Effects of loading rate on root pullout performance of two plants in the eastern Loess Plateau, China Postprint

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Abstract

Root pullout performance of plants is an important mechanical basis for soil reinforcement by plant roots in the semi-arid areas. Studies have shown that it is affected by plant factors (species, ages, root geometry, etc.) and soil factors (soil types, soil moisture, soil bulk densities, etc.). However, the effects of loading rates on root pullout performance are not well studied. To explore the mechanical interactions under different loading rates, we conducted pullout tests on Medicago sativa L. and Hippophae rhamnoides L. roots under five loading rates, i.e., 5, 50, 100, 150, and 200 mm/min. In addition, tensile tests were conducted on the roots in diameters of 0.5–2.0 mm to compare the relationship between root tensile properties and root pullout properties. Results showed that two root failure modes, slippage and breakage, were observed during root pullout tests. All M. sativa roots were pulled out, while 72.2% of H. rhamnoides roots were broken. The maximum fracture diameter and fracture root length of H. rhamnoides were 1.22 mm and 7.44 cm under 100 mm/min loading rate, respectively. Root displacement values were 4.63% ($±0.43±0.52±0.7)and17.7(±1.8)Nunder100mm/minforM.sativaandH.rhamnoides,respectively.Valuesof
soilfrictioncoefficientunder100mm/minwassignificantlylargerthanthoseunderotherloadingratesforboth
Nunder100mm/minand173.53(±$38.53) mm • N under 200 mm/min, respectively. Root pullout force was significantly related to root diameter (P<0.01). Peak root pullout force was significantly affected by loading rates when the effect of root diameter was included (P<0.01), and vice versa. Except for the failure mode and peak pullout force, other pullout parameters, including root pullout strength, root displacement, root-soil friction coefficient, and root pullout energy were not significantly affected by loading rates (P>0.05). Root pullout strength was greater than root tensile strength for the two species. The results suggested that there was no need to deliberately control loading rate in root pullout tests in the semi-arid soil, and root pullout force and pullout strength could be better parameters for root reinforcement model compared

with root tensile strength as root pullout force and pullout strength could more realistically reflect the working state of roots in the semi-arid soil.

Full Text

Preamble

Effects of loading rate on root pullout performance of two plants in the eastern Loess Plateau, China

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Abstract: Root pullout performance of plants is an important mechanical basis for soil reinforcement by plant roots in semi-arid areas. Studies have shown that it is affected by plant factors (species, age, root geometry, etc.) and soil factors (soil types, soil moisture, soil bulk density, etc.). However, the effects of loading rates on root pullout performance are not well studied. To explore the mechanical interactions under different loading rates, we conducted pullout tests on *Medicago sativa* L. and *Hippophae rhamnoides* L. roots under five loading rates: 5, 50, 100, 150, and 200 mm/min. In addition, tensile tests were conducted on roots with diameters of 0.5-2.0 mm to compare the relationship between root tensile properties and root pullout properties. Results showed that two root failure modes—slippage and breakage—were observed during root pullout tests. All *M. sativa* roots were pulled out, while 72.2% of *H. rhamnoides* roots were broken. The maximum fracture diameter and fracture root length of *H. rhamnoides* were 1.22 mm and 7.44 cm under the 100 mm/min loading rate, respectively. Root displacement values were 4.63% ($±0.43±0.52±0.7)Nand17.7(±1.8)Nunder100mm/minfor*M.sativa* and * H.rhamnoides*, respectively.Themaximumpulloutstrengthvaluesfor * M.sativa*and*H.rhamnoides*were38.38(±5.48)MPaunder150mm/minand12.47(±1.43)MPaunder100mm/
soilfrictioncoefficientunder100mm/minwassignificantlylargerthanthoseunderotherloadingratesforboths
M.sativa*and*H.rhamnoides*were87.83(±21.55)mm·Nunder100mm/minand173.53(±$38.53) mm · N under 200 mm/min, respectively.

Root pullout force was significantly related to root diameter (P<0.01). Peak root pullout force was significantly affected by loading rates when the effect of root diameter was included (P<0.01), and vice versa. Except for the failure mode and peak pullout force, other pullout parameters—including root pullout strength, root displacement, root-soil friction coefficient, and root pullout energy—were not significantly affected by loading rates (P>0.05). Root pullout strength was greater than root tensile strength for both species. The results suggest that there is no need to deliberately control loading rate in root pullout tests in semi-arid soil, and root pullout force and pullout strength could be better parameters for root reinforcement models compared with root tensile strength, as root pullout force and pullout strength could more realistically reflect the working state of roots in semi-arid soil.

Keywords: plant roots; soil reinforcement; loading rate; root pullout properties; root-soil interaction; loess area

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1 Introduction

Exposed to water, wind, and other external forces, soil slopes are susceptible to erosion and unstable events. Soil erosion has become one of the most serious eco-environmental problems in China and other countries, with soil erosion in the arid and semi-arid areas of the Chinese Loess Plateau being particularly prominent. Controlling soil erosion and protecting unstable slopes with vegetation is becoming increasingly popular (Mickovski and Ennos, 2003; De Baets et al., 2006; Peng and Lin, 2013). The beneficial hydrological effects of vegetation on slope protection mainly include the interception of rainfall, the reduction of splash erosion by raindrops, and the control of surface runoff (Ruan et al., 2022; Simon and Collison, 2002). Besides, plant roots can mechanically reinforce soil and improve slope stability (De Baets et al., 2008; Cislaghi et al., 2021; Spiekermann et al., 2021).

The mechanical effects of plant roots on soil consist of the reinforcement of shallow soil by fine and shallow roots (Wang et al., 2015), the anchorage by coarse and deep roots (Reubens et al., 2007; Stubbs et al., 2019), and the traction by lateral roots (Abdi et al., 2009; Zhang et al., 2014). The strengthening effect of roots on soil is primarily due to friction at the root-soil interface and root anchorage against soil shear deformation. In shallow soil, the root system strengthens soil through complex mechanical interactions between roots and soil to enhance soil shear strength (Operstein and Frydman, 2000; Pollen and Simon, 2005). Under certain stress conditions, the root system would start to slip out of soil or show a tendency to slip. Friction against slippage is then generated at the root-soil interface, which combines root tensile strength with soil shear strength and improves the strength of the root-soil composite (Cohen et al., 2011; Fan and Tsai, 2016; Yildiz et al., 2018).

Due to the complexity of plant root structure and root-soil interaction, it is difficult to quantify the ability of roots to reinforce soil and stabilize slopes. Existing comprehensive models of root reinforcement generally take into account root geometry, root mechanical properties, and root-soil mechanical interactions (Dupuy et al., 2005; Schwarz et al., 2010a). As one of the most important parameters of root mechanical properties, root tensile strength has been widely studied (Leung et al., 2015; Giadrossich et al., 2016; Zhang et al., 2019). These studies have focused on the measurement of root tensile strength, the exploration of root failure mechanisms, and the quantification of root-soil interaction (Abernethy and Rutherfurd, 2001; Mickovski et al., 2007).

Root pullout properties, which aim to characterize root-soil interaction, have also been extensively explored. Existing research has shown that root pullout force is affected by root length, root branching pattern, root curvature, and soil moisture content (Mattia et al., 2005; Stokes et al., 2009; Mickovski et al., 2010; Zhang et al., 2020a). The root-soil friction coefficient largely depends on soil type and soil water content (Schwarz et al., 2010a). The action of root-soil friction results in different failure modes of roots in pullout tests. For example, small roots tend to break under dry conditions but slip out under wet conditions in cohesive soils (Pollen, 2007; Schwarz et al., 2011). When the pullout force on roots exceeds the maximum static friction between roots and soil, the roots tend to slide gradually, and the friction changes from static friction to sliding friction (Schwarz et al., 2010a). Roots are likely to break when root pullout force is greater than the maximum root tensile force, or be pulled out when root pullout force is smaller than the maximum root tensile force (Leung et al., 2018).

Many researchers have studied factors that affect root pullout characteristics, such as root diameter, root length, root bifurcation, and soil moisture content (Osman et al., 2011). However, most have focused only on the effect of these factors on peak pullout force. For example, peak pullout force of plant roots increases with root diameter, root length, and the number of lateral roots (Schwarz et al., 2010b; Ji et al., 2018). Under certain conditions, root pullout force decreases with soil water content in a power function (Zhang et al., 2020b). However, few studies have focused on root pullout energy, which can be used to show the ability of the root system to resist external forces during the pulling process and can reflect the reinforcing effect of the root system on soil shear strength from an energy perspective.

The ability of plant roots to protect slopes varies with plant species, and the performance of root-soil interactions of different plant roots can be evaluated through root pullout tests. Roots for in situ pullout tests can be exposed by trenches dug around plants (Norris, 2005; Vergani et al., 2016) or by high-pressure water/air (Marden et al., 2005; Giadrossich et al., 2017). Various chucks and stretching devices are used to pull out roots (Abernethy and Rutherfurd, 2001; Docker and Hubble, 2008; Schwarz et al., 2011). Nevertheless, almost no device can control the loading rate of root pulling except for the device used by Schwarz et al. (2011), and no results have been reported about the specific effect of loading rate on root reinforcement. In reality, plant roots are subjected to complex loads including runoff and wind. Landslides or slope failures triggered by rainfall and/or wind generally occur at rates ranging from 1 to 300 mm/min (Liu and Shih, 2013; Hungr et al., 2014; Iverson et al., 2015). Root tensile properties are affected by loading rates, with existing research showing that plant roots stretched at larger tensile rates exhibit greater root tensile strengths (Cofie and Koolen, 2001; Zhang et al., 2012), and roots could break more easily under larger loading rates (Ji et al., 2018). However, there is a lack of in-depth research on the effect of loading rate on root-soil interaction, which could limit the smooth and accurate conduct of root pullout tests.

Therefore, the aims of this study were: (1) to investigate how loading rates affect root pullout properties, including maximum displacement, peak pullout force, root-soil friction coefficient, and root pullout energy; (2) to discuss root failure modes, fracture root length, and diameter of pulled roots under different loading rates; and (3) to suggest a suitable loading rate for root pullout tests in semi-arid areas. This study can provide a reference for better understanding the effects of test methods on the measurement of root-soil interaction and support the evaluation of soil reinforcement by plant roots.

2.1 Study Area

This study was carried out in Taiyuan City (37°27 –38°25 N, 111°30 –113°09 E), located in the eastern Loess Plateau of China with an annual average temperature of 9.5°C. Monthly average temperatures range from –6.4°C in January to 23.0°C in July. The altitude ranges from 760 to 2670 m a.s.l., with an average value of approximately 800 m a.s.l. The study area has a typical continental climate with relatively dry air and low precipitation. Annual precipitation is 468.4 mm, and average annual evaporation is 1644.9 mm. Precipitation is mainly concentrated from June to August.

2.2 Preparation of Samples

Soil used in the experiment was taken from Juewei Mountain in the northwest of Taiyuan City. After being air-dried and crushed in the laboratory, it was sieved with a 3-mm sieve for preparation. The soil was a sandy loam. Roots of *Medicago sativa* L. and *Hippophae rhamnoides* L. were collected from cultured plants in cultivation boxes (50 cm × 50 cm × 50 cm) containing the soil. *M. sativa* is a perennial herbaceous plant, and *H. rhamnoides* is a deciduous shrub. Due to their strong resistance to low temperature and drought, they are widely planted and have become pioneer plants for ecological, water, and soil conservation in the arid and semi-arid areas of the Loess Plateau, China. We placed the boxes in a natural environment and watered 0–2 times weekly according to rainfall conditions. After growing for 4 months, the roots were excavated using a water flushing method. Healthy and intact root samples were selected and trimmed to a length of 16.0 cm for root pullout and tensile tests. Root diameter was measured using a digital vernier caliper with an accuracy of 0.03 mm. Roots were marked every 40 mm and measured three times per marked position to obtain the average root diameter. They were stored in a refrigerator at 4°C to maintain freshness.

Remolded soil samples embedding the roots were prepared for root pullout tests (Fig. 1 [Figure 1: see original paper]). The sandy loam was filled and compacted in five layers in cubic iron test chambers (200 mm × 200 mm × 200 mm) at soil densities of 1.45 g/cm^3 (*M. sativa*) and 1.43 g/cm^3 (*H. rhamnoides*) using the WDW-5 electronic universal testing system (UTS, Changzhou Sanfeng Instrument Technology Co., Ltd., Changzhou, China). The boxes had two removable plates, one of which had a narrow gap (60 mm × 10 mm) in the center for exposing the roots. Compaction speed was 50 mm/min. During compaction, two 16.0 cm-length roots (free length 4.0 cm + buried length 12.0 cm) were placed vertically into the narrow gap of each box (root burial angle 90°) at a spacing of 60 mm when the soil was loaded to the second layer. The surface of each preceding soil layer was roughened before adding a new soil layer. Soil water content of the remolded samples was 9.74% (*M. sativa*) and 8.44% (*H. rhamnoides*) as determined by the oven-dry method.

In this study, the diameter ranges of *M. sativa* and *H. rhamnoides* were 0.5–1.0 mm and 0.8–2.0 mm, respectively. Remolded samples were stored for 24 h at 4°C before root pullout tests to ensure firm bonds between roots and soil.

Fig. 1 Pullout tests were conducted on roots embedded in remolded samples. (a) Remolded samples; (b) Root pullout test.

2.3 Root Pullout Tests

Root pullout tests were conducted on the remolded soil samples using a WDW-5 UTS connected with an SH-200 digital force gauge (SUNDOO, Foshan Zhunce Electronics Co., Ltd., Foshan, China). A total of 44 roots of *M. sativa* and 43 roots of *H. rhamnoides* were tested. A 20 mm-wide medical tape was wrapped around the free end of the roots to prevent slippage or breakage during the pulling process. The free end of the roots in remolded samples was first fixed in the clamp of the force gauge. After setting the reading of the force gauge to zero, the root was then pulled under a set loading rate (Fig. 1b). Five loading rates—5, 50, 100, 150, and 200 mm/min—were used in this study. They were all within the landslide rate range, which can be used to reflect the performance of root systems during landslides. After the root was completely pulled out or broken, data including peak pullout force, fracture root diameter, fracture root length, and force-displacement curve were recorded and saved. Fracture root length was the distance between the upper clamp and fracture point. Fracture root diameter was the average value of root diameter at a distance of 10 mm near the fracture point of the two fractured root segments after fracture. Root displacement was the change in position of the root from its initial position in soil to its final failure position. Parameters of root pullout properties, including pullout strength (PR; MPa) and root-soil interface friction coefficient (; Xie, 1990), were calculated as follows:

$$PR = \frac{F_p}{\pi D^2/4}$$

where F_p is the peak root pullout force (N) and D is the average root diameter (mm).

$$\mu = \frac{F_p}{\gamma_s L \cos(\theta)}$$

where γ_s is the soil bulk density (g/cm^3), L is the root burial depth (cm), and θ is the root burial angle (rad).

Root pullout energy (V_ε; mm · N) is the work done by external force when the peak pullout force is reached, which is:

$$V_\varepsilon = \int_0^x \frac{F(x)}{d}\, dx$$

where $F(x)$ is the curvilinear relationship between pullout force and displacement before peak pullout force, x is the displacement before the peak pullout force (mm), and d is the root diameter (mm). Root pullout energy can be used to show the ability of the root system to resist external forces during the pulling process and can reflect the reinforcing effect of the root system on soil shear strength from an energy perspective.

2.4 Root Tensile Tests

The purpose of root tensile tests was to estimate the strength of individual roots and compare it with the strength measured in root pullout tests. Roots selected for tensile tests had similar diameters as those in the root pullout tests. Root tensile tests were conducted on 16.0 cm-length roots of both species using the WDW-5 UTS. To decrease rupture and slippage at the clamping position, we wrapped 20 mm-wide medical tape at each end of the roots before testing. Stretching speed was 100 mm/min. The peak tensile force and corresponding root deformation of each test were measured and recorded. Only data from roots broken away from the clamps were regarded as valid. A total of 21 roots of *M. sativa* and 37 roots of *H. rhamnoides* were successfully tested. Root tensile strength (TR; MPa) was calculated by:

$$TR = \frac{F_T}{\pi D^2/4}$$

where F_T is the peak root tensile force (N).

Root elastic modulus (E; MPa) was calculated by:

$$E = \frac{F_T}{\pi D^2/4 \cdot \varepsilon}$$

where ε is the root elongation (%), equal to root deformation at failure divided by the original gauge length (160 mm).

2.5 Data Analysis

Data were analyzed using SPSS 2020. One-way analysis of variance (ANOVA) was used to evaluate the influence of species and loading rates on fracture diameter, fracture length, displacement, root-soil friction coefficient, peak pullout force and strength, and pullout energy. Analysis of covariance (ANCOVA) was used to analyze differences in root pullout performance under different loading rates. Significant influence of loading rates and species on root pullout properties was tested at the P<0.05 level. Correlation analysis was carried out on pullout properties and affecting factors, loading rate, and root diameter. Graphs were plotted using OriginPro 2016.

3.1 Fracture Root Diameter and Fracture Root Length

In this study, 39 roots of *M. sativa* and 36 roots of *H. rhamnoides* were successfully tested. No significant difference in root diameter existed between tested samples under different loading rates (Table 1). All *M. sativa* roots exhibited slippage failure, while 26 *H. rhamnoides* roots exhibited breakage failure. This indicates that the failure mode of *M. sativa* roots is mainly sliding failure, while that of *H. rhamnoides* roots is mainly breakage failure. Most slippage failures of *H. rhamnoides* roots occurred under the 100 mm/min loading rate.

Table 1 Root diameters of different species used in the pullout tests

<table>
<tr><th>Species</th><th>Loading rate (mm/min)</th><th>Number of roots successfully tested</th><th>Average root diameter (mm)</th></tr>
<tr><td><i>Medicago sativa</i> L.</td><td>5</td><td>7</td><td>0.72$±0.06<i>a</i>|||50|8|0.74±0.04<i>a</i>|||100|8|0.72±0.05<i>a</i>|||1 <i>Hippophaerhamnoides</i>∗ <i>L</i>.|5|7|1.35±0.13<i>a</i>|||50|7|1.37±0.13<i>a</i>|||100|7|1.37±0.0</td></tr>
</table>

Note: Different lowercase letters within the same column indicate significant differences among different loading rates at P<0.05 level. Mean±SD.

Fracture root diameter of *H. rhamnoides* did not change significantly among different loading rates (Fig. 2 [Figure 2: see original paper]). Fracture root length under the 150 mm/min loading rate was significantly smaller than that under the 100 mm/min loading rate (Fig. 2b). The maximum fracture diameter and fracture length were 1.22 mm and 7.44 cm, respectively, both observed under the 100 mm/min loading rate.

Fig. 2 Fracture diameter (a) and fracture length (b) of *Hippophae rhamnoides* roots under different loading rates. Different lowercase letters indicate significant differences among different loading rates at P<0.05 level. Bars are standard errors.

3.2 Root Displacement

Differences in root displacement at peak pullout force were not significant among different loading rates. Root displacement was 4.63% ($±0.43±$0.52%) of the total root length for *M. sativa* and *H. rhamnoides*, respectively. Root displacement of *H. rhamnoides* was about twice that of *M. sativa* (Fig. 3 [Figure 3: see original paper]). This could be mainly attributed to large differences in root displacement due to the different root diameters of the two plants.

Fig. 3 Root displacement of *Medicago sativa* and *Hippophae rhamnoides* under different loading rates. Different lowercase letters indicate significant differences among different loading rates at P<0.05 level. Different uppercase letters indicate significant differences between two species at P<0.05 level. Bars are standard errors.

3.3 Peak Root Pullout Force and Root Pullout Strength

Peak root pullout force increased from 5 to 100 mm/min and then decreased from 100 to 200 mm/min for both *M. sativa* and *H. rhamnoides*. The maximum pullout force values were 14.58 ($±0.72)Nand17.68(±1.82)Nunderthe100mm/minloadingratefor∗ M.sativa ∗ and ∗ H.rhamnoides∗, respectively.Peakpulloutforceof ∗ H.rhamnoides ∗ was12.20(±$5.40) N, which was greater than that of *M. sativa*. Significant difference in peak pullout force was only observed under the 5 mm/min loading rate for *M. sativa*, while no significant difference in peak pullout force was observed among different loading rates for *H. rhamnoides* (Fig. 4 [Figure 4: see original paper]). The peak pullout force of *H. rhamnoides* was greater than that of *M. sativa* under all loading rates except 150 mm/min.

Root pullout strength varied with loading rate for both *M. sativa* and *H. rhamnoides* (Fig. 4b). The maximum pullout strength was 38.38 ($±5.48)MPafor∗ M.sativa ∗ underthe150mm/minloadingrateand12.47(±$1.43) MPa for *H. rhamnoides* under the 100 mm/min loading rate. Root pullout strength of *M. sativa* was significantly greater than that of *H. rhamnoides*.

Fig. 4 Root peak pullout forces (a) and strengths (b) of *Medicago sativa* and *Hippophae rhamnoides* under different loading rates. Different uppercase letters indicate significant differences between two species at P<0.05 level. Different lowercase letters indicate significant differences between loading rates at P<0.05 level. Bars are standard errors.

For *H. rhamnoides*, root slippage force and breakage force increased with root diameter in power functions (Fig. 5 [Figure 5: see original paper]), and root pullout strength decreased with root diameter in power functions (Fig. 5b).

Peak root pullout force and root pullout strength of slippage roots were greater than those of breakage roots. This was primarily due to the difference between sliding failure and breakage failure mechanisms of the root system.

Fig. 5 Correlation of root pullout force (a) and root pullout strength (b) of *Hippophae rhamnoides* roots in breakage and slippage failure with root diameter.

3.4 Root-Soil Friction Coefficient

Root-soil friction coefficient of *M. sativa* and *H. rhamnoides* increased from 5 to 100 mm/min loading rate and then decreased from 100 to 200 mm/min loading rate. The root-soil friction coefficient under the 100 mm/min loading rate was significantly larger than those at other loading rates for both species (Fig. 6 [Figure 6: see original paper]). Root-soil friction coefficient was significantly different among different loading rates for *M. sativa*, but not significantly different among different loading rates for *H. rhamnoides*. *M. sativa* had a significantly greater root-soil friction coefficient than *H. rhamnoides*.

3.5 Root Pullout Energy

Root pullout energy of *M. sativa* and *H. rhamnoides* did not change significantly with loading rate (Fig. 6b). The maximum root pullout energy of *M. sativa* and *H. rhamnoides* was 87.83 (\$±21.55)$mm \cdot Nunderthe100mm/minloadingrateand173.53(\pm$\$38.53) mm • N under the 200 mm/min loading rate, respectively. *H. rhamnoides* had significantly greater root pullout energy than *M. sativa*.

Fig. 6 Root-soil friction coefficients (a) and root pullout energy (b) of *Medicago sativa* and *Hippophae rhamnoides* under different loading rates. Different lowercase letters indicate significant differences between loading rates at P<0.05 level. Different uppercase letters indicate significant differences between species at P<0.05 level. Bars are standard errors. Boxes in figure 6b indicate the IQR (interquartile range, 75th to 25th percentile of the data). The median value is shown as a line within the box. Black square shows the mean. Whiskers extend to the most extreme value within 1.5×IQR.

3.6 Root Tensile Properties

Root tensile properties were significantly different between root diameter classes (P<0.05; Fig. 7 [Figure 7: see original paper]). For both species, root tensile force increased while root tensile strength and elastic modulus decreased with root diameter (Fig. 7). *M. sativa* showed higher root tensile properties than *H. rhamnoides*.

Fig. 7 Tensile force and strength (a) and elastic modulus (b) of roots in different diameter classes. Different lowercase letters indicate significant differences among different diameter classes at P<0.05 level. Different uppercase letters indicate significant differences between species at P<0.05 level. Bars are standard errors.

3.7 Comparison of Root Tensile Properties and Root Pullout Properties

Under the 100 mm/min loading rate, peak root pullout force and root tensile force were positively correlated with root diameter in power functions for *M. sativa* (Fig. 8 [Figure 8: see original paper]) and *H. rhamnoides* (Fig. 8b), while root pullout strength and root tensile strength were negatively correlated with root diameter for *M. sativa* (Fig. 8c) and *H. rhamnoides* (Fig. 8d). It can be seen that the peak pullout force and pullout strength, as well as the tensile force and tensile strength of the roots, are related to root diameter. Besides, the effect of root diameter may be more pronounced under the 100 mm/min loading rate.

Fig. 8 Correlation of root pullout force and root tensile force with root diameter for *Medicago sativa* (a) and *Hippophae rhamnoides* (b), and correlation of root pullout strength and root tensile strength with root diameter for *Medicago sativa* (c) and *Hippophae rhamnoides* (d).

Mean root pullout strengths of *M. sativa* and *H. rhamnoides* were 35.18 ($±1.78)*MPaand*10.78(±$0.63) MPa, respectively. Mean root strength obtained from pullout tests was considerably greater than that obtained from tensile tests. This is expected because the force required to induce failure in pullout tests was considerably higher than that in tensile tests for roots with the same diameter in sandy loam.

3.8 Correlation of Root Diameter and Loading Rate with Root Pullout Performance

No significant correlation was observed between loading rate and pullout parameters (Table 2). Correlations between root diameter and parameters varied with species. For *H. rhamnoides*, root diameter was only significantly correlated with peak pullout force and pullout strength. For *M. sativa*, root diameter was correlated with root-soil friction coefficient as well as peak pullout force and pullout strength. Besides, a positive correlation existed between peak root pullout force and fracture root diameter for *H. rhamnoides.* Root displacement was negatively related to fracture root diameter. No significant relationship was observed between pullout performance and fracture root length.

Table 2 Correlation coefficients of root diameter and loading rate with pullout performance of *Medicago sativa* and *Hippophae rhamnoides* roots

Parameter	*Medicago sativa*		*Hippophae rhamnoides*			
	Loading rate	Root diameter	Loading rate	Root diameter	Fracture root diameter	Fracture root length
Root displacement	-0.422*	—	—	—	—	—
Peak pullout force	0.627**	0.718**	—	0.603**	-0.809**	-0.544**
Pullout strength	0.379*	-0.435**	—	—	—	—
Root-soil friction coefficient	—	—	—	—	—	—
Pullout energy	—	—	—	—	—	—

Note: , P<0.05 level; **, P<0.01 level. Dashes indicate no significant correlation.*

Considering the effect of root diameter, ANCOVA was used to study the effect of different loading rates on root pullout performance. Peak pullout force was significantly different among different loading rates for *M. sativa* (F=4.62, P=0.005) and *H. rhamnoides* (F=2.71, P=0.049), but root pullout strength was not significantly different for *M. sativa* (F=1.98, P=0.120) and *H. rhamnoides* (F=2.13, P=0.102). Besides, root-soil friction coefficient was significantly different for *M. sativa* (F=3.61, P=0.015) but not significantly different for *H. rhamnoides* (F=2.62, P=0.055).

4.1 Root Failure Modes

In this study, all *M. sativa* roots were pulled out, while 72.2% of *H. rhamnoides* roots were broken. Root tensile strength of *H. rhamnoides* was significantly lower than that of *M. sativa*, which mainly resulted from differences in root diameter between the two species, as their root tensile forces were not significantly different. This was the main reason that *H. rhamnoides* roots were easier to break than *M. sativa* roots. Two root failure modes were observed during root pullout tests in this study: breakage failure and slippage failure, similar to phenomena found in other research (Pollen, 2007; Schwarz et al., 2010a). Generally, roots exhibit breakage failure when root tensile force is less than the maximum root-soil friction force. Conversely, roots tend to exhibit slippage failure (Pollen, 2007; Leung et al., 2018). Root pullout force is determined not only by friction between the root system and soil but also by root tension resistance (Osman et al., 2011). Besides, root failure in tensile tests is likely initiated at weak points within roots, which are prone to stress concentration (Hales et al., 2013; Wang et al., 2019). Root tensile strength is the maximum tensile force that a root system per unit area can bear before breaking (Genet et al., 2005), and root pullout strength reflects the maximum friction force between the root system and soil per unit area of roots (Norris, 2005; Giadrossich et al., 2013). These reasons could usually result in lower root tensile strength than pullout strength, as observed in this study, where root pullout force and pullout strength of *M. sativa* and *H. rhamnoides* were greater than root tensile force and tensile strength.

Some studies have shown that fine roots are more likely to break into segments, while thick roots are easier to pull out in pullout tests (Pollen, 2007; Schwarz et al., 2010a), which is not consistent with our results. The reason for this phenomenon may be that root-soil friction is affected by complex factors like curvature and elasticity of roots, as well as root length and number of root branches (Schwarz et al., 2010a; Cohen et al., 2011; Schwarz et al., 2011). Mechanical models of root reinforcement, such as the Wu-Waldron model (Waldron, 1977; Wu et al., 1979) and root bundle model (Schwarz et al., 2011), involve root tensile force or root pullout force. These are generally measured by root tensile tests and root pullout tests and can differ even for the same roots. Besides, significant differences in pullout force could exist between slippage roots and breakage roots in pullout tests. To make root reinforcement models more comprehensive and practical, we considered root pullout force and root pullout strength in the models instead of root tensile force and root tensile strength.

4.2 Effects of Root Diameter and Loading Rate on Root Pullout Behavior

Root peak pullout force and strength were relatively less affected by loading rate and depended mainly on root diameter. The negative correlation between root pullout strength and root diameter is consistent with the relationship between root tensile strength and root diameter (Osman et al., 2011). The observed specific relationship that root-soil friction coefficient decreased with root diameter has not been previously reported. The possible reason is that increases in root diameter cause changes in root surface unevenness as the root system grows. *M. sativa* roots had larger diameters and could have smoother surfaces, resulting in decreased friction coefficient. The presence of nodes or microscopic features on root bark might have a greater effect on root-soil friction coefficient than root diameter. Nevertheless, no such results are currently available, and future studies are needed.

Roots with larger diameter generally have higher cellulose content (Genet et al., 2005) and lower limited root elongation. Roots loosen more rapidly during pullout tests, which is part of the reason for the decrease in displacement with root diameter. Variation in root displacement in pullout tests is also inseparable from soil conditions. For example, Schwarz et al. (2011) showed that root displacement at peak pullout force increased with increasing size of dominant root diameter in a bundle of roots. The relationship between root diameter and root pullout energy was not obvious.

Loading rates affected the failure mode of roots. Roots broke at different distances under different loading rates, while the location of root damage was relatively fixed due to very similar fracture diameters. The maximum peak pullout forces of the two plants were observed at the 100 mm/min loading rate. No statistically significant difference in peak pullout force was observed among different loading rates when the effect of root diameter was included, which is similar to a previous study (Ji et al., 2018). However, peak pullout force was significantly affected by loading rates when the effect of root diameter was excluded. Except for failure mode and peak pullout force, other pullout parameters—including root pullout strength, root displacement, root-soil friction coefficient, and root pullout energy—were not significantly affected by loading rates. Greater values of pullout force, root-soil friction coefficient, and pullout energy were observed under the 100 mm/min loading rate in this study. Loading rates greater or smaller than 100 mm/min resulted in decreased root pullout force (strength) that could be conservative for estimates of root reinforcement and slope stability analysis. Based on these findings, if the conditions and instruments of root pullout tests are limited, there is no need to deliberately control loading rate in root pullout tests due to its insignificant effect on root pullout properties. In this study, influencing factors such as soil type, soil water content, and root length were fixed, and the range of root diameter of the two species was relatively limited. Therefore, the effect of loading rate on root pullout performance under other conditions should be deeply analyzed in future research.

5 Conclusions

To explore whether pullout performance of herbaceous plants and shrubs is affected by loading rates, we carried out laboratory pullout tests on the roots of *M. sativa* and *H. rhamnoides*. Results showed that two root failure modes—slippage and breakage—were observed during root pullout tests. Modes were affected by loading rates, as well as by mechanical properties of plant roots and root-soil interaction. Root pullout force was significantly related to root diameter. Peak root pullout force was significantly affected by loading rates when the effect of root diameter was included, and vice versa. Except for failure mode and peak pullout force, other pullout parameters—including root pullout strength, root displacement, root-soil friction coefficient, and root pullout energy—were not significantly affected by loading rates. For these two species, root pullout strength was greater than root tensile strength. Results suggest that there is no need to deliberately control loading rate in root pullout tests, and root pullout force and pullout strength could be better parameters for root reinforcement models compared with root tensile force and tensile strength, as root pullout force and pullout strength could more realistically reflect the working state of roots in soil.

Conflict of 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.

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