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The pullout behavior of plant roots in highly saturated soil mass

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ABSTRACT

Anchoring of plant root systems in the soil may downgrade in a highly moist soil condition during rainfall. Research on the pullout behavior of the root and its relationship with soil water condition are important to enhance the understanding of root reinforcement in the soil. This research carries out *in-situ* pullout tests on single plant roots, and effect of soil water conditions on the pullout behavior of roots in the field is investigated. Major findings concluded from this research are: (1) a sharp drop in the pullout resistance of soil-root interfaces after reaching the peak is observed regardless of soil water contents; (2) the initial pullout stiffness decreases with root length; (3) plant roots in the soil with high soil water contents have lower pullout stiffness; (4) the pullout displacement may reach to 50 to 200 mm at the maximum pullout resistance, and it is affected by soil water content and root length.
Keywords: root-soil interaction; in-situ pullout tests; soil moisture contents

1 INTRODUCTION

Plants and root systems play an important role in protecting the soil from erosion and instability. Plant root systems contribute anchoring and shearing resistance to the soil. Soil suction increases when water uptake through plant roots takes place, and resulting in an increase in soil shear strength. Plant root systems provide reinforcement to the surrounding soil mass through bonding resistance between roots and soils. Research on the mechanical behavior of root reinforcement in the soil has gained attention in the past two decades. The mechanical behavior of root systems may vary with different types of root system structures due to a wide variety of plant species. Effective root reinforcement in the soil relies on favorable root anchoring. Ennos (1990) indicated that the pullout behavior of plant roots in the soil was affected by root length and soil strength. A critical root length (L_{crit}) was proposed by Ennos (1990). Roots in the soil may undergo pullout failure if root length is less than L_{crit}, whereas, roots may break if root length is greater than L_{crit}. Mickovski et al (2007) indicated that the pullout resistance of roots in sand depended on material stiffness, root architecture and the soil suction. The maximum pullout resistance depended strongly on the presence and position of lateral roots, i.e. it increases with depth. This was because of the increased stresses acting in the sand at depth due to the overburden height of sand. Pollen (2007) indicated that roots that pull out or break in the soil during soil mass failure were determined on by soil water content and soil strength. Roots are likely to pull out of the soil at large root diameters when subjected to shear deformations, whereas, at small root diameters, roots may break in the soil. The threshold root diameter between root breaking and pullout in the soil depends on the soil strength. A great proportion of root pullout at large root diameters are expected in the soil with greater soil strength. Schwarz et al (2011) showed the importance of root tortuosity and root branching points for prediction of individual root pullout behavior in the soil. In addition, soil type and water content also affected the pullout resistance of roots in the soil. The displacement at the maximum pullout force increased with increasing root diameter and with root tortuosity. Increasing volumetric water contents in the soil causes a perceptible decrease on the soil-root interfacial friction.

The soil-root bond strength provides anchoring resistance for plants to resist strong wind induced during typhoons. Soil water contents may increase significantly during high-intensity rainfall, and soil strength decreases with soil water contents. Anchoring of root systems in the soil may change in a highly moist soil condition during rainfall. Consequently, toppling and uprooting of plant can be commonly seen during typhoons along with high-intensity rainfall.

This paper aims to investigate the pullout behavior of plant roots in the soil with various water contents. Plant species used in this study are Paper Mulberry (*Broussonetia papyrifera*). The relationship of pullout resistance vs. displacement for single roots in the soil with various water contents is obtained through *in-situ* pullout tests. The effect of soil water contents on the pullout behavior, i.e. the maximum displacement at the peak pullout force and pullout stiffness of plant roots is investigated. In addition, the role of root length in the pullout behavior of roots in the soil is also discussed.

2 MATERIALS AND METHODS

2.1 Experimental site

The experimental site is located at the west campus of Kaohsiung University of Science and Technology, Taiwan. The site is covered with different plant species. The soil at the site is mostly clayey sand with small amount of gravel. Dry unit weight of the soil is 14.5 kN/m^3; Liquid limit and plastic limit of the soil are 27 and 18, respectively. The soil particle distribution curve is shown in Fig. 1.

The plant species used in the study is Paper Mulberry, a fast-growing tree. The number of the samples at the site is enough for this study. The breast height diameter (BHD) used in the experiment ranges from 0.05 m to 0.25 m, and height of the plant ranges from 3 to 4 meters at the site.

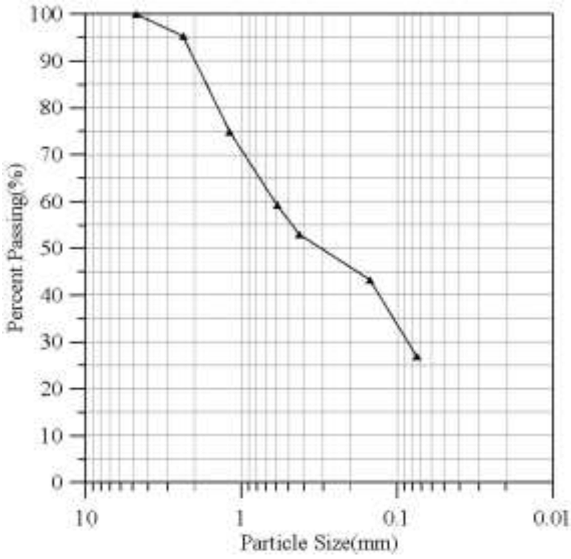

Fig. 1 The soil particle distribution curve at the site.

2.2 Test apparatus

A pullout apparatus for single roots in a root system is designed and manufactured. The apparatus is motor-driven, and it can be used in the pullout test for single roots in any orientations in the soil. The pullout force is measured by a load cell with a capacity of 5 kN, and the pullout displacement is measured by a displacement transducer with a capacity of 100 cm. The pullout apparatus is shown in Fig. 2. The pullout rate is 10 mm/min. A data acquisition device is used to record the pullout force and displacement during the test. A sleeve-type clamping system is designed and used to firmly clamp single roots in the soil.

2.3 Pullout resistance of plant roots

The relationship of pullout stress vs. pullout displacement for single roots is obtained. Geometry of plant roots is measured by excavating the roots after each pullout test. The soil-root bond strength (τ_b) is calculated by the following equation:

$$\tau_b = F_{ult} / A_R \qquad (1)$$

where F_{ult} is the ultimate pullout force for a single root in the soil; A_R is the surface area of the root in the soil.

Fig. 2 Pullout apparatus for plant roots.

3 RESULTS AND DISCUSSION

3.1 Pullout behavior of plant roots in the soil

Pullout tests for single plant roots in the soil were carried out at different soil water contents. Figure 3 and 4 show the normalized pullout stress vs. displacement for roots in the soil with water content of 8.6% (low saturation) and 40.2% (high saturation), respectively. The pullout stresses in the y-axis are normalized with respect to the ultimate pullout stress for each test. The data for various root lengths are shown in each figure. The variations of pullout stress with displacement are somewhat different for different root length. The pullout displacement at the peak pullout force ranges from 25 mm to 200 mm in this study.

The pullout behavior of single plant roots in the soil is different for various root lengths and soil water contents. To visualize the pullout behavior of the plant roots, the displacement at the peak pullout force and the initial pullout stiffness in the pullout stress vs. displacement relationship are obtained for each test. Figures 5 and 6 show the variation of the displacement at the peak pullout force with soil water contents at the level of root length of 110 mm and 230 mm, respectively. The displacement at the peak pullout force increases with soil water content at a lower root length (110 mm), whereas, at a higher root length (230 mm), the trend between the displacement at the peak pullout force and soil water contents is not clear.

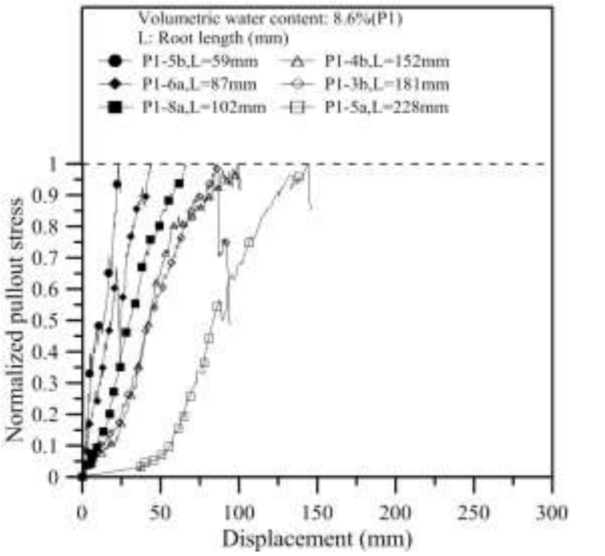

Fig. 3 Normalized pullout stress vs. pullout displacement for roots in the soil with water content of 8.6%.

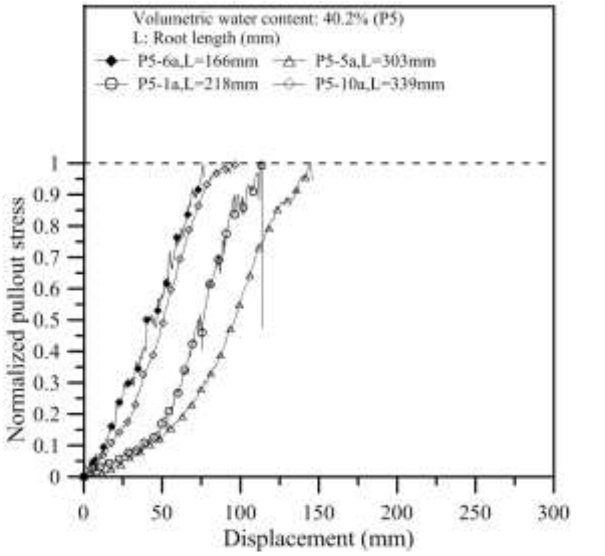

Fig. 4 Normalized pullout stress vs. displacement for roots in the soil with water content of 40.2%.

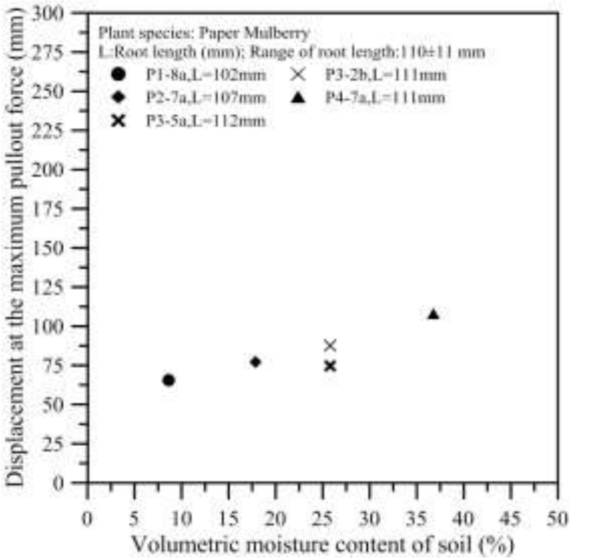

Fig. 5 Variation of the displacement at the peak pullout force with soil water contents at root length of 110 mm.

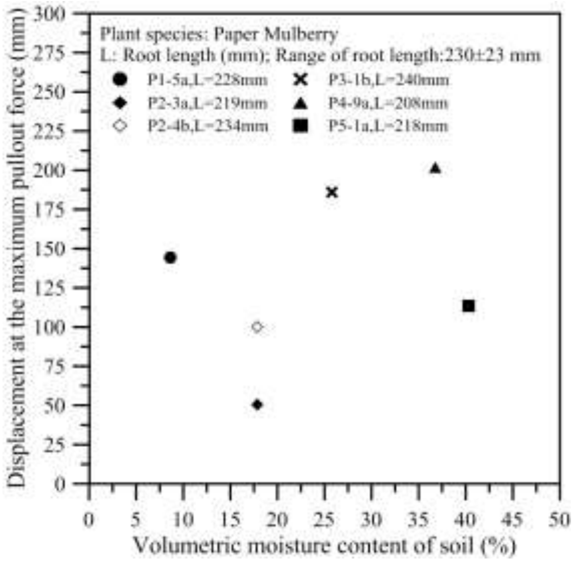

Fig. 6 Variation of the displacement at the peak pullout force with soil water contents at root length of 230 mm.

In addition, Figure 7 shows that relationship between the displacement at the peak pullout force and root length at various soil volumetric water contents, 8.6%, 25.8% and 40.3%. The displacement at the peak pullout force increases with root length at low soil water content (8.6%), whereas the trend between the displacement at the peak pullout force and root length is not clear for higher soil water contents in this study. This results are similar to the results presented by Ennos (1990). In addition, the geometry and characteristics of roots tested may not be uniform. The tortuosity of roots and branching pattern may also affect the performance of the root in the pullout behavior in the soil.

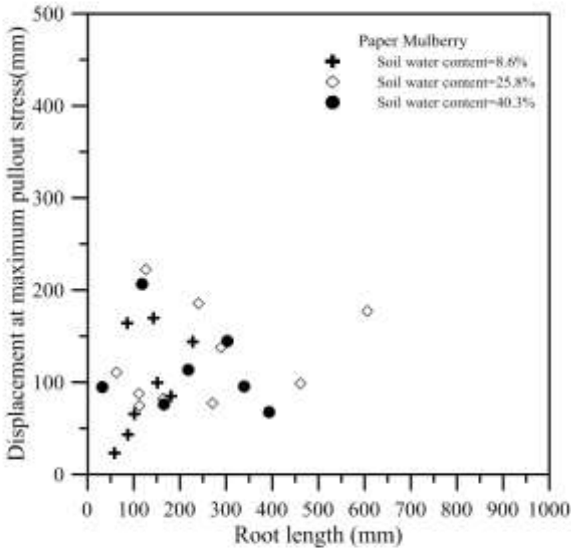

Fig. 7 Relationship between the displacement at the peak pullout force and root length at various soil water contents.

3.2 The pullout stiffness of soil-root interfaces

The pullout stiffness of roots is an indicator of how stiff the sol-root interface is in the soil. Figures 8, 9 and 10 show the variation of initial pullout stiffness with root length in the soil at water content of 8.6% (low soil saturation), 25.8% (moderate soil saturation) and 40.2% (high soil saturation), respectively. The initial pullout stiffness is defined as the ratio of pullout stress to pullout displacement at the early stage of the relationship of pullout force vs. displacement. The pullout stiffness for plant roots in the soil decreases with root length irrespective of soil water contents. Plant roots in the soil with high soil water contents have lower pullout stiffness compared with that with low water contents. Long single roots subjected to pullout force may develop more elongation at the early stage of the pullout force due to favorable root anchoring in the soil, and resulting in a greater pullout displacement. The soil-root interfacial stiffness at low water contents is greater than that at high soil water contents. Long roots in the soil with high water contents are likely to be less stiff when subjected to pullout forces.

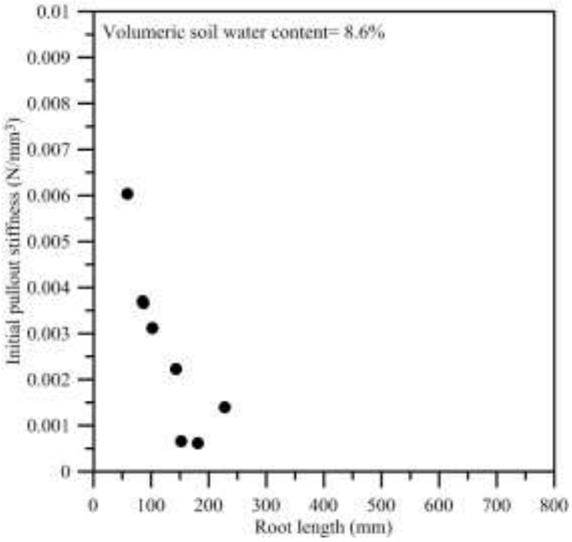

Fig. 8 Initial pullout stiffness vs. root length for soil water content of 8.6%.

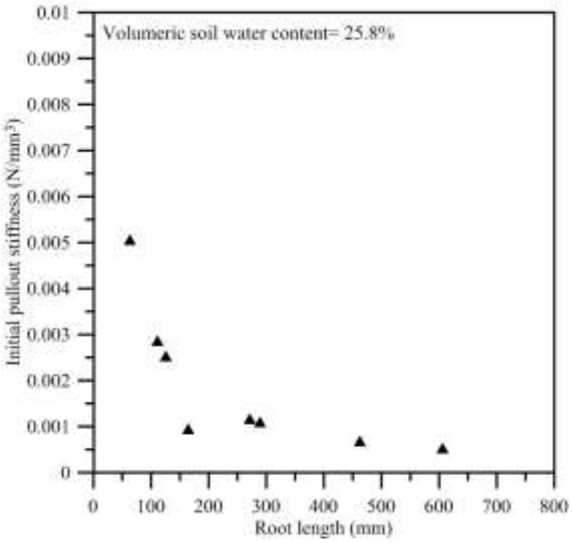

Fig. 9 Initial pullout stiffness vs. root length for soil water content of 25.8%.

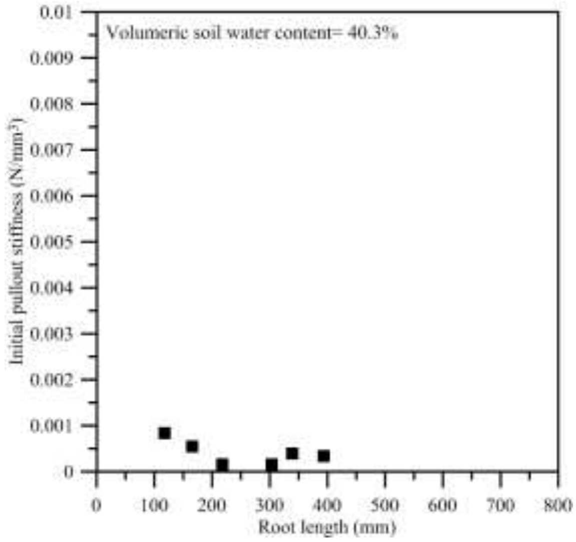

Fig. 10 Initial pullout stiffness vs. root length for soil water content of 40.2%.

4 Conclusion

This paper investigates the pullout behavior of single plant roots in the soil. Roots of Paper Mulberry are used in the study. The relationships of pullout resistance vs. displacement for single roots in the soil with different soil water contents are obtained through *in-situ* pullout tests. The pullout displacement at the peak pullout force ranges from 25 mm to 200 mm in this study. The displacement at the maximum pullout force increases with root length at low soil water content (8.6%). In addition, the initial pullout stiffness for plant roots in the soil decreases with root length at various soil water contents. Long roots in the soil with high water contents are likely to be less stiff in the soil-root interface when subjected to pullout forces.

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