Untangling the influence of soil moisture on root pullout property of alfafa plant postprint

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Abstract

Root pullout property of plants was of key importance to the soil reinforcement and the improvement of slope stability. To investigate the influence of soil moisture on root pullout resistance and failure modes in soil reinforcement process, we conducted pullout tests on alfalfa (Medicago sativa L.) roots at five levels (40, 30, 20, 10 and 6 kPa) of soil matric suction, corresponding to respectively 7.84%, 9.66%, 13.02%, 19.35% and 27.06% gravimetric soil moisture contents. Results showed that the maximal root pullout force of M. sativa decreased in a power function with increasing soil moisture content from 7.84% to 27.06%. Root slippage rate increased and breakage rate decreased with increasing soil moisture content. At 9.66% soil moisture content, root slippage rate and breakage rate was 56.41% and 43.58%, respectively. The threshold value of soil moisture content was about 9.00% for alfalfa roots in the loess soil. The maximal pullout force of M. sativa increased with root diameter in a power function. The threshold value of root diameter was 1.15 mm, because root slipping force was greater than root breaking force when diameter >1.15 mm, while diameter \$ \$1.15 mm, root slipping force tended to be less than root breaking force. No significant difference in pullout forces was observed between slipping roots and breaking roots when they had similar diameters. More easily obtained root tensile force (strength) is suggested to be used in root reinforcement models under the condition that the effect of root diameter is excluded as the pullout force of breaking roots measured in pullout tests is similar to the root tensile force obtained by tensile tests.

Full Text

Preamble

Untangling the Influence of Soil Moisture on Root Pullout Properties of Alfalfa Plants

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Abstract: The pullout properties of plant roots are critical for soil reinforcement and slope stability improvement. To investigate how soil moisture affects root pullout resistance and failure modes during soil reinforcement, we conducted pullout tests on alfalfa (*Medicago sativa* L.) roots at five soil matric suction levels (40, 30, 20, 10, and 6 kPa), corresponding to gravimetric soil moisture contents of 7.84%, 9.66%, 13.02%, 19.35%, and 27.06%, respectively. Results showed that the maximum root pullout force of *M. sativa* decreased as a power function with increasing soil moisture content from 7.84% to 27.06%. The root slippage rate increased while the breakage rate decreased with rising soil moisture content. At 9.66% soil moisture content, the root slippage and breakage rates were 56.41% and 43.58%, respectively. The threshold soil moisture content for alfalfa roots in loess soil was approximately 9.00%. The maximum pullout force increased with root diameter following a power function. The threshold root diameter was 1.15 mm, because the slipping force exceeded the breaking force when diameter >1.15 mm, while the opposite occurred when diameter $ $1.15 mm. No significant difference in pullout forces was observed between slipping and breaking roots of similar diameters. Since the pullout force of breaking roots measured in pullout tests is similar to the tensile force obtained from tensile tests, we suggest using the more easily measured root tensile force (strength) in root reinforcement models, provided the effect of root diameter is excluded.

Keywords: shallow landslides; root reinforcement; soil moisture content; threshold root diameter; root pullout force; soil conservation

1 Introduction

Slope instability arising from natural factors—including geological, topographical, climatic, and hydrological conditions—as well as human activities such as construction and unsustainable land use, not only damages surface vegetation but also triggers soil erosion, landslides, and collapses that seriously threaten human livelihoods and safety (Knapen et al., 2006). Consequently, biotechnical measures are widely employed to improve slope stability, reduce soil erosion, and accelerate vegetation restoration (Gray and Sotir, 1996). These approaches are more environmentally harmonious than traditional methods that rely primarily on masonry and sprayed concrete (Cui and Lin, 2013). Vegetation effectively stabilizes shallow landslides, typically at depths less than 2.0–3.0 m, which corresponds to the zone of plant root activity (Norris and Greenwood, 2008).

The mechanical effects of vegetation on slope protection mainly derive from soil reinforcement by shallow fibrous roots and soil anchorage by deep taproots (Liang et al., 2017a; Stubbs et al., 2019). Root-soil interactions enhance soil shear strength (Fan and Tsai, 2016; Yildiz et al., 2018). Pullout tests reveal that root-induced soil strength enhancement depends primarily on frictional resistance generated by displacement between roots and soil, which transmits and bears external loads together with the soil matrix to increase slope stability. Root failure modes during pullout include breakage and slippage (Pollen, 2007; Schwarz et al., 2010; Giadrossich et al., 2013; Giadrossich et al., 2017; Ji et al., 2018). Generally, root breakage refers to fracture into two segments at a midpoint along the root, while root slippage indicates complete or near-complete extraction from the surrounding soil. These distinct failure modes are related to the mechanical properties of plant-mediated soil reinforcement (Schwarz et al., 2010).

Differences in root morphology, root strength, and soil strength are considered fundamental causes of varying failure modes (Ennos, 1990; Dupuy et al., 2005; Mickovski et al., 2007; Schwarz et al., 2011). Additionally, the magnitude of root-soil friction significantly affects failure modes during pullout (Pollen, 2007). When a root’ s tensile resistance exceeds the friction between root and soil, slippage is more likely; otherwise, the root breaks, leaving one fractured segment extracted while the other remains in the soil (Abernethy and Rutherfurd, 2001).

Researchers have further investigated soil, root, and interaction factors including soil strength, bending forces from obstacles (e.g., stones), root diameter, length, tortuosity, branching, tensile strength, and root-soil friction (Stokes et al., 1996; Schwarz et al., 2010; Cohen et al., 2011), concluding that root failure during pulling results from combined multiple factors. Existing research shows that different plants exhibit different root pullout resistances, arising from variations in both soil strength and root diameter. Generally, thicker roots with greater tensile strength produce stronger pullout resistance (Schwarz et al., 2010), provided soil moisture around the roots is relatively low. Excessive soil moisture increases root slippage and decreases pullout resistance (Hales and Miniat, 2017). High soil moisture content also elevates soil pore pressures, considerably reducing slope stability (Hales and Miniat, 2017).

Soil moisture conditions also greatly affect root moisture content and consequently root tensile strength. Studies show that dried roots with 50% less moisture than fresh roots are over twice as strong (Hales and Miniat, 2017), likely due to root dehydration causing diameter shrinkage (Zhang et al., 2019). While soil moisture content affects pullout resistance and failure modes, the specific relationships between soil moisture content and root pullout force or failure mode remain unclear. Additionally, Pollen (2007) suggests a threshold root diameter exists during pullout: roots larger than this threshold tend to slip, while smaller roots tend to break. However, due to limited research, whether this threshold exists for other plants and the detailed relationship between threshold diameter and pullout resistance remain unknown.

Therefore, this study aimed to: (1) comprehensively evaluate the pullout properties of alfalfa (*Medicago sativa* L.), a pioneer herbaceous plant widely used for slope vegetation restoration; (2) reveal the specific relationships between soil moisture content and root pullout force and failure mode; and (3) determine the threshold root diameter and its relationship with pullout properties. This research is significant for understanding friction anchorage between roots and soils and provides a theoretical basis for biotechnical slope protection engineering.

2.1 Study Area

The experiment was conducted at the College of Water Resources Science and Engineering, Taiyuan University of Technology, Taiyuan City, Shanxi Province, China, in 2017. Taiyuan City (37°54 N, 112°33 E) is located in north-central Shanxi Province, with elevations ranging from 760 m to 2670 m above sea level and an average elevation of approximately 800 m. The annual average temperature is about 9.5°C, with an average frost-free period of 202 days. Average annual precipitation is about 400 mm, while evaporation reaches about 1800 mm. The study area has a typical continental climate with relatively dry air and low precipitation, situated in the semi-arid Loess Plateau of China.

2.2 Soil Samples

Alfalfa was planted in cubic containers measuring 50 cm in length, width, and height (Fig. 1a [Figure 1: see original paper]), as it is widely cultivated in China for high-quality forage and water/soil conservation. The planting soil was loess collected near Taiyuan City, air-dried, ground, and sieved through a 4-mm mesh. To maintain natural bulk density and uniformity, soil was filled in five 10-cm layers, achieving a bulk density of 1.37 g/cm^3 measured by the central knife method. Potted plants were grown under natural conditions for 12 months. To determine the soil moisture characteristic curve, soil matric suction was measured at 25 cm depth using a hydraulic tensiometer, with corresponding gravimetric soil moisture content measured by oven drying. Tensiometers were buried during soil loading, and moisture content samples were taken at the same depth. Three replicates of matric suction and moisture content were recorded per container on eleven occasions. To characterize alfalfa root diameter and length, 30 samples were excavated from containers. Root length was measured with a tape gauge and diameter with a vernier caliper. Alfalfa roots were taproot-shaped with few small fibrous roots, ranging from 0.44 to 1.55 mm in diameter and 5 to 30 cm in length (Fig. 1b).

2.3 In Situ Pullout Tests

Vertical in situ pullout tests were performed on alfalfa roots (Fig. 2 [Figure 2: see original paper]). Soil samples were saturated by adding water to each container 24 hours before testing. Soil matric suction was recorded daily until reaching target values of 6, 10, 20, 30, and 40 kPa, at which point pullout tests were conducted. Two failure modes were observed: root slippage and root breakage. The experimental procedure consisted of: (1) exposing a 3-cm root segment and fixing it to the clamp of a HANDPI NK-100 dynamometer (HANDPI, Yueqing Handpi Instruments Co., Ltd., China); (2) measuring root diameter three times at 1 cm from the soil surface and averaging the values (D, mm); (3) zeroing the dynamometer and pulling vertically at constant speed until root failure, recording the peak force (F, N); and (4) calculating slippage and breakage rates as the ratio of roots failing in each mode to the total tested under each matric suction. The total numbers of roots tested at 6, 10, 20, 30, and 40 kPa were 27, 29, 27, 28, and 28, respectively. To determine the threshold root diameter, additional pullout tests were conducted on 57 roots under the threshold soil moisture content where slippage and breakage rates were equal.

2.4 Data Analysis

Statistical analysis was performed using SPSS v16.0 for Windows (SPSS, Chicago, IL, USA). Relationships among variables were analyzed using linear or power law functions. Differences in maximum root pullout force among the five moisture conditions were tested by ANOVA. Figures were generated using Excel 2007.

3.1 Relationships of Soil Moisture Content with Root Slippage and Breakage Rates

A power function relationship existed between soil matric suction and gravimetric soil moisture content (Fig. 3 [Figure 3: see original paper]). Moisture contents corresponding to the five suction levels (40, 30, 20, 10, and 6 kPa) were 7.84%, 9.66%, 13.02%, 19.35%, and 27.06%, respectively. Root slippage and breakage rates were closely related to soil moisture content (Fig. 4 [Figure 4: see original paper]). Lower moisture content resulted in higher breakage rates, while higher moisture content increased slippage rates. Breakage rate decreased with moisture content following a power function ($y=3747.6x^{-1}.^{95}$, $R^2=0.9620$, $P<0.05$). Slippage and breakage rates were equal at approximately 9.00% soil moisture content, which can be considered the threshold moisture content for the two failure modes of alfalfa roots in loess soil.

3.2 Relationships of Maximum Root Pullout Force with Soil Moisture Content and Soil Matric Suction

Maximum pullout forces were 12.94 ($±0.77), 12.21(±0.83), 11.96(±0.82), 11.29(±0.64), *and*9.61(±$0.71) N at soil moisture contents of 7.84%, 9.66%, 13.02%, 19.35%, and 27.06%, respectively. Maximum root pullout force decreased linearly with increasing soil moisture content ($P<0.05$; Fig. 5a [Figure 5: see original paper]) and increased logarithmically with increasing soil matric suction ($P<0.05$; Fig. 5b). Significant differences in maximum pullout force were only observed between the 27.06% moisture content and all other moisture levels.

3.3 Relationship Between Root Diameter and Maximum Root Pullout Force

At 9.00% soil moisture content, where slippage and breakage probabilities were nearly equal, differences in root diameter and maximum pullout force between slipping and breaking roots were not significant (Table 1). Root diameter significantly affected maximum pullout force. Both slipping and breaking forces increased with root diameter following power functions. A threshold diameter of 1.15 mm was identified: breaking force exceeded slipping force at diameters <1.15 mm, while the opposite occurred at diameters >1.15 mm (Fig. 6 [Figure 6: see original paper]).

3.4 Effects of Root Diameter and Soil Moisture Content on Maximum Root Pullout Force

Both soil moisture content (F=32.703, P=0.008) and root diameter (F=13.793, P=0.025) significantly affected maximum root pullout force (Table 2). However, their interaction effect was not significant (F=2.472, P=0.248), meaning root diameter' s effect on pullout force was consistent across moisture levels, and moisture content' s effect was consistent across root diameters.

4 Discussion

Soil moisture conditions affected root pullout properties, including maximum pullout force and slippage/breakage rates. While this phenomenon has been reported previously (Giadrossich et al., 2013), the specific linear decrease of maximum pullout force with moisture content or logarithmic increase with matric suction has not been documented. Chang et al. (2018) found that maximum pullout force of *Photinia fraseri* taproots first increased then decreased with moisture content, suggesting the linear relationship observed here may not apply to other species or soil types. This is because moisture effects on pullout force depend on mechanical impacts on both soil and root systems. Increasing root moisture content causes linear diameter expansion and linear tensile strength reduction (Zhang et al., 2019), decreasing breaking root pullout force. Simultaneously, higher soil moisture reduces soil shear strength, weakening root-soil binding and decreasing slipping root pullout force. However, excessively dry soil does not necessarily increase pullout force. Extreme dryness can create soil cracks and root-soil gaps, reducing cohesion and friction (Hallett and Newson, 2005). The lowest moisture content in this study (7.84%, 40 kPa) represented water-stressed conditions without obvious soil cracking, so the low pullout force phenomenon caused by extreme drying did not occur, though it cannot be excluded in natural environments. Moderate moisture facilitates water film formation between soil particles and good root-soil integration (Harlan, 1973). The observed linear and logarithmic relationships likely exist only within a specific moisture range.

Root breakage rate was negatively correlated with soil moisture content, while slippage rate was positively correlated. A critical moisture content of approximately 9.00% (corresponding to ~30 kPa matric suction) was identified where slippage and breakage rates were equal. Above this threshold, increasing moisture raised slippage rates and reduced breakage rates, likely because excessive moisture increases pore water pressure and reduces soil cohesion, decreasing root-soil friction (Fredlund et al., 1996) and consequently reducing root reinforcement and slope stability.

The two failure modes generally exhibit different pullout forces: breakage force equals root tensile force, while slippage force depends on root-soil interface friction. Mechanical models of root reinforcement (e.g., Wu-Waldron model (Waldron, 1977; Wu, 1979), fiber bundle model (Pollen and Simon, 2005), root bundle model (Schwarz et al., 2011)) face the common question of whether to use root tensile force or pullout force. This study found no significant difference in pullout capacity between slipping and breaking roots when diameter differences were negligible (Table 1). Since breaking root pullout force primarily results from tensile force, we suggest using the more easily measured root tensile force in reinforcement models, with the precondition that root diameter effects are excluded.

Root diameter in tensile tests is typically measured near the breaking point, whereas in pullout tests it is measured at the soil surface, yielding larger values for the same root. Root tensile force generally increases with diameter following power functions (Comino and Marengo, 2010; Liang et al., 2017b; Vergani et al., 2017), as does maximum pullout force (Li et al., 2006; this study). For a given species, larger-diameter roots have greater length and soil contact area, producing stronger root-soil friction bonds. Pollen (2007) proposed a theoretical threshold diameter: above it, soil-root friction exceeds root tensile strength, causing breakage; below it, roots slip if friction bond strength is less than tensile strength, unless branching creates sufficient friction to cause breakage. This study identified the threshold diameter (1.15 mm) under moderate moisture where slippage and breakage rates were balanced. Extreme moisture levels favored only one failure mode, preventing threshold identification. Thus, failure mode was affected by the interaction of root diameter and moisture content, though maximum pullout force was not significantly influenced by this interaction.

Lateral roots are important for soil reinforcement, as demonstrated by the traction effect of *Pinus yunnanensis* lateral roots (Zhou et al., 1998). Roots with lateral branches generally show greater pullout resistance than unbranched roots (Mickovski et al., 2007). Alfalfa root systems include taproots, branch roots, creeping roots, and rhizomatous roots (Nan et al., 2014), but most alfalfa has taproots, so lateral roots were not the focus of this study. For species with abundant lateral roots, their contribution should not be ignored in pullout property investigations.

5 Conclusions

Root pullout properties are important for root reinforcement and slope stability. This study focused on soil moisture effects on alfalfa root pullout behavior. Pullout tests showed that maximum alfalfa root pullout force decreased linearly with soil moisture content or increased logarithmically with soil matric suction. Under moderate moisture conditions (30 kPa matric suction or ~9.00% moisture content), slippage and breakage probabilities were nearly equal. Lower moisture content favored root breakage, while higher moisture content promoted root slippage. Although failure mode was affected by the interaction of root diameter and moisture content, maximum pullout force was not significantly influenced by this interaction. No significant difference in pullout capacity was observed between slipping and breaking roots when diameter differences were negligible. The pullout force of breaking roots was similar to tensile force from tensile tests. Therefore, we suggest using the more easily obtained root tensile force (strength) in root reinforcement models, provided the effect of root diameter is excluded.

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