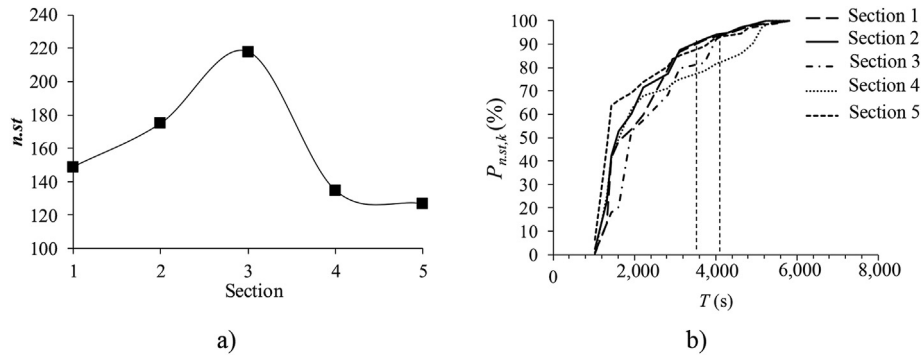


Fig. 16. a) Total number of uprooted stems at each examined section; and b) values of $P_{n,st,k}$ over time.

k -th section, $n_{st,k}$, with respect to the total number of colored stems uprooted at the end of the run, n_{st} . This figure confirms that the uprooting process follows three evolution phases: The first phase, for time $T < T_3$, where the value of the percentage, $P_{n,st,k}$, increases rapidly with an almost linear trend; the second phase, for instants $T_3 < T < T_4$, where the value of the percentage, $P_{n,st,k}$, slowly increases; and the third phase, for $T > T_4$ where the percentage, $P_{n,st,k}$, maintains an almost constant value. Thus, the majority of the vegetation is uprooted by flow for $T < T_3$.

4. Discussion

4.1. Relation between the uprooting evolution and the roots' geometrical and mechanical characteristics

The results obtained in the previous section indicate that the evolution of the uprooting along the bend is strongly related to the

variation of the roots' geometrical and mechanical characteristics. In particular, the results have shown that the uprooting is significant at the apex section, where the roots are characterized by low values of the resistance force. On the contrary, the uprooting is less evident along the channel reach between the inflection section and the bend entrance and close to the inner bank of the bend exit, where the roots are characterized by high values of the resistance force. In order to further highlight this behaviour, Fig. 17 compares the values of the resistance force, $F_{max,m}$, with those of the total number of the uprooted stems, n_{st} . From Fig. 17, it is clear that $F_{max,m}$ and n_{st} behave with opposite trends: At the apex section, $F_{max,m}$ has the minimum value while n_{st} has the maximum value.

The results have also indicated that the values of the resistance force are strongly influenced by the length and the thickness of the roots. The comparison between Figs. 7 and 14 has shown that the uprooting especially develops where the mean root length, $\bar{L}_r$, has

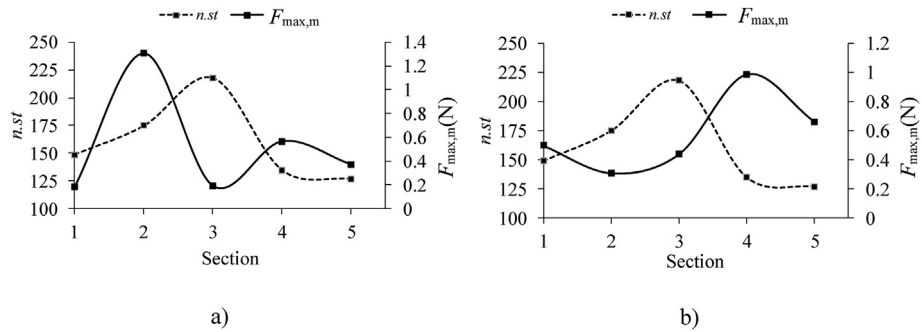


Fig. 17. Comparison between $F_{max,m}$ and the total number of uprooted stems n_{st} : a) close to the outer bank; and b) close to the inner bank.

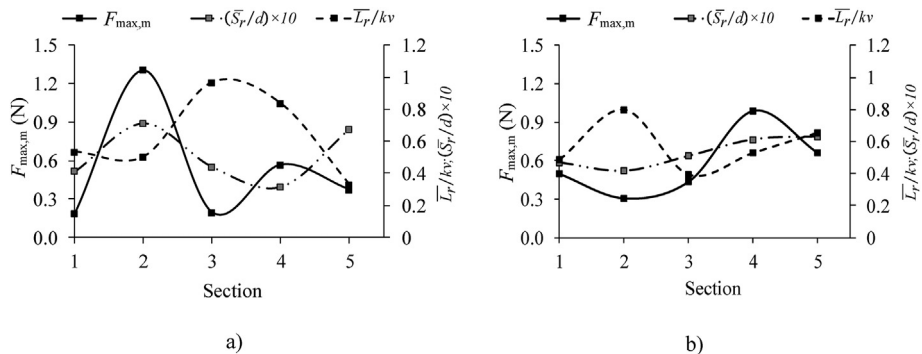


Fig. 18. Comparison between $F_{max,m}$ and the roots' length and thickness, $\bar{L}_s/k_v$ and $\bar{S}_r/d$: a) close to the outer bank; and b) close to the inner bank.

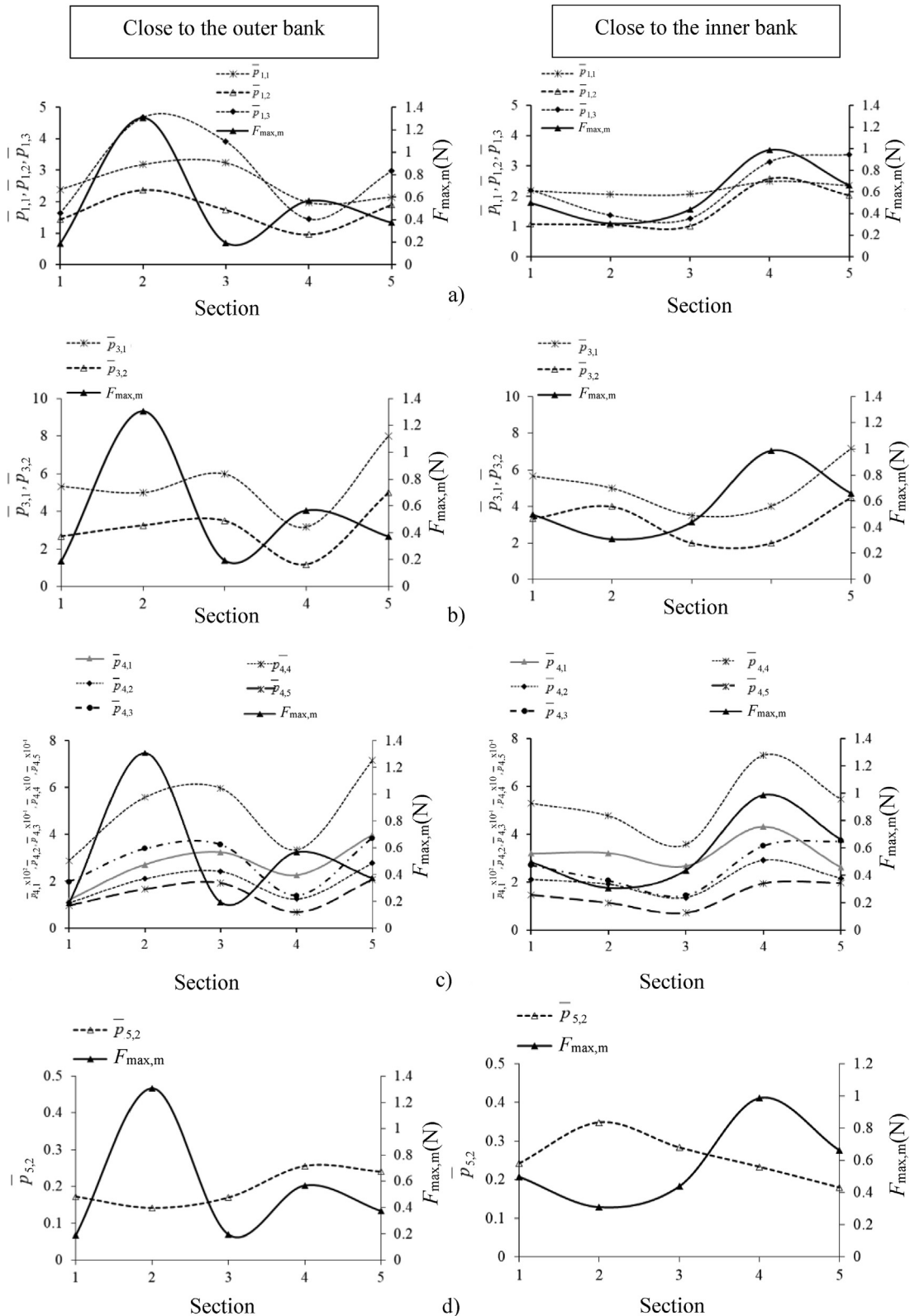


Fig. 19. Comparison between the values of $F_{\max,m}$ and the values of the most significant parameters describing the radical apparatus architecture along the bend: a) first class, $\bar{p}_{1,j}$; b) third class, $\bar{p}_{3,j}$; c) forth class, $\bar{p}_{4,j}$; and d) fifth class, $\bar{p}_{5,j}$.

high values. This result is consistent with some previous literature findings indicating that the uprooting rate depends on the length of the root (Perona et al., 2012; Crouzy et al., 2014), thus, confirming that the root length could be considered as an indicator of the

vegetation condition, and that the root resistance and rooting length are important inputs for establishing plant resilience to uprooting (Edmaier et al., 2011, 2015). This behavior is also highlighted in Fig. 18 which compares the values of the resistance force,

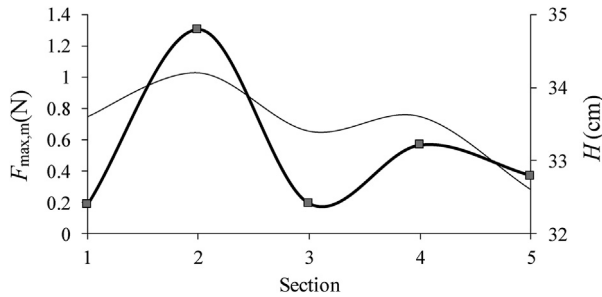


Fig. 20. Comparison between $F_{\max,m}$ and H along the outer bank.

$F_{\max,m}$, along the bend with those of the normalized mean root length, $\bar{L}_r/kv$, and of the normalized mean root thickness, $\bar{S}_r/d$. It is clear that the roots with high values of the resistance force (i.e., those close to the outer bank of the bend entrance and close to the inner bank of the bend exit) also are characterized by high values of the mean thickness; the roots characterized by low values of resistance force (such as close to the outer bank of the apex section) are also characterized by low values of the mean thickness. This is in line with results obtained by Yang et al. (2016) who identified increasing values of the tensile resistance for increasing roots diameters. Furthermore, the roots with high values of the resistance force (i.e., those close to the outer bank of the bend entrance and close to the inner bank of the bend exit) are also characterized by low values of the mean length; the roots characterized by low values of resistance force (such as those close to the outer bank of the apex section) also are characterized by high values of the mean length. Previous studies (Bailey et al., 2002; Bau et al., 2019; Edmaier et al., 2015; Ennos, 1990) have established, on the basis on static tensile tests, that the root resistance increases as the root length increases, but the root breaks when its length is greater than a critical length value (i.e., the so-called critical rooting length). According to Ennos (1990), the root resistance force is proportional to the length only up to such a critical rooting length, whose value is, in turn, proportional to the root's radius. Thus, the results obtained in the current study could suggest that close to the outer bank of the apex section, where low values of the root thickness are found, the critical rooting length has values lower than those obtained at the bend entrance, where the high values of the root thickness are obtained. This behavior could facilitate the rooting process at the apex section.

The results have also shown that the values of $F_{\max,m}$ along the bend also are strongly related to the characteristic architecture of the radical apparatus. Fig. 19 compares the values of the resistance force with those of some significant parameters, $\bar{p}_{k,j}$. It can be seen that high values of the resistance force are obtained where the radical apparatuses are characterized by high encumbrance and geometry (Figs. 9a and 9b), low number of roots (Fig. 19b), and low solidity (Fig. 19d). Low values of resistance force are especially obtained at the apex section, where the radical apparatuses are characterized by limited values of encumbrance, high number of roots, and low bushyness.

4.2. Relation between the evolution of uprooting and the variation of water surface elevation

The results have also indicated that the variation of the root resistance force is strongly influenced by the variation of water surface elevation along the bend. This behavior can also be observed in Fig. 20 which compares the values of $F_{\max,m}$ along the outer bank of the bend with that of the water surface elevation, H . It is clear that $F_{\max,m}$ has two oscillations, damping downstream, with

a high first peak at the bend entrance and a second lower peak at the bend exit. This suggests that, in addition to the downstream water surface slope, because of the changing channel curvature, the resistance force varies along the bend like a damped oscillating system. Thus, the variation of the roots' resistance force along the bend follows the variability of the water surface elevation. This also is consistent with the observation of Hussner et al. (2009) which indicated that high water depths contribute to favor the plant resistance. Furthermore, the trend of the water surface elevation shown in Fig. 13 is consistent with that observed by Termini (2009) in the same meandering bend as that of the current study, but in the absence of vegetation on the bed. Thus, it can be concluded that, as an effect of the changing channel curvature, the water surface slope varies along the bend as a damped oscillating system and this behavior affects the root resistance force, and, consequently, the uprooting process.

5. Conclusions

An experimental program has been done at the Hydraulic Laboratory of the Department of Engineering – University of Palermo (Italy) with the aim to investigate the effect of channel's curvature on root characteristics of herbaceous mature vegetation and the flow-induced uprooting.

The main conclusions obtained in the current study can be summarized as follows:

- 1) The channel's curvature and its variation influence the geometrical and the mechanical characteristics of the roots along the bend. As a consequence, the flow-induced uprooting is not uniform within the bend;
- 2) High values of the root resistance force have been found where the roots are characterized by high thickness and low length and with radical apparatus characterized by high encumbrance and low number of roots. A first peak value of the resistance force is obtained close to the outer bank at the bend entrance and a second lower peak is found at the bend exit. Thus, the results have suggested that, in addition to the downstream water surface slope, because of the changing channel curvature, the resistance force varies along the bend like a damped oscillating system.
- 3) The flow-induced uprooting especially develops close to the outer bank along the channel reach between the bend entrance and the bend apex where the root resistance force has a decreasing trend. At the apex section, the root resistance force has a minimum value and the roots are characterized by high values of the mean length and low values of the mean thickness and the radical apparatuses are characterized by limited values of encumbrance, high number of roots, and low bushyness.
- 4) The uprooting process follows three evolution phases: In the first phase, the extension of the eroded vegetated-bed areas increases rapidly; in the second phase, the extension of the eroded vegetated-bed areas increases more slowly; in the third phase, the eroded vegetated-bed areas maintain an almost constant value.

Although the current study refers to laboratory conditions, the results obtained in the current study can be extended to river reaches subjected to flow-induced bed vegetation erosion. Based on the obtained results, the uprooting process should be more evident in the first phase of a flooding event; after this phase, the uprooting process should increase much more slowly. Furthermore, along the bend, the distribution of the vegetated-bed eroded areas is non-uniform, thus, affecting the hydraulic resistance along the bend.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

This work has been partially supported by Italian National Research Programme PRIN 2017, with the project “*IntEractions between hydrodyNamics flows and bioTic communities in fluvial Eco-systems: advancement in dischaRge monitoring and understanding of Processes Relevant for ecosystem sustainability by the development of novel technologieS with field observatioNs and laboratory testinG (ENTERPRISING)*”.

References

- Bailey, P., Currey, J., & Fitter, A. (2002). The role of root system architecture and root hairs in promoting anchorage against uprooting forces in *Allium cepa* and root mutants of *Arabidopsis thaliana*. *Journal of Experimental Botany*, 53(367), 333–340.
- Bau, V., Zen, S., Calvani, G., & Perona, P. (2019). Extracting the critical rooting length in plant uprooting by flow from pullout experiments. *Water Resource Research*, 55(12), 10424–10442.
- Bertin, C., Yang, X., & Weston, L. (2003). The role of root exudates and allelochemicals in the rhizosphere. *Plant and Soil*, 256, 67–83.
- Bertoldi, W., Siviglia, A., Tettamanti, S., Toffolon, M., Vetsch, D., & Francalanci, S. (2014). Modeling vegetation controls on fluvial morphological trajectories. *Geophysical Research Letters*, 41(20), 7167–7175.
- Corenblit, D., Tabacchi, E., Steiger, J., & Gurnell, A. (2007). Reciprocal interactions and adjustments between fluvial landforms and vegetation dynamics in river corridors: A review of complementary approaches. *Earth Science Reviews*, 84, 56–86.
- Crouzy, B., Edmaier, K., & Perona, P. (2014). Biomechanics of plant anchorage at early development stage. *Journal of Theoretical Biology*, 363, 22–29.
- De Baets, S., Poesen, J., Reubens, B., Wemans, K., De Baerdemaker, J., & Muys, B. (2008). Root tensile strength and root distribution of typical Mediterranean plant species and their contribution to soil shear strength. *Plant and Soil*, 305, 207–226.
- De Serio, F., Ben Meftah, M., Mossa, M., & Termini, D. (2018). Experimental investigation on dispersion mechanisms in rigid and flexible vegetated beds. *Advances in Water Resources*, 120, 98–113.
- Edmaier, K., Burlando, P., & Perona, P. (2011). Mechanisms of vegetation uprooting by flow in alluvial non-cohesive sediment. *Hydrology and Earth System Sciences*, 15, 1615–1627.
- Edmaier, K., Crouzy, B., & Perona, P. (2015). Experimental characterization of vegetation uprooting by flow. *Journal of Geophysical Research Biogeoscience*, 120, 1812–1824.
- Ennos, A. R. (1990). The anchorage of leek seedlings: The effect of root length and soil strength. *Annals of Botany*, 65, 409–416.
- Ennos, A. R. (1993). The scaling of root anchorage. *Journal of Theoretical Biology*, 161(1), 61–75.
- Galkovskiy, T., Mileyko, Y., Bucksch, A., Moore, B., Symonova, O., Price, C. A., Topp, C. N., Iyer-Pascuzzi, A. S., Zurek, P. R., Fang, S., Harer, J., Benfey, P. H., & Weitz, J. S. (2012). GiA roots: Software for the high throughput analysis of plant root system architecture. *BMC Plant Biology*, 12, 116.
- Goodman, A. M. (2005). Mechanical adaptations of cleavers (*Galium aparine*). *Annals of Botany*, 95, 475–480.
- Gran, K., & Paola, C. (2001). Riparian vegetation controls on braided stream dynamics. *Water Resources Research*, 37(12), 3275–3283.
- Gregory, P. (2006). *Plant roots, Growth, activity and interaction with soils*. Oxford: Blackwell Publishing Ltd.
- Gurnell, A. M., Bertoldi, W., & Corenblit, D. (2012). Changing river channels: The roles of hydrological processes, plants and pioneer fluvial landforms in humid temperate, mixed load, gravel bed rivers. *Earth-Science Reviews*, 111, 129–141.
- Hussner, A., Meyer, C., & Busch, J. (2009). The influence of water level and nutrient availability on growth and root system development of *Myriophyllum aquaticum*. *Weed Research*, 49, 73–80.
- Karrenberg, S., Blaser, S., Kollmann, J., Speck, T., & Edwards, P. (2003). Root anchorage of saplings and cuttings of woody pioneer species in a riparian environment. *Functional Ecology*, 17(2), 170–177.
- Konrad, C. P. (2012). Reoccupation of flood plains by rivers and its relation to the age structure of floodplain vegetation. *Journal of Geophysical Research*, 117, G00N13.
- Liu, Y., Gao, J., Lou, H., Zhang, J., & Cui, Q. (2011). The root anchorage ability of *Salix alba* var. *tristis* using a pull-out test. *African Journal of Biotechnology*, 10(73), 16501–16507.
- Mickovski, S., Hallett, P., Bransby, M., Davies, M., Sonnenberg, R., & Bengough, A. (2009). Mechanical reinforcement of soil by willow roots: Impacts of root properties and root failure mechanism in controlled laboratory tests. *Soil Science Society of America Journal*, 73(4), 1276–1285.
- Mossa, M., Ben Meftah, M., De Serio, F., & Nepf, H. M. (2017). How vegetation in flows modifies the turbulent mixing and spreading of jets. *Scientific Reports*, 7(1), 6587.
- Murray, A., Knaapen, M., Tal, M., & Kirwan, M. (2008). Biomorphodynamics: Physical-biological feedbacks that shape landscapes. *Water Resources Research*, 44, W11301.
- Nepf, H. M. (2012). Hydrodynamics of vegetated channels. *Journal of Hydraulic Research*, 50(3), 262–279.
- Pasquale, N., & Perona, P. (2014). Experimental assessment of riverbed sediment reinforcement by vegetation roots. In A. E. A. Schleiss (Ed.), *Proceedings of the RiverFlow 2014, international conference on fluvial hydraulics* (pp. 553–561). Lausanne, Switzerland: IAHR.
- Perona, P., Molnar, P., Crouzy, B., Perucca, E., Jiang, Z., McLelland, S., Wuthrich, D., Edmaier, K., Francis, R., Camporeale, C., & Gurnell, A. (2012). Biomass selection by floods and related timescales: Part 1. Experimental observations. *Advances in Water Resources*, 39, 85–96.
- Pollen, N. (2007). Temporal and spatial variability in root reinforcement of streambanks: Accounting for soil shear strength and moisture. *Catena*, 69, 197–205.
- Polvi, L., Wohl, E., & Merritt, D. M. (2014). Modelling the functional influence of vegetation type on streambank cohesion. *Earth Surface Processes and Landforms*, 39, 1245–1258.
- Sand-Jensen, K. (2008). Drag forces on common plant species in temperate streams: Consequences of morphology, velocity and biomass. *Hydrobiologia*, 610, 307–319.
- Schwarz, M., Cohen, D., & Or, D. (2011). Pullout tests of root anchorage and natural bundles in soil: Experiments and modelling. *Journal of Geophysical Research*, 116, F02007.
- Tal, M., & Paola, C. (2010). Effects of vegetation on channel morphodynamics: Results and insights from laboratory experiments. *Earth Surface Processes and Landforms*, 35(9), 1014–1028.
- Termini, D. (2009). Experimental observations of flow and bed processes in a large-amplitude meandering flume. *Journal of Hydraulic Engineering*, 135(7), 575–587.
- Termini, D. (2016). Experimental analysis of the effect of vegetation on flow and bed shear stress distribution in high curvature bends. *Geomorphology*, 274, 1–10.
- Termini, D. (2021). Investigation of a gravel-bed river's pattern changes: Insights from satellite images. *Applied Sciences*, 11(5), 2103.
- Termini, D., & Di Leonardo, A. (2018). Turbulence structure and implications in exchange processes in high-amplitude vegetated meanders: Experimental investigation. *Advances in Water Resources*, 120, 114–127.
- Termini, D., & Piraino, M. (2011). Experimental analysis of cross-sectional flow motion in a large amplitude meandering bend. *Earth Surface Processes and Landforms*, 36(2), 244–256.
- Waisel, Y., Eshel, A., & Kafkafi, U. (2002). *Plant roots: The hidden half*. New York, Basel: Marcel Dekker.
- Yang, Y., Chen, L., Li, N., & Zhang, Q. (2016). Effect of root moisture content and diameter on root tensile proprieties. *PLoS One*, 11(3), e0151791.