Arboriculture & Urban Forestry 2011. 37(1): 35–40

Research Note: Observed Symmetry and Force of *Plantanus* × *acerifolia* (Ait.) Willd. Roots Occurring Between Foam Layers Under Pavement

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Abstract. Root damage to infrastructure is common in the urban environment. Many problems could be avoided if more were known about tree root growth patterns and the forces involved. This study looks at the growth symmetry and forces from four roots to aid in the development of a computer model.

Two primary roots, each from two trees, that were growing between two foam layers under pavement for 10 years were harvested and sectioned to measure radial growth symmetry to assist in the development of a computer simulation of root growth under pavement. The indentations in the foam created by the root growth were replicated using a universal loading press to estimate the radial growth pressure. Root growth was offset upward when close to the tree trunk, but shifted to a downward offset within 1 m from the trunk. Load penetration testing of the foam suggested a minimal load of 0.35–0.40 MPa to replicate the foam deformation.

Key Words. Infrastructure Damage; Root Diameter Growth; Root Pressure; Sidewalk Lifting.

Tree roots that grow under sidewalks or other urban infrastructure are known to cause millions of dollars worth of damage annually in the United States (McPherson and Peper 1995). Damage occurs as roots increase in diameter and displace the concrete or other materials to the point at which they break or are seriously deformed (Randrup et al. 2001; Costello and Jones 2003). While many tree-based solutions have been presented, engineering solutions are also available. That is, the infrastructure can be designed to withstand the loads that trees can produce. However, one of the first requirements of engineers is to know the forces for which they need to design. There is little research on the forces that tree roots can exert in urban systems.

One approach to modeling the forces involved in root growth under pavement is to develop a Finite Element Model (FEM). This would involve creation of a stylized, computer-generated "root" element that can change diameter to simulate radial growth and impose stresses on a layered pavement section design of defined engineering behavior over a specific area. To do this, root growth patterns and forces need to be defined.

Root pressure has been studied in axial soil penetration (Gill and Miller 1956; Taylor and Ratliff 1969; Bengough and MacKenzie 1994) and also in radial displacements (Misra et al. 1986), which must exceed the soil matrix resistance to displacement. Roots had been observed to generate axial growth pressures of 0.3–1.3 MPa and radial growth pressures in the range of 0.5–0.9 MPa (Eavis et al. 1969; Misra et al. 1986; Whalley and Dexter 1993; Clark et al. 1999). Studies have generally focused on herbaceous material and nonsuberized roots less than 3 mm in diameter, within 5 cm of the root tip, thus providing limited insight into the nature of large tree roots associated with pavement displacements. Rhizosphere biologists and agronomists have developed an understanding of both axial and radial root growth in soils presenting resistance to deformation, or impedance such as in compacted soils (Abdalla et al. 1969; Graf and Cooke 1980; Richards and Greacen 1986; Bengough and Mullins 1990; Bengough et al. 1997; Kirby and Bengough 2002). Again, while helpful in understanding soil compaction effects or response to impedance in young root penetration of soils in for agronomic benefit, the research has been limited to very small roots.

Root growth pressures in woody plants in the range of 0.8 MPa have been suggested (MacLeod and Cram 1996). Internal root pressure can be directly measured in the range of 0.05 to 0.15 MPa (Steudle and Meshcheryakov 1996), which can inform expected loading in the external growth capacity to displace surrounding soils. Researchers are still, however, limited in terms of their understanding large woody tree roots in phased perennial growth within a pavement section design marked by permanent expansions and rest periods as soil displacement occurs and root growth phase slows in seasonal patterns.

For urban tree issues, descriptions and overviews of the tree root-pavement conflict exist, including consideration of environmental parameters on root growth occurrence and behavior (Randrup et al. 2001; Costello and Jones 2003). Descriptive or corrective observations have been described in relation to tree trunk to pavement distance (Barker 1989), aspects of occurrence (Kopinga 1994), or protective method (Smiley 2008). Timing of conflict development has been related to proximity (Barker 1989), age of tree, and age of pavement surface (Mudrick 1990). Researchers have yet to fully define the physical attributes of radial growth pattern over time, how the environmental-morphological systems translate into differential growth pressure capacities over species or how the layered system in pavement design would influence root morphology in size, branch occurrence, or cross-sectional shape.

As a root grows, it must displace the surrounding soil. While root growth pressure measurement is an important aspect for study, the ability to exceed the surrounding soil's nonconfined shear strength is required to displace soil to accommodate radial growth. As such, the soil environment is of practical importance in considering urban tree root growth patterning. The pattern of perennial growth in a woody root is possibly an indication of displacement opportunity and likely stress distribution growth response. Relationships between mechanical advantage and root cross-sectional shape in shallow horizontal roots close to the root-shoot transition are well developed in some forest conifers (Eis 1974; Coutts 1983; Coutts et al. 1999). Eccentric root growth can reflect impediments to displacement in the soil by stones or structures. There is commonly accepted field wisdom in root decay investigation for an expectation of an upward offset in cambial growth. Such growth offset would be consistent with both lesser confining resistance (unit soil weight above versus displacing downward against all subtending soil solids) and loading induced growth adaption from wind-sway in i-beam and t-beam root descriptions (Coutts et al. 1999; Weber and Mattheck 2005).

Discussions of tensile loading on buttress roots and the development of root plate architecture (Fayle 1968; Vogel 1996; Coutts 1983; Coutts 1987; Gartner 1997; Nielson 2009) suggest an upward growth adaptation. However, at some distance, root form shifts to a different configuration, wherein roots adopt a rope-like morphology in secondary growth (Fayle 1968; Eis 1974; Wilson 1975; Coutts et al. 1999). What seems to be lacking is data on radial growth direction from the pith as distance from the trunk increases through and beyond the structural root plate of an urban tree. A root could be concentric or even have downward growth offset, but display a net lift in soil position if the resistance to displacement downward was high compared to a lesser energy use requirement for an upward soil displacement.

Smiley (2008) presented data from an experiment where London Plane trees *Plantanus* × *acerifolia* (Ait.) Willd. were grown next to various pavement protection systems for 10 years. One treatment used a double layer of extruded rigid polystyrene foam board (Foamular 150, Owens-Corning) to separate the root zone from the pavement wearing surface. At the conclusion of the experiment, the pavement surface was removed and roots were counted and measured under the foam layer. It was discovered that a limited number of roots had grown between the two layers of foam. Upward pavement surface displacement was measured in the study and was reported to be 1.5 mm mean lift in the foam protection treatment (Smiley 2008). The presumption is that root expansion resulted in corresponding deformation or displacement of the foam.

The study presented a novel system to begin definition of a root element to model growth impacts in a pavement section finite element model. The roots were between two homogenous foam layers of equal likelihood for displacement. The foam is able to be defined and the root-caused deformation can be replicated in the laboratory with standard engineering test methods. Root growth pattern upward versus downward, or horizontally versus vertically in cross-sectional view, could verify any need for growth directional offset in a computerized root for first iteration definition of the computerized root growth model.

While the comparison of root caused foam deformation and laboratory simulated testing cannot define the maximum force generated by the roots, it can certainly establish a possible minimal force. This information can then be applied to an FEM for further modeling of root-pavement conflicts. FEM has been initiated with empirical testing of a mechanical simulation of a root in compacted sand (Grabosky 2009).

The purpose of the current study was to use the roots grown between foam layers to: document gross root growth pattern, that is, to determine if there is an upward or downward growth offset in lateral root growth; to document the nature of the foam failure caused by radial root growth; and to replicate the foam deformation to estimate the minimum forces generated by radial tree root growth. In a study like this, having a large number of roots to examine would be highly desirable. However, since it was the intent of the original research project to exclude roots from between the foam boards, the opportunity to have well-developed, ten-year-old roots grown in this foam board environment could not be discarded. The information derived is only a starting point for the study of tree root growth morphology and forces. As such, the data presented are to inform computer model root simulation characteristics, and not to be considered generally representative of a root inventory or general species behavior for growth under pavement. The data does provide a first, albeit limited, data set for tree roots growing under pavement.

MATERIALS AND METHODS

Root sections from trees in the foam treatment set were opportunistically harvested, photographed for growth direction, labeled with associated foam pieces, and shipped in boxed sections for analysis at Rutgers Urban & Community Forestry Labs. Two major roots each from two trees as treatment replicates (labeled tree A and B for this paper), were available for analysis. The foam-pavement system was located 50 cm from the center of the tree trunk, which had grown from 4 cm measured at 0.15 m elevation to a final 8.7 and 7.1 cm diameter at 1.37 m elevation (trees A and B respectively), in the ten-year duration of the study. Pavement surface lift from trees A and B were 2.41 and 1.78 mm, respectively, as measured against elevation benchmarks (Smiley 2008). Smaller roots were not measured for sectioning and measurement as the study authors were interested in the larger foam deformations in this limited set of root observations. The foam sections were labeled upper and lower and taped into position around the excised root section for shipping, thus determining and preserving the direction of the root (up versus down). The plane between the foam sections was considered the horizontal measurement plane.

Roots were measured in transverse section every 5 cm. The bark inclusive radius distance from root perimeter to the pith in the vertical and horizontal directions were measured to the nearest millimeter. Mean radius for each section was used to develop whole-root sample means. Upward growth radius from pith was subtracted from downward growth radius to provide an estimator for vertical growth offset for each section, with zero representing the pith centered within the root. Data reported here divided this estimator by its section vertical diameter and were compiled and reported as percentages. Percentage data were transformed by taking the arcsine of the square root prior to analysis. Similarly an estimator for horizontal root growth offset was developed by subtracting left width from right width from the pith (viewed from proximal toward distal end in transverse section with top labeled). Measured parameters were averaged and used to distinguish general behaviors for whole root sections, acknowledging the fact that root taper and length differences would influence variance between root sections.

Tree B root 1 had a downward growth offset for the entire root sampling length. One root from each tree was located in a direct line of 50 cm from trunk center while one root from each tree came into the pavement section from an arced line from the trunk. The two nondirect roots were thus estimated within 10 cm to provide a method to plot data as a function of distance by section number. Comparison between roots was not the motive of the study. Tree effect on replicate behavior was tested as a parameter in a General Linear Model. Growth offset tests against a null hypothesis of symmetry in vertical and horizontal planes relative to the pith were conducted as one sample t-test for each root. Analysis was conducted in Minitab v14 (State College, PA, U.S.).

Deformation in foam sections was measured for depth and width every 2.65 cm along the foam on both upper and lower panels to determine whether foam deformation was offset upward or downward for comparison to the radial root growth in that zone.

A loading jig was developed to replicate deformation in the foam. A section of *Acer platanoides* L. branch wood (Figure 1) was used as a surrogate root section. The actual root was not used due to the destructive nature of the sectioning protocol. The wood section was mounted to a metal plate. The metal-wood jig was used with a recess bearing to “float” on the upper platen on a universal press as the foam section rested directly on the lower platen. Original sections of the foam board were cut to 40.6 cm × 7.6 cm × 5.1 cm for use in the test. The press was programmed to push into the foam at a constant rate. Two depths of 18 mm and 27 mm were imposed to replicate foam deformation from root growth. Three 27 mm depth and two 18 mm depth tests were conducted. Load was measured every 15 seconds in pounds force during the loading sequence. Distance traveled was set to a uniform rate of penetration. For the 18 mm deformation, it was set at 4.5 mm/three hours, three-hour hold/rest, repeated for a total of four loadings to final deformation of 17.8 mm. For the 27 mm deformation, it was set at 6.75 mm/three hours, three-hour hold/rest, repeated for a total of four loadings to a final deformation of 26.7 mm. Load press output were converted from pound force to Newtons and divided by the loading surface area (3.8 cm curve distance x 7.6 cm foam width) of the jig to provide N cm^{-2} for comparison to related root studies (Grabosky 2009).

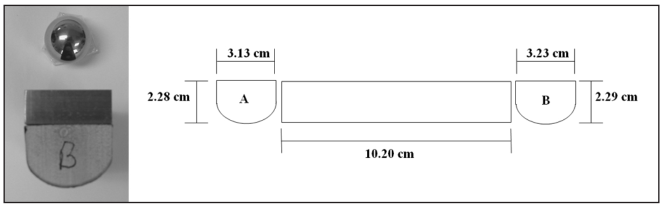

Figure 1. Schematic photograph and drawing of the wood-metal loading jig to impose load onto foam sections. Drawing and dimension details the wooden section. The photo shows the end view of the loading jig with the ball-bearing used to “float” the jig against the travel surface of the upper platen, which produced the load. The ball fit into a recess milled into the metal plate matched to recess centered on the upper platen on the load press.

RESULTS

Tree roots considered ranged from 14 to 28 mm mean radius (Table 1). Maximum bark thickness measured by dial caliper was 1.6 mm (data not shown). Tree origin was not related to growth offset in vertical/horizontal planes ($p = 0.243$ and $p = 0.99$, respectively). All four roots were observed to have an overall downward growth offset (less than zero when zero defines a vertically symmetrical growth) from the pith in one sample t-test ($p < 0.001$ in all cases). Roots A1, B1, and B2 could not reject a zero growth offset in the horizontal plane ($p = 0.142$, 0.702 and 0.587 respectively) in one sample t-test. Root A2 had a side growth offset ($p = 0.041$). Using sample section vertical diameters against horizontal diameters in a paired t-test, roots were larger in the horizontal dimension compared to the vertical by 4.5 ± 1.1 mm std. error ($p < 0.001$), which was not related to tree source ($p = 0.130$). In tree A, the five sections (25 cm) of both roots closest to the trunk, and the first two sections (10 cm) in Tree B root 2 closest to the trunk had an upward growth offset, shifting to a downward offset for the rest of the length of the root section (Figure 2).

The five foam penetration tests showed a consistent behavior (Figure 3). The foam pressure–deformation curve suggested that 0.35–0.4 MPa was needed for penetration to 28 mm. Cracking of the foam was observed in the load testing, but not observed in the root-deformed field sections, and was attributed to the differences in rate of loading increase between multi-year root growth and the load press simulation.

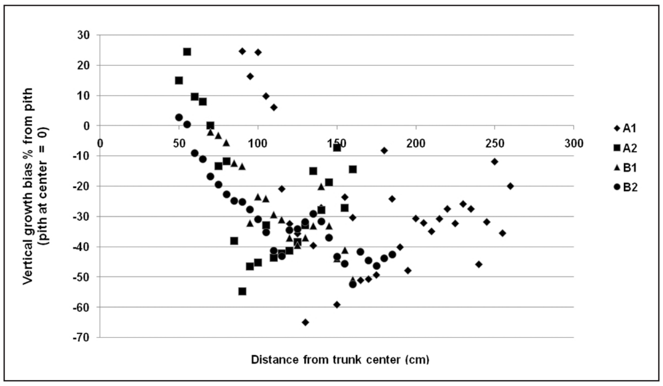

Figure 2. Growth offset as a percentage of root diameter along the distance of the root that was under pavement. Distances for roots A1 and B1 are estimates within 10 cm of true zero.

DISCUSSION

The Foamular provided a uniform medium to observe radial secondary growth patterns in woody roots. Of course, the laboratory testing process was used to simulate a multiple year process. Material aging over years often increases brittleness in the foam used, and seasonal daily temperature fluctuations combined with root growth periodicity have not been accounted for in this bench-scale test. When considering how the foam-root relationship develops under a lime-based concrete slab needs to additionally consider pore-water leachate impacts on foam material behavior in addition to the deformation forces imposed by a perennial increase in root diameter in seasonal secondary radial growth events.

A dissymmetric root growth pattern, or eccentric growth ring development, is not unexpected. Observations of dissymmetric growth in forest trees has been documented and suggested to follow stress patterns which change as the tree ages and with distance from the tree trunk as the loading pattern also shifts (Nicoll and Dunn 1999). Adaptive root growth in response to mechanical stimulation has been demonstrated (Stokes et al. 1995). In addition to active loading from tree movement, the physical relationship between root and soil and the soil resistance to deformation needs to be taken into account. As root growth displaces soils, the resistance to displacement eventually suggests an upward growth strategy because soil overburden lifting against gravity become less than displacement resistance in other directions through the cumulative soil profile. The observations of these four roots is consistent with previous observations, where an upward offset close to the trunk (or Zone of Rapid Taper) shifts to a downward growth offset, eventually become concentric at some distance from the tree trunk (Fayle 1968; Weber and Mattheck 2005). While a radial growth offset in a downward direction was observed, root growth in a soil system under pavement and loading influences could provide different results. It is reasonable to imagine that long term soil displacement resistance upward would take less energy than equivalent displacements downward due to compaction requirements for soil in layered pavement installation.

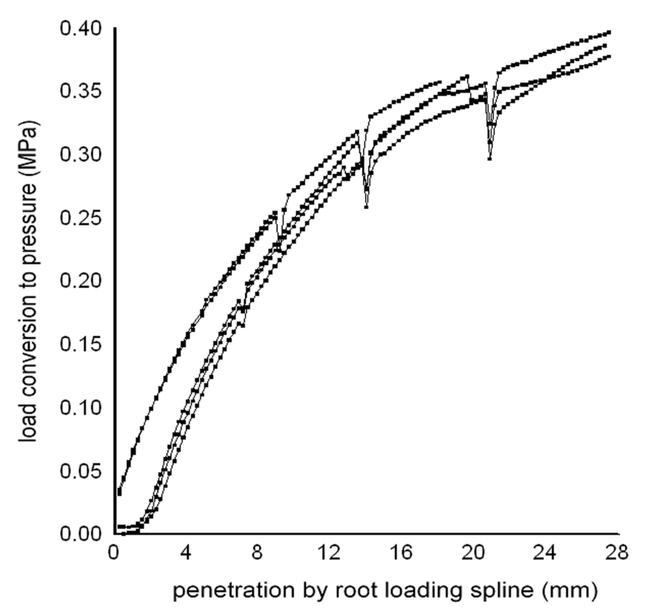

Figure 3. Pressure-penetration curves of foam sections to produce deformations to depths defined by observed multi-year root growth. Three curves generated to 27 mm at 2.25 mm h^{-1} with a three-hour load, three-hour rest period loading sequence. Two curves generated to 18 mm at 1.5 mm h^{-1} with three hour load, three-hour rest period loading sequence. Load was later converted to MPa by dividing load by contact surface of the loading jig on the foam.

The minimum radial root growth forces found (0.35–0.40 MPa) are somewhat lower than the maximum forces described for herbaceous root (0.50 to 0.90 MPa) or some tree species in fine root penetration in pipes (Stützel and Bosseler 2007) in the range of 1.2 MPa in *Quercus robur* J.F.Ehrh and 0.88 MPa in *Robinia pseudoacacia* L. This may be due to the difference in goals of the experiment, which describes foam deformation as a minimum to displacement, rather than for other material in pipe jointing or maximum force description. There are also differences in methodology used and herbaceous root tips. Nonsuberized woody plant root tips may not adequately describe radial force in woody roots over time. Additional research is needed to more clearly define the forces from the radial growth of wood plants.

The observed root growth patterns could be used in a computer simulation as an alternative scenario to cylindrical root development to design both pavement parameters and to develop a test of root depth changes by overburden displacement. The data from this test corroborates data and general observations in the literature, and they suggest equal opportunity root growth in a computerized simulation of root radial growth depending on distance from the trunk. The data set is too small to suggest any general trend in root growth below pavement or within the species.

Table 1. Dimension measurement data from four roots growing under concrete sidewalk between two foam protection layers. Offset measurements relative to root pith were measured as radius to edge in horizontal (defined by foam panel interface) and vertical (perpendicular to defined horizontal plane) directions. Left and right horizontal were defined by view from proximal end of the root section toward the distal end of the collected root sample.

TREE label	A		B	
ROOT label	1	2	1	2
Section (5 cm) count	35	23	19	28
Mean (S.E.) root vertical diameter (mm)	31 (1.1)	35 (1.4)	31 (0.7)	52 (0.6)
Mean up (+) versus down (-) vertical growth offset as % (S.E.)	-27 (3.7)	-22 (4.6)	-27 (3.3)	-31 (2.7)
Mean (S.E.) root horizontal diameter (mm)	35 (1.4)	45 (2.9)	25 (0.7)	60 (1.7)
Mean left (+) versus right (-) horizontal growth offset as % (S.E.)	8 (5.2)	-13 (6.0)	2 (4.2)	2 (3.3)
Mean (S.E.) vertical-horizontal dia. growth differential (mm)	-3.3 (1.5)	-10.1 (3.0)	5.5 (1.0)	-8.1 (2.0)

Acknowledgments. Our thanks to the Rutgers Center for Advanced Infrastructure and Transportation and the LTAP program lab for use of the loading press. Thank you also to Amir Roueenfar (load press), Christopher Aydin (root milling/ pith measures), and Paul Remelgado (foam measures) for aspects of data collection during their research internships.

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Résumé. Les dommages par les racines aux infrastructures sont communs en environnement urbain. De nombreux problèmes peuvent être évités si plus de connaissances étaient disponibles à propos des patrons de croissance des racines d'arbres et des forces impliquées. Cette étude s'intéresse à la symétrie de la croissance et aux forces de quatre racines afin de développer un modèle informatique. Deux racines primaires provenant de deux arbres qui poussaient entre deux couches de mousse sous une surface pavée durant 10 ans ont été recueillies et sectionnées pour mesurer la symétrie de la croissance radiale afin d'aider au développement d'une simulation informatique de croissance des racines sous une surface pavée. Les empreintes dans la mousse qui ont été créées par la croissance racinaire ont été reproduites au moyen d'une presse universelle de charge afin d'estimer la pression de la croissance radiale. La croissance racinaire a été décalée vers le haut lorsqu'à proximité du tronc, mais s'est déportée vers le bas à l'intérieur d'une distance de 1 m par rapport au tronc. Le test de pénétration de charge dans la mousse suggère une charge minimale de 0,35-0,40 MPa afin de reproduire la déformation dans la mousse.

Zusammenfassung. Ein Schaden an der Infrastruktur durch Wurzeln ist in der Stadt sehr gewöhnlich. Viele Probleme könnten vermieden werden, wenn mehr über das Wurzelwachstum und die beteiligten Kräfte bekannt ware. Diese Studie schaut auf die Wachstumsymmetrie und die Kräfte von vier Wurzeln, um daraus ein Computermodel zu entwickeln. Zwei primäre Wurzeln aus zwei Bäumen, die während zehn Jahren zwischen zwei Schaumschichten unter dem Pflaster wachsen, wurden geerntet und sektioniert, um die Symmetrie des radialen Wachstums zu messen, um eine Hilfestellung für die Entwicklung einer Computersimulation des Wurzelwachstums unter dem Pflaster zu liefern. Die Eindrücke in dem Schaum, die durch das Wurzelwachstum entstanden waren, wurden unter Verwendung einer universalen Presse zu Bestimmung der radialen Ausdehnung repliziert. Das Wurzelwachtum war in der Nähe des Stammes nach oben eindrücklich, aber es veränderte sich zu einer nach unten gerichteten Ausdehnung innerhalb eines Meters von Stamm. Die Untersuchung des Schaums auf Lasteintrag zeigte minimale Lasten von 0.35 – 0.40 MPa, um die Schaumverformung zu replizieren.

Resumen. El daño de las raíces a la infraestructura es común en el medio urbano. Muchos problemas podrían ser evitados si se conociera más de los patrones de crecimiento de las raíces y las fuerzas implicadas. Este estudio mira la simetría del crecimiento y las fuerzas de cuatro raíces para ayudar en el desarrollo de un modelo de computadora. Dos raíces primarias de dos árboles, que estuvieron creciendo entre dos capas de espuma bajo el pavimento por 10 años fueron cosechadas y seccionadas para medir la simetría del crecimiento radial y asistir en el desarrollo de una simulación en computadora del crecimiento de las raíces bajo el pavimento. Las aplicaciones de espuma para el crecimiento de la raíz fueron replicadas usando una carga de presión universal para estimar la presión radial del crecimiento. El crecimiento de la raíz fue hacia arriba cuando se cerró hacia el tronco, pero cambia hacia abajo dentro de 1 metro del tronco. La prueba de penetración de la carga de la espuma sugirió una carga mínima de 0.35-0.40 MPa para replicar la deformación de la espuma.