

Root characteristics of willows on waterway banks

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ABSTRACT: Shipping traffic on inland waterways can cause pressure fluctuations in the embankment, leading to shallow landslides. As the soil in the relevant parts of the embankment is almost completely saturated with porewater suction is not relevant. Therefore, roots stabilise banks primarily for mechanical reasons. However, stability analyses often do not consider mechanical root reinforcement. The retaining forces of roots of bushes and trees in a bank slope are rarely known due to a lack of information about the distribution and the characteristics of roots. Thus, the BAW investigated mechanical root reinforcement in field tests. During one summer period willow brush mattresses grew on a bank in a test basin with varying water levels. Then, pull out tests were carried out on 400 individual roots. After that, root excavations provided characteristic information including rooting depth and growth direction. Many commonly used models consider roots as a linear elastic fibre. The results of the pull-out-tests show rather a nonlinear force-displacement relationship of roots when pulled vertically. This agrees with soil-mechanical considerations. However, these vertical tests are not directly comparable to the more-dimensional effects during sliding failure.

Keywords: waterway embankment; mechanical root reinforcement

1 INTRODUCTION

In slopes and embankments, a change in pore water pressure can trigger shallow landslides. Such pressure changes are often caused by heavy rainfall (Murgia et al. 2022). On inland waterways, ship-induced water level changes can also lead to excess pore water pressure in the subsoil, causing landslides of the underwater embankment. To prevent the embankment from sliding, the BAW Code of Praxis GBB recommends stabilising the banks with additional surface weight (BAW 2011).

Roots reinforce the soil, both hydrologically and mechanically. Hence, plant-based solutions may stabilise banks through their roots. In the case of underwater landslides, the affected soil body is fully saturated, and the hydrological effects are negligible. Therefore, this paper focuses on mechanical root reinforcement.

In shallow landslides, the upper layer of soil slides downwards while the layers below remain stable. Roots growing through the shear zone lead to anchoring in stable soil layers. During sliding, they form additional retaining forces (Murgia et al. 2022).

An increase in pore water pressure decreases the effective shear strength. This can cause an embankment to become unstable (Murgia et al. 2022). In newly installed plant-based slope stabilisation systems, the roots are thin. In this case, the soil movement stretches the roots, generating tensile forces within them. The forces increase as long as the displacement continues, until the roots fail (Mao et al. 2012)

The main difficulty in estimating root reinforcement in plant-based bank protection is that neither the root

distribution in the bank nor the retaining forces provided by individual bank plants roots are known. Since willow brush mattresses develop especially strong roots, the BAW investigated this method of bank protection in a field test in 2021.

2 MATERIALS AND METHOD

The test took place on an 8 m wide embankment consisting of dense medium to coarse sand in a test basin in Karlsruhe. Loose sand was used to compensate for a declining gradient in the upper embankment area, achieving a slope inclination of 1:3. Separated by species, willow rods were laid close together on the embankment, using white willow (*Salix alba*), basket willow (*Salix viminalis*) and purple willow (*Salix purpurea*). They were fixed with wire and covered with sand (Figure 1(a)).

For 23 weeks shoots and roots grew from the rods, influenced by changing water levels in the test basin simulating a stage hydrograph of the Upper Rhine river. Thereafter, pull-out tests on roots were conducted. First, the roots were cut off at the rods and the rods were removed. Then each root was vertically pulled out of the saturated soil using a pull-out device which is shown in Figure 1(b). The device was attached to a footbridge above the test basin. During the test, a draw wire sensor measured the displacement. The tensile force was recorded, using a 200 N load cell. Afterwards, the root diameter was gauged at the upper end, and the length L_1 of the primary root section that has been pulled-out was

measured. (Figure 1(b)). The maximum pull-out force F_{max} and its corresponding displacement at maximum

pull-out force $s(F_{max})$ were automatically determined using a moving average to reduce measurement noise.

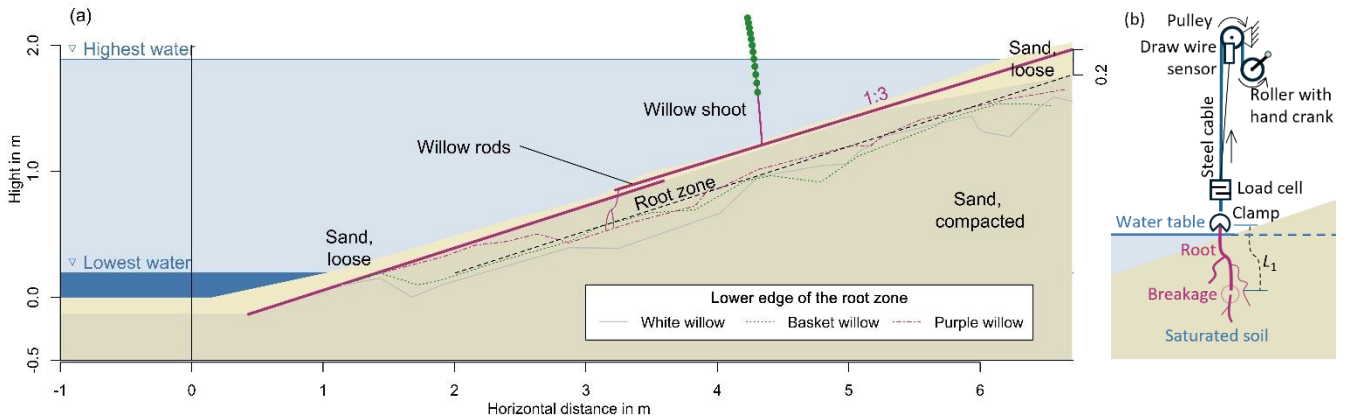


Figure 1. (a) Cross section through the test basin. (b) pull-out device

Test results were discarded if another root was intertwined with the pulled root, or if the root broke at the clamp. After data verification, 390 evaluable tests remained, including breakage failures and slippage failures.

Thereafter, data on root distribution, root diameter along root length, root orientation, and thickness of the root zone were collected during excavations.

The BAW released the data and a detailed test description under DOI: 10.48437/c598d3-52647b.

3 RESULTS AND DISCUSSION

The excavation revealed, that the roots grew either laterally or vertically. These growth directions may be due to constricted space caused by narrowly laid rods. The roots were thicker at the ends of the rods than in between the ends. This generates zones with different root contents in the embankment. Figure 1(a) shows the thickness of the rooted zone. It varies depending on the willow species and the location on the slope. The zone is located only above the lowest water table. It was thicker under the overlap of willow rods and at the upper end of the slope. Between the ends of the rods, the thickness of the root zone was only 20 cm. Presumably, the high soil density prevented a thicker root zone. Therefore, Li et al. (2025) investigated this relationship further.

The root density was evaluated at six locations. The median was 1300 roots per m^2 with a range of 900–3800 roots per m^2 .

Figure 2(a) illustrates the cross-sectional area (CSA) distribution assuming a circular root cross section calculated at the upper end of the pulled-out root. The data show a strong dominance of thin roots. Table 1 shows the range of values for the respective willow species.

Deviating from this, only a few thicker roots were pulled out. These may be outliers which can distort statistical results.

Figure 2(b) compares CSA and maximum tensile force for roots with a CSA less than 9 mm^2 . The data appear to have a proportional relationship. However, a more complex model may provide a better statistical fit. Therefore, both proportional regression and a power-law function were calculated for each species. An analysis of variance (ANOVA) compares the residual sums of squares. A significance level of $\alpha = 0.05$ was chosen for all analyses. If statistical outliers are disregarded, the difference is not significant. Hence, for thin roots, a proportional relationship may be assumed. Figure 2(b) shows the linear regressions and the range of values for which regressions have the same prediction level as a power-law function.

The proportional regressions accounts for 80%–89% of the variability in maximum tensile force. Their slopes refer to a constant maximum tensile stress σ_{max} . This is defined as the quotient of F_{max} and CSA. Thus, maximum tensile stress may be considered as a material constant. However, roots are composed of organic material whose properties, due to growth, are variable in space and time.

If maximum stress is assumed to be constant, this presumes a homogeneous material. In contrast, previous studies have suggested that roots consist of an inhomogeneous material. Its failure stress decreases with larger CSA according to a negative power-law function. However, this conclusion is challenged (Boldrin et al. 2018).

Table 1. Value range without outliers

Species	CSA [mm^2]	Diameter [mm]
White willow	≤ 2.8	≤ 1.9
Purple willow	≤ 1.3	≤ 1.3
Basket willow	≤ 3.1	≤ 2.0

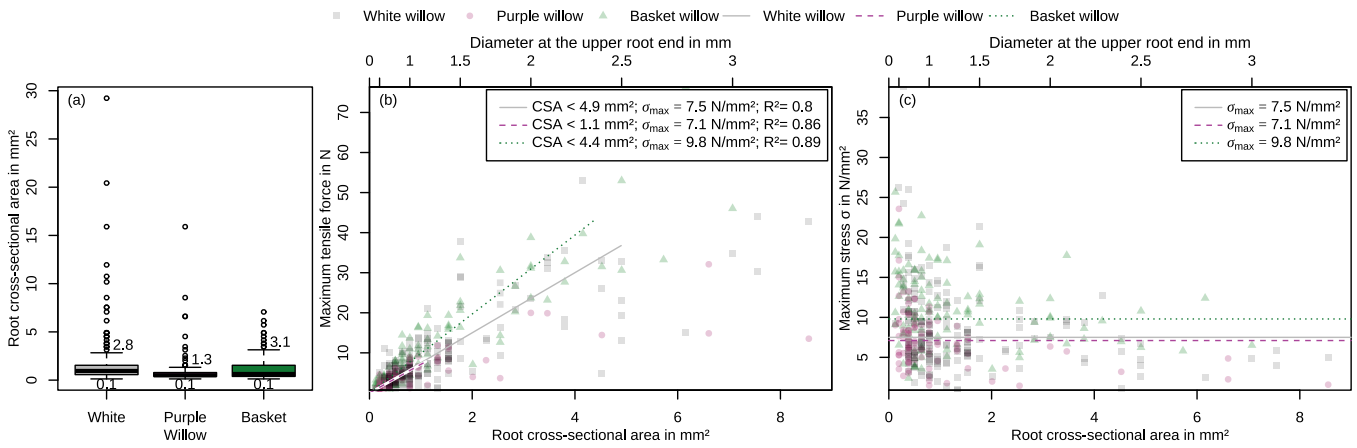


Figure 2. (a) Boxplot of cross-sectional area (CSA) at the root's upper end. (b) CSA for roots with a CSA lower 9 mm² vs. maximum tensile force and proportional regressions. (c) Maximum stress at the root's upper end vs. CSA

Based on their study of various plant species, Mao et al. (2018) concluded, that for roots of the same age and root topological order the failure stress is independent of CSA. Boldrin et al. (2018) suspected that the higher values of thinner roots could be attributed to shrinkage due to drying.

The roots in our tests were all of the same age when pulled-out of the saturated soil. They were wet when the diameter was measured. Nevertheless, the maximum stress showed extreme noise for thin roots, which over-estimates the maximum stress for thin roots (Figure 2(c)). This noise is presumably mainly a result of deformation of the roots during measurement with the calliper gauge, which has an accuracy of only 1/10 mm. Wet thin roots can easily be deformed. However, this inaccuracy is of negligible importance for predicting maximum force, if the maximum force is correlated with the CSA (Figure 2(b)).

To predict root reinforcement, both the maximum force and the displacement at which the maximum force acts must be considered. Figure 3 displays these two variables for each test. Despite high noise, the maximum force is assumed to be proportional to its corresponding displacement. An ANOVA showed that a power-law function is insignificantly different. The gradient of the regression is interpreted as an average system stiffness k of roots in soil.

The coefficient of determination R^2 shows that the proportional regressions account only for 52%–69% of the variability in maximum tensile stress. The remaining variance could be due to different interactions between roots and soil.

Roots fail due to breakage or slippage. However, only 4% of the roots failed due to slippage, each at low values of maximum force and corresponding displacement (e.g. black line in Figure 3). Therefore, slippage is of negligible importance and other factors cause the remaining variance. The curves of the broken roots differ considerably. Some roots broke once (yellow). Others

showed multiple breaks although the root was not branched (purple). Some show low stiffness (green). Others show a high one (yellow again). Stiffness often decreases with displacement (dark blue). In some cases, a plateau of maximum force is reached (light blue). Presumably, the individual root architecture causes the different curves. When a root is pulled, it transfers part of the induced tensile force to the surrounding soil. The tensile force in the root decreases with increasing depth. Breakage occurs, when the tensile stress reaches the failure stress. If the root is fully homogenous and has a uniform CSA, the tensile stress would be greatest at the top, causing failure to occur there. In reality, CSA varies with depth, so stress also varies, and failure occurs where the failure stress is first exceeded. Excavated roots showed that the CSA changes irregularly. Figure 4(a) visualises the change in diameter on 13 sample roots. In 50% of cases, the extracted part of the primary root L_1 (see Fig. 1(b)) was between 13 cm and 23 cm long. Due to the variability in CSA the location of the breaking point is unpredictable.

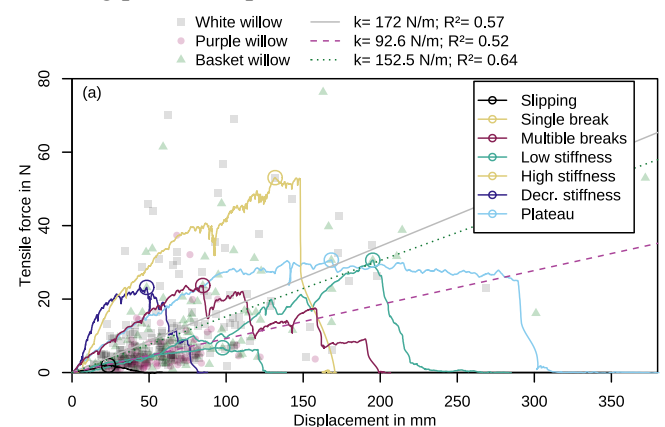


Figure 3. Maximum tensile force vs. the corresponding displacement $s(F_{max})$ of all roots (single dots), force-displacement curves of some roots using an average mean of 30 values, proportional regressions for the different willow species

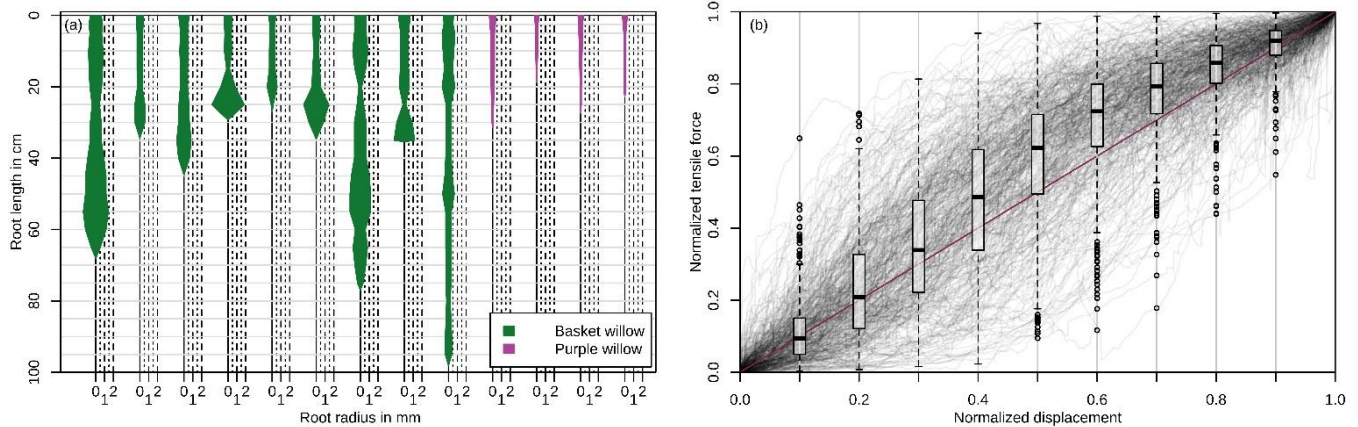


Figure 4. (a) Change in primary root radius along root length of 13 excavated roots (b) Normalized force F/F_{\max} vs. displacement $s/s(F_{\max})$ in the pull-out tests

In tensile tests, Boldrin et al. (2018) and Li and Stutz (2025) found that the stress-strain curve has a degressive trend. Figure 4(b) shows that individual roots behave very differently in the pull-out tests. Just 20% of the force-displacement curves are almost linear. At least 45% of them are degressive. In contrast, 14% are progressive. Some of the latter deviate considerably downwards from a linear progression. The data do not provide a clear indication of when the phenomenon occurs. However, horizontal root orientation was noted in a few tests. These tests showed a particularly great downward deviation. Consequently, a difference in the direction of pulling and the direction of growth may also result in a progressive curve. This should be the case regarding roots in a shear zone. Therefore, it might be difficult to determine the basal root reinforcement during shallow landslides using the data of vertical tensile tests.

4 CONCLUSIONS

During a growth period, a willow bush mattress can form a densely rooted soil layer that is at least 20 cm thick in densely compacted sandy soils. The roots are mostly thinner than 2 mm. 96% of roots broke during pull-out tests. For these roots, the maximum tensile force is proportional to the cross-sectional area. This indicates that the maximum tensile stress is constant.

However, the force-displacement curves of individual roots are highly variable. They depend on the individual root architecture and root orientation. As each root behaves differently, it is almost impossible to predict how force will be distributed among the roots when they act simultaneously. The knowledge is essential to select the best fitting calculation model (Mao et al. 2012, Meijer 2021). It is uncertain whether vertical pull-out test results can be transferred to a basal shear zone. To examine this an experiment is required that physically measures the basal root reinforcement during sliding.

5 ACKNOWLEDGEMENTS

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