Postprint: Response of Salix psammophila Straight Root Tensile Properties to Cyclic Loading

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Date: 2022-06-02T00:00:00+00:00

Abstract

To reveal the soil reinforcement performance of plants in wind erosion areas after long-term exposure to strong winds causing repeated loading on their root systems, Salix psammophila, a widely distributed soil and water conservation plant species in the Shendong mining area, was selected as the research subject. Axial cyclic loading tests were conducted on 1-5 mm diameter class Salix psammophila taproots using a TY8000 servo-controlled universal testing machine to investigate the response of taproot tensile properties to repeated loading-unloading effects simulated by wind pulling. The results showed that: (1) After undergoing cyclic loading, the ultimate tensile force of taproots was positively correlated with root diameter by a power function, while tensile strength was negatively correlated with root diameter by a power function, similar to the relationships between taproot tensile force, tensile strength, and root diameter under single loading. (2) After cyclic loading, the tensile force and tensile strength of taproots across all diameter classes were enhanced compared with single loading, with significant differences ($P<0.05$). The tensile force and tensile strength of 1-2 mm, 2.5-3.5 mm, and 4-5 mm taproots increased by 60% and 60%, 48% and 50%, and 31% and 32%, respectively. (3) The force-displacement curves of taproots exhibited obvious periodic cyclic characteristics during the cyclic process. With increasing cycle number, the spacing between hysteresis loops gradually closed, and the area of hysteresis loops formed by loading-unloading curve segments consequently decreased, indicating diminishing capacity to resist plastic deformation that eventually stabilized. The cumulative elongation rate of taproots increased with cycle number, which could be divided into a rapid growth stage and a slow growth stage. (4) After both single and cyclic loading, elastic stress, ultimate stress, and elastic modulus of taproots were negatively correlated with root diameter, while cumulative elastic strain and ultimate strain showed no relationship with root diameter. After cyclic loading, elastic stress, ultimate stress, and cumulative elastic strain increased significantly, whereas ultimate strain showed the pattern: single loading > cyclic loading, and elastic modulus exhibited no regular pattern under different loading conditions. In summary, after undergoing low-cycle cyclic loading of erosion forces to a certain degree, Salix psammophila root systems can better adapt to the external environment, enhance resistance to erosion forces, and are more conducive to exerting soil-fixing effectiveness.

Full Text

Response of Salix psammophila Straight Root Tensile Properties to Cyclic Loading

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Abstract

To clarify the mechanical properties of straight roots in response to repeated loading and unloading induced by simulated high wind drawing, axial cyclic load tests were applied to straight roots of *Salix psammophila*. These roots had diameters ranging from 1-5 mm, with specific testing focused on the 2.5-3.5 mm and 4-5 mm classes, using a TY8000 servo-controlled testing machine. The objective was to reveal the soil-fixing ability of plants in wind-eroded areas after their roots experienced repeated stressing by strong long-term winds. Results show the following: (1) The tensile force of straight roots after cyclic loading was positively correlated with diameter based on a power function relationship; the tensile strength after cyclic loading was negatively correlated with root diameter based on a power function, similar to the relationship between tensile force, tensile strength, and root diameter under monotonic load. (2) Compared with monotonic loading, the tensile force and tensile strength after cyclic loading of straight roots across all diameter classes were significantly enhanced ($P < 0.05$). Specifically, the tensile force and tensile strength of 1-2 mm roots increased by 60% and 60%, respectively; for 2.5-3.5 mm roots, the increases were 48% and 50%; and for 4-5 mm roots, the increases were 31% and 32%. (3) During the cycling process, the force-displacement curve of straight roots showed obvious cyclic characteristics with increasing cycle number; the hysteresis loop spacing gradually closed while the area decreased, indicating that the capacity to resist plastic deformation became weaker but tended toward stability. The accumulated elongation of straight roots increased with cycle number and could be divided into a rapid growth stage and a slow growth stage. (4) The elastic stress, ultimate stress, and elastic modulus of straight roots were negatively correlated with root diameter after both monotonic and cyclic loading, while the accumulated elastic strain and ultimate strain showed no relationship with root diameter. The elastic stress, ultimate stress, and accumulated elastic strain after cyclic loading across all diameters were enhanced compared to monotonic loading; the ultimate strain followed the pattern monotonic load > cyclic load, and the elastic modulus showed no significant difference between loading types.

Keywords: *Salix psammophila*; cyclic load; tensile strength; deformation characteristic; straight roots

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1.1 Study Area Overview

The study area is located in the Shendong mining region, with geographic coordinates of 39°11 -39°29 N, 110°00 -110°24 E, at an elevation of 1100–1250 m. The area receives approximately 500 mm of annual precipitation. The natural vegetation includes species such as *Amorpha fruticosa*, *Hippophae rhamnoides*, *Artemisia ordosica*, and *Sabina procumbens*.

1.2 Root Collection and Preparation

Test roots were collected from healthy *Salix psammophila* plants and cut to lengths of 1.61 ± 0.16 m, 1.47 ± 0.22 m, and 1.62 ± 0.21 cm for different diameter classes. Root samples were sorted into three diameter classes: 1-2 mm, 2.5-3.5 mm, and 4-5 mm. All samples were soaked in water at room temperature for 24 hours before testing to ensure consistent moisture content. The TY8000 testing machine was used with a loading rate of 10 $mm \cdot min^{-1}$ and a force measurement precision of 0.01 N.

1.3.1 Tensile Testing Method

The axial tensile test method followed standard procedures for root biomechanical testing. Root specimens were clamped with a gauge length of 4 cm and loaded at a constant displacement rate until failure. Force and displacement data were recorded continuously throughout the test.

1.3.2 Deformation Characteristics

Relative elongation was calculated using the formula: $\gamma = (\Delta L/L) \times 100\%$, where ΔL is the displacement and L is the original gauge length. This parameter was used to quantify the deformation characteristics under both monotonic and cyclic loading conditions.

1.3.3 Constitutive Parameter Calculation

The elastic modulus (E) was calculated from the linear elastic portion of the stress-strain curve. Ultimate stress and strain were determined at the point of root failure. Elastic stress was defined as the stress at the elastic limit, and accumulated elastic strain represented the cumulative deformation across all loading cycles.

1.4 Data Processing

All data were processed using Excel 2010, SPSS 20.0, and Origin software. Statistical significance was assessed at $P < 0.05$. Regression analysis was performed to establish relationships between root diameter and mechanical parameters.

2.1 Straight Root Strength Response to Cyclic Loading

The tensile force of straight roots after cyclic loading showed a power function relationship with diameter: $Y = 21.612X^{1 \cdot 6743}$, $R^2 = 0.9214$. Compared with monotonic loading, tensile force increased significantly across all diameter classes ($P < 0.05$). The tensile strength after cyclic loading was negatively correlated with diameter following the relationship Y = 29.2X - 0.453, $R^2 = 0.7204$ for one diameter range and Y = 50.915X - 0.625, $R^2 = 0.7379$ for another. The enhancement effects were most pronounced in smaller diameter roots, with 1-2 mm roots showing 60% increases in both tensile force and strength, while 4–5 mm roots showed 31% and 32% increases, respectively.

[Figure 2: see original paper] shows the tensile force and tensile strength of straight roots before and after cyclic loading, demonstrating the consistent improvement across diameter classes.

2.2 Deformation Characteristics During Cyclic Loading

During cyclic loading, the force-displacement curves exhibited characteristic hysteresis loops that gradually closed as cycle number increased. The area within hysteresis loops decreased progressively, indicating reduced energy dissipation and diminished capacity to resist plastic deformation, though this stabilization occurred by cycle 10. Accumulated elongation increased with cycle number, following a two-stage pattern: an initial rapid growth stage (cycles 1-5) and a subsequent slow growth stage (cycles 6–10). The maximum accumulated elongation reached 2.88 mm for the smallest diameter class.

The relative elongation (r) and residual strain (Sr) showed diameter-dependent responses, with smaller roots exhibiting greater relative deformation. The cyclic deformation characteristics revealed that roots experienced progressive alignment of cellulose microfibrils and gradual loosening of the cellular structure.

2.3 Constitutive Characteristics Under Monotonic and Cyclic Loading

[Figure 3: see original paper] presents typical tensile force-displacement curves after cyclic loading, showing the nonlinear behavior and failure points. [Figure 4: see original paper] illustrates the relationship between accumulated elongation and cycle number, highlighting the two-stage deformation pattern. [Figure 5: see original paper] compares the ultimate stress-strain curves under monotonic and cyclic loading conditions.

summarizes the constitutive parameters for each diameter class under both loading types. The elastic stress (σe) and ultimate stress (σu) were significantly higher after cyclic loading ($P < 0.05$), while the elastic modulus (E) showed no consistent pattern. The ultimate strain (u) was lower under cyclic loading compared to monotonic loading, indicating that pre-conditioning reduced extensibility. The accumulated elastic strain (a) increased with cyclic loading, reflecting cumulative microstructural changes.

3.1 Effects of Cyclic Loading on Ultimate Force and Strength

The significant enhancement of tensile properties after cyclic loading can be attributed to thigmomorphogenetic responses, as described by Jaffe (1973). The repeated mechanical stimulation likely induced secondary cell wall thickening and increased cellulose deposition, particularly in smaller diameter roots. The power function relationships indicate that size-dependent responses are consistent with the mechanical design of roots, where smaller roots serve as tension elements requiring higher specific strength. The 60% improvement in 1-2 mm roots suggests these fine roots are particularly responsive to mechanical conditioning.

3.2 Deformation Characteristics After Cyclic Loading

The hysteresis behavior reflects viscoelastic properties and internal friction within the root tissue. The closing of hysteresis loops indicates strain hardening and reduced internal energy dissipation as the root structure reorganizes. The two-stage accumulated elongation pattern corresponds to initial cell wall adjustments followed by stable microstructural configuration. These findings align with studies on other species such as *Heteropappus altaicus* and *Poa sphondylodes* in similar environments.

The reduction in ultimate strain after cyclic loading suggests that pre-stressed roots become less extensible but stronger, a trade-off that may enhance soil reinforcement under repeated wind loading. The lack of correlation between elastic modulus and loading type indicates that stiffness is primarily determined by root anatomy rather than loading history.

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4 Conclusion

Cyclic loading significantly enhances the tensile force and strength of *Salix psammophila* straight roots across all diameter classes, with greater improvements

observed in smaller roots. The force-displacement response shows characteristic hysteresis that stabilizes after approximately 10 cycles. Accumulated elongation follows a two-stage pattern, and constitutive parameters indicate increased stress capacity but reduced ultimate strain after cyclic preconditioning. These results demonstrate that roots in wind-eroded environments develop improved mechanical properties through adaptive responses to repeated loading, supporting their role in soil stabilization. The findings provide a mechanical basis for understanding plant-soil interactions in aeolian environments and inform selection of appropriate species for ecological restoration projects.

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Note: Figure translations are in progress. See original paper for figures.