

TREE ROOT INTRUSION IN SEWER SYSTEMS: REVIEW OF EXTENT AND COSTS

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ABSTRACT: Interference between trees and sewer systems is likely to occur in old systems and in cracked pipes. Factors that contribute to damage include old pipes with joints, shallow pipes, small-dimension pipes, and fast-growing tree species. Because roots are reported to cause >50% of all sewer blockages, costs associated with root removal from sewers is substantial. In smaller-dimension pipes, root removal every year or every other year is common. Major resources are put into replacement and renewal of existing pipes, which is sometimes accelerated because of root intrusion. Collapse repair costs are greater than new construction, but costs associated with root removal may be one-sixth the cost of pipe replacement/renewal due to roots. Major breaks and stoppages seem to occur more frequently in older systems than in new. Therefore, it seems worthwhile to carry out preventative maintenance of the older parts of the sewer system.

INTRODUCTION

Roots in sewers have been described in the literature on several occasions. Geyer and Lentz (1964) found that roots were a major cause of sewer stoppage in U.S. cities. Hood (1957) described how the problem of root and fungus growth in sanitary sewers and storm drains could be controlled. Sullivan et al. (1977) reported from a survey of 64 U.S. cities to determine the extent and effect of roots in sewers. The study revealed that roots are a major sewer maintenance problem and roots in conjunction with grease and sand contributed to clogged sewers, reducing flow characteristics.

Holmes et al. (1982) edited a major publication based on an international conference on restoration of sewer systems. Several papers mentioned problems associated with root growth in sewers. Rolf and Stal (1994) described the problem, including remediation methods for Malmö in Sweden. McPherson and Peper (1995) presented costs related to root intrusion in eight U.S. and Canadian cities, and Randrup (2001) presented data from a survey among all cities in Denmark.

Initial defects in sewer systems are usually the result of poor construction (Sullivan et al. 1977; Schrock 1994; Brennan et al. 1997), excessive loading (Schrock 1994), leaky joints (Schrock 1994), inadequate connections (Randrup and Falda-gar 1997; Stal and Rolf 1998), or third party interference (Schrock 1994). Root intrusion can expand an existing opening in sewers, allowing quantities of the surrounding soil to enter through the defect, further weakening the structure, and ultimately leading to breakage and collapse of the sewer structure (Schrock 1994). The roots themselves can have a detrimental effect on hydraulic conditions in the sewer by creating a local flow restriction. This increases the possibility of overload by screening out the solids, which further restricts flow and reduces velocity. The frequency of overload also has an effect on the structure's rate of deterioration.

Many references indicate that tree roots do not damage the

infrastructure. They suggest that the infrastructure is poorly built and the reason for interrelations between tree roots and infrastructures are related to engineering and design failures [e.g., Cutler (1995), Brennan et al. (1997), and Coder (1998)]. Whatever the reason, the resulting repair of the sewer systems is often costly (Rolf and Stal 1994; Randrup 2001) and may result in damage to the trees themselves (Stal 1996).

Following a discussion of construction practices, urban soils, and root distribution, this paper reviews literature in three areas: (1) Factors contributing to sewer damage by roots; (2) an overview of associated costs; and (3) new areas for research.

SEWER SYSTEM CONSTRUCTION, URBAN SOILS, AND ROOT DISTRIBUTION

Sewers are conduits that carry wastewater or drainage water from an area. Sewer collection systems consist of sanitary, storm, or combined conduits. A sanitary sewer carries water-borne wastes containing minor quantities of inadvertent storm, surface, and ground water from residences, commercial buildings, industrial plants, and institutions. A storm sewer carries storm runoff, along with street waste and wash water or drainage. It excludes domestic and industrial wastewater. Typically found in older cities, combined sewers are collection systems that carry a mixture of domestic and industrial wastewater along with storm runoff (Schrock 1994). The fact that certain sewer lines contain nutrients for vegetation increases the potential for roots to "seek" and penetrate lines.

Construction of Sewers

In the past, sewers were constructed mainly of vitrified clay, brick, and concrete. Modern sewers (typically made after 1960) include plastic, ductile iron, steel, and reinforced concrete. These materials often have adequate compressive strength, and some have tensile strength (Schrock 1994; Randrup 2001). Rolf and Stal (1994) explained that, before 1960, sealing materials in Sweden were made of yarn and cement, which are easy for roots to penetrate. Between the two World Wars, clay-packed joints and cement seals were used in the United Kingdom, and these are now beginning to break because they are susceptible to drying (Brennan et al. 1997). Since the 1960s, rubber seals have been used. They create more flexible joints, are simpler to install, and provide an effective watertight seal that is not affected by drying. From 1880 to 1960, Danish sewer pipes were made in sections and joints were created when one pipe end was pushed into the socket of another pipe section. First, half the area between the end and the socket was filled with loose rope to center the

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pipe end. Then, fill material (concrete, clay, or asphalt) was forced into the joint to keep it tight. The joints became stiff and cracked if the soil settled. These joints were assumed to have a lifetime of 25–30 years, after which time deterioration of the rope and fill material would result in leaks. Standards for better and tighter joints have been in place since the 1980s. In concrete pipes, joints need to be tight at 30 kPa. In PVC pipes, joints need to be tight at 50 kPa (Randrup and Faldager 1997). According to an evaluation among four U.S. communities, bitumastic hot-poured joints were better at resisting root penetration than either cement mortar joints or lime mortar joints (Geyer and Lentz 1964). Further, it was concluded that data were not yet available on the ability of plastic and other “never-type joints” to resist root penetration. It was assumed that these never jointing systems would be superior to mortar-type joints.

When existing service connecting pipes need to be replaced or repaired, the new part will usually be of PVC. A concrete and a PVC pipe cannot be directly joined because they are of different dimensions and thicknesses in materials. Therefore, a special converter needs to be used. Use of conversions may be a risk in terms of root intrusions, because mistakes are often made when the converters are installed (Stal and Rosenlof 1995; Randrup and Faldager 1997).

In Denmark there are approximately 20,000 km of main pipes, 30,000 km of separated wastewater pipes, and 30,000 km of separated storm-water pipes (Randrup and Faldager 1997). In 1994 there were an estimated 965,000 km of sanitary and combined sewers in the United States (Schrock 1994), and in 1982 the United Kingdom had a total of 235,000 km of public sewers (Perkins 1982; Reed 1982).

Urban Soils and Root Distribution

Root growth is opportunistic: roots proliferate in areas suitable for growth (Harris et al. 1999). Urban soils, however, are often not optimal for root growth. Craul (1992) defined urban soils as mediums which had been disturbed, manipulated, or handled in some way that changed or modified their properties and attendant characteristics; there are very few urban soils that do not exhibit evidence of anthropogenic modification to some degree, which often influences growing conditions negatively. Kopinga (1991) described how restricted volumes of soil influenced the supply of moisture and nutrients to urban trees. Jim (1998a,b) found that, for soils in Hong Kong, most had lost the natural horizon with morphological features of fill materials such as poor structure and artificial layering. The soils were excessively stony and coarse textured, with abundance of building rubble and other foreign substances. These conditions now seem to be broadly accepted within the urban situation. A number of sources describe the way an urban tree should be established in relation to these nonoptimal growing conditions [e.g., Bradshaw et al. (1995), Watson and Himelick (1997), and Harris et al. (1999)]. Nicoll and Coutts (1997) explained that, if a root branch encounters a better condition (e.g., near the surface), it will become a dominant part of the root. Such “compensatory growth” occurs where a branch root is growing in better conditions than the original root tip. Rolf et al. (1995) argued that, if the conditions in a tree-planting pit are not good, tree roots might grow into a nearby pipe trench. The nonoptimal growing conditions found in urban settings may induce root growth in atypical locations.

Cutler (1995) explained that roots grow toward an increasing water gradient and appear to need at least a continuous surface film to direct them to the water (in a sewer pipe). Thus, when intact drains and other service pipes are cooler than the surrounding soil or if moisture escapes from a water-carrying underground pipe, there is a potential for root growth due to the moisture gradient developed in the soil. Coder (1998)

stated that pipes made of dense materials have additional thermal interactions with the soil because of liquid temperatures moving inside. The greater the differential of temperatures, the greater chance of pore space development at the soil-pipe interface. So, if a pipe is cooler than the surrounding soil, moisture will condense around it, creating conditions conducive to root growth.

All roots share the common characteristic that their continued elongation depends on the division and subsequent extension of cells in the apical meristem (root tip) (Russell 1977). This cell-by-cell growth enables roots to penetrate small openings in sewer pipes (Schrock 1994). Stal and Rolf (1998) stated that roots grow into pipes only when the pipe joints are unable to withstand pressure, and Bradshaw et al. (1995) stated that the only drains that become blocked by tree roots are those that are old, usually made of clay pipes, and in bad condition. Modern plastic drains are unlikely to suffer. Depending on the size of the crack in a pipe and the adjacent soil type, soil particles and roots may pass through the sewer defects.

Forces exerted by secondary root growth (diameter growth) can lift light structures such as paths, curbs, paving slabs, boundary walls, or occasionally single-story buildings (e.g., garages or porches) (Biddle 1998). MacLeod and Cram (1996) stated that, if roots are growing under structures where secondary growth may be a potential cause of structural damage, this growth will occur year after year and displacement of structures will be progressive because woody roots increase in diameter by producing a new growth ring each year. Furthermore, it was stated that radial pressures of woody roots would be exerted over a relatively large area, whereas axial forces of root tips are applied at a point. Thus, radial pressures generate a far greater total force than do axial pressures. Radial pressures, as a result of secondary root growth, are likely to occur once a root has entered a crack in a sewer and can thus worsen existing damage. Harris et al. (1999) stated that, once a root enters a sewer, the conditions of aeration, moisture, and nutrients are so favorable that it inevitably grows until it clogs the sewer. No studies have been conducted to support this statement, however.

FACTORS ASSOCIATED WITH SEWER SYSTEM DAMAGE

Sewer System Breakage and Frequency of Root Intrusion

There is an estimated 965,000 km of sanitary and combined sewers in the United States and approximately 50 major main breaks per 1,650 km/year for a total of 30,000 breaks annually. Furthermore, approximately 500 stoppages occur per 1,600 km/year (1,000 mi/year), amounting to an estimated 300,000 stoppages annually (Schrock 1994). An additional 100,000 stoppages yearly were the responsibility of private residents. According to Schrock (1994), roots cause >50% of all stoppages in sewer systems and most structural failures are caused by roots, corrosion, soil movement, and inadequate construction combined. This gives approximately 250 stoppages/800 km (500 mi) or 1 stoppage due to roots per every 3.2 km (2 mi) of pipe in the United States. Schrock (1994) referred to the Water Research Center in the United Kingdom, which has researched trends during a 10-year period up to the mid-1980s. It indicated a 3% annual increase in problems. Approximately 5,000 collapses and 200,000 blockages occurred each year in the United Kingdom.

Schrock (1994) distinguished between different types of failures of sewer systems (Table 1). It is seen that roots may cause structural failures to pipes, but usually this is associated with inadequate construction.

Rolf and Stal (1994) presented data on root intrusions from

TABLE 1. Type of Sewer Failure [from Schrock (1994)]

Type of failure (1)	Cause of failure (2)
Sewer collapse	Difficult ground conditions, large wastewater flow, adjacent utility impacts, traffic congestion, or deep excavation
Structural failures	Roots, corrosion, soil movement, and inadequate construction combined
Blockages	Sediment, roots, intrusions (connections or foreign bodies), and grease or encrustation or both

TABLE 2. Tree Root Intrusion in Relation to Pipe Dimension [from Rolf and Stal (1994)]

Pipe dimension (mm) (1)	Number of Root Intrusions/1,000 m			Average distance between Class 2 and Class 3 intrusions (m) (5)
	Class 1 (2)	Class 2 (3)	Class 3 (4)	
225	11	2	1	333.3
300	8	2	1	333.3
375	11	3	1	250.0
400	7	4	1	200.0
450	6	1	0	1,000.0
500	5	1	1	500.0
600	7	1	1	500.0
750	2	1	1	500.0

Note: All figures are rounded up to nearest full number. Class 1: small and few roots in pipe but no water leakage evident. Class 2: coarse roots penetrate further into pipe and are in water flow. Class 3: large roots or numerous roots at one site.

Malmö, Sweden. In Table 2, the data are listed according to degree of root intrusion. According to Table 2, there are a majority of root intrusions in the smaller dimension pipes, but most were classified as Class 1, small and few roots in the pipe and no water leakage evident. Class 3 penetrations, large roots or numerous roots at one site, seemed to be equally distributed in all types of sewer dimensions, with one intrusion per 1,000 m in all pipe dimensions. In general, between one and five serious root intrusions were found per 1,000 m.

Harris et al. (1999) reported on a fruitless Mulberry (*Morus alba* "Streibling"), which was planted in a newly filled sewer trench in northern California. Two of its roots had crushed a sewer line 100 mm in diameter <4 years after the tree was planted.

Displacement of underground services had been reported and could be the result of diameter growth of roots or slight movement of the roots in reaction to sway of the trunk or the branches (Brennan et al. 1997). Continuous, nonjointed pipes should be relatively unaffected by such displacements caused by root growth. On highly shrinkable clay soils, tree roots may contribute to soil drying [e.g., Cutler and Richardson (1989) and Biddle (1998)]. When clay shrinks, pipes may then move. However, Brennan et al. (1997) stated that more important than the shrinkable clay soils is the design and quality of the pipe materials, as well as the standards of workmanship and supervision during construction of the pipeline.

Brennan et al. (1997) stated that modern materials and joints between pipes should prevent most root problems in the future. Data presented by Rolf and Stal (1994) confirm this belief. They found a significant drop in root intrusions in pipes constructed after 1970 (two intrusions per 1,000 m of pipe). Pipes constructed before 1970 had 6–11 Class 1 intrusions per 1,000 m of pipe, 1–2 Class 2 intrusions per 1,000 m, and, on average, 1 Class 3 intrusion per 1,000 m. These findings are in agreement with Stal and Rosenlof (1995) who found 67 cases of root intrusion in new pipes (laid between 1979 and 1985) among 37 municipalities. The number of intrusions varied

from 1 to 13 in each municipality, and the pipes were primarily made of concrete with a dimension noted as "minor." Survey data showed five individual cases of root intrusions into PVC pipes, of which the local sewer system managers could document none. Likewise, Randrup and Faldager (1997) surveyed all Danish municipalities for tree root intrusion problems and found only five examples of root intrusions into sewer systems laid after 1979.

Root penetration seems to be most severe in service connection pipes, where sewer depth is less and construction may not have been adequately inspected (Sullivan et al. 1977; Schrock 1994). In a Danish survey (Randrup 2001) found that service-connecting pipes had more root intrusions than main pipes; however 43% of all respondents reported roots in both connecting pipes and main pipes. Rolf et al. (1995) wrote that root plugging was a common problem in service connections.

Tree Species

From a list of 13 different common trees seen in Danish urban areas, willow (*Salix spp.*), birch (*Betula spp.*), poplars (*Populus spp.*), and elm (*Ulmus spp.*) were mentioned as species causing the greatest problems with root intrusion (30, 25, 23, and 6%, respectively) (Randrup 2001). Stal and Rosenlof (1995) mentioned in a study of tree root intrusions into newer pipe systems that willow and poplar dominated the vegetation next to the pipes (with intrusions). However, this answer was based on a question giving the options: willow and poplar, birch, or linden (*Tilia spp.*).

Harris et al. (1999) reported a list of 100 species of trees and shrubs that cannot be planted closer than 2 m to a sewer main in a street in Adelaide, Australia. An additional list includes 95 species that cannot be located closer than 3.5 m to a sewer main and 30 species that cannot be planted in a street in any drainage area. Randrup (2001) found that the distance between sewers with root intrusions and the subject tree ranged from <3 m (48%) to between 3 and 6 m (44%). It was concluded that distances up to 6 m constituted the high-risk zone in Denmark. Cutler and Richardson (1989) reported on distances between trees and associated to buildings. They frequently found distances of >20 m between the tree and the damaged building.

Maintenance Practices Influencing Root Growth in Sewers

Control and removal of roots in a sewer is an important and ongoing maintenance operation, and an effective root program requires an understanding of root growth (Schrock 1994). Sullivan et al. (1977) stated that conventional root control practices such as cutting appeared to encourage root growth, which is the general assumption today. Schrock (1994) stated that, although root cutting corrects the immediate problem, in the long term, roots frequently grow back more vigorously after each cutting operation. Watson (1994) showed that, after roots have been cut, they usually grow back and often in greater numbers than before the cut. Therefore, Schrock (1994) recommended that each root cutting should be followed by chemical treatment or by flooding the pipeline with scalding water to retard root regrowth.

Hood (1957), Schrock (1994), Groninger et al. (1997), and Harris et al. (1999) have described herbicides used to control root growth. These methods may be effective and regularly used but may also constitute a threat to the environment. In Denmark, herbicide use on all public land will be banned after 2003 (Kristoffersen and Tvedt 1999).

Different types of fabrics have been promoted to reduce growth around sewer systems [e.g., Coder (1998) and Edwards

et al. (1999)]. Schrock (1994) concluded that the most effective root control method is to prevent roots from entering a sewer in the first place. Installing watertight lines that are free from imperfections and will not crack, break, or deteriorate during service is the ideal solution. This may require that materials and construction methods meet or exceed current standards and also may necessitate increasing on-site inspection during the installation of pipelines and service connections. Rolf and Stal (1994) described a planning-related approach in three examples from Malmö, Sweden. When root intrusion was diagnosed as problematic, each site was treated differently depending on the technical, aesthetical, cultural, and economic values of the belowground and aboveground features.

COSTS OF TREE ROOT INTERFERENCE WITH SEWER SYSTEMS

Conflicts between tree root growth and infrastructure can result in expenditures for root removal (pruning) and repair of sewers. However, other "hidden" costs can be more difficult to quantify than expenditures for direct repairs. For example, traffic delays and detours due to roads being repaired because of sewer system collapse sometimes seriously affect large numbers of people for hours or even days and cities may pay fees required to settle or adjudicate cases where tree roots have been blamed for blockages and associated flooding. Also, cities may require the installation of root barriers to prevent or forestall future conflicts and repeated root pruning may result in costs associated with the removal and replacement of trees that have become liabilities. Information on the magnitude of these expenditures is important to understand the scope of the tree root/infrastructure problem and how funds are distributed among a variety of solutions.

Costs of tree root intrusions in municipal sewer systems may be estimated by use of the following model:

$$\text{costs}_{\text{annual}} = R + M + T + I + H$$

where R = repair and replacement of existing pipes; M = mitigation and prevention of blockage by roots (root barriers, root pruning, etc.); T = tree removal and replacement; I = inspection and repair program administration; and H = hidden costs (traffic delays, liability issues, etc.).

Unfortunately, because little research exists on these expenditures, there are no conclusive findings concerning the distribution of fiscal resources. At best there are trends that indicate patterns of expenditures. These trends are based on survey results from 15 cities in the United States and Canada (McPherson and Peper 1995) and from national surveys from Sweden (Stal 1996) and Denmark (Randrup 2001). These studies

may not apply directly to cities in different regions of the world. Only one study has attempted to quantify "hidden costs," and it is limited to California cities and cost related to tree root interference with sidewalks and curbs (McPherson 2000).

The estimates of tree root related cost to sewer systems may be conservative because repair cost was lacking for half the cities in the sample made by McPherson and Peper (1995). Stal (1996) had costs presented by 69% of the sample of all Swedish cities, and Randrup (2001) had costs presented by only 12–31% of all Danish cities (Table 3).

Repair of Tree-Related Damage

For eight U.S. and Canadian cities, annual sewer repair costs ranged from \$0.11 to \$6.39 per tree (McPherson and Peper 1995). The mean annual repair costs was \$1.66 ($\pm$ \$2.07) per tree. It was stated that the high cost (\$6.39) in Vancouver was due to the large number of clay and concrete lines that are >100 years old with large, old trees placed in perfect position to invade the lines.

Expenditures associated with repairing tree damaged sewer lines range from 13 to 30% of the annual tree program budgets in Sacramento (13%), Atlanta (15%), Rock Valley (20%), and Vancouver (30%). McPherson and Peper (1995) did not distinguish between concrete and sewer repair costs attributed to tree-related damage, and as such the average costs were \$4.28 ($\pm$ \$3.87) and ranged from \$0.18 to \$13.65.

Total concrete and sewer repair costs averaged 25% of total tree program budgets ($\pm$ 19%) and ranged from 0.4 to 63%. Some cities had relatively low costs per tree but relatively high costs as a percentage of program budgets. This fact is primarily caused by their relatively small program budgets but relatively large street tree populations.

In a Danish study, cost related to pipe replacement/renewal due to root intrusion averaged \$1.56 per capita or \$38,824 ($\pm$ \$57,387) per city/year and ranged from \$0 to \$266,666 per city/year (Randrup 2001). Fifty-two percent of all cities had costs of only \$4,133 ($\pm$ \$2,843), whereas the remaining 48% had costs of \$67,733 ($\pm$ \$65,158). Possible causes of the variability in costs within the studied groups were not addressed by the survey.

The Danish Environmental Protection Agency (DEPA) (1992) projected that the Danish cities would spend approximately \$107,000,000/year in the period from 1995 to 2000 for renewal of sewer systems, excluding wastewater treatment plants and service-connection pipes. Randrup (2001) found that expenditures for renewal of pipes because of tree root intrusions accounted for approximately 7% of the total ex-

TABLE 3. Studies of Tree Roots in Sewer Systems

Location (1)	Problem (2)	Study period (3)	Annual costs (U.S. dollars) (4)	Reference (5)
City of Malmö, Sweden	Tree root related costs to damaged sewer pipes	1994	0.375 Mio.	Rolf and Stal (1994)
37 cities in Sweden	Survey of tree roots in sewer systems newer than 1979	1993–1994	—	Stal and Rosenlöf (1995)
Public systems in Sweden	Survey of tree roots in sewer systems	1993	0.76/capita 6.2 M* (total) 0.028 M/city ^a 4.28/tree ^a	Stal (1996)
7 U.S. and 1 Canadian city	Cost for repairing sewer lines damaged by street trees	1991–1994	—	McPherson and Peper (1995)
Public systems in Denmark	Survey of tree roots in sewer systems	1996–1997	1.82/capita 8.1 M (total) 0.045 M/city	Randrup and Faldager (1997) and Randrup (2001)

*The figure is regarded as conservative: (1) Roots may be part of reason for pipe renewal—in this study only roots being cause of pipe renewal was included; (2) only city-owned pipes were included; and (3) it was believed that not all cities really knew extent of problem.

^aCosts includes concrete and sewer repair costs.

penses. However, there is uncertainty with this estimate because it is difficult to separate costs for pipes that are renewed because of root intrusions from overall system renewals.

Although there seems to be limited data available in relation to costs of sewer system maintenance specifically in relation to root intrusions, both Bernhardt and Swiecki (1993) and McPherson and Peper (1995) found that tree managers in the United States had stated that root damage to sidewalks, curbs, and gutters was far more pervasive and costly than the damage to sewers. The issue of who pays for these infrastructure repairs can be contentious. Expenses for infrastructure repair may be covered by one department (street maintenance departments), whereas trees usually are managed in another department, such as parks (Barker 1983; Morell 1992; Rolf and Stal 1994). Usually, cities will only pay for repair on the public part of the sewer system. Because most root intrusions are found in service connection pipes (in yards), the majority of repair might be borne by residents.

Mitigation and Prevention/Root Pruning

Different methods of root cutting are frequently used in most places [e.g., Schrock (1994)]. Rolf and Stal (1994) mentioned that in some cases annual root cutting is needed, leading to high maintenance costs. Randrup (2001) found that expenses related to root cutting were approximately 1.2% of the total expenses related to maintenance of the Danish sewer system, or approximately \$0.26 per capita. Annual root removal costs averaged \$6,530 ($\pm$ \$11,777) per city and ranged from \$0 to \$65,000 per city. However, 83% of all cities had costs of only \$2,521 ($\pm$ \$2,179) per year, whereas the remaining 17% had costs of \$27,143 ($\pm$ \$18,576) per year. Possible causes of the variability in costs within the studied groups were not addressed by the survey.

In Sweden, annual root removal costs averaged \$5,500 per city, and expenditures for renewal of pipes was approximately \$16,000 per city (Stal 1996).

Tree Removal and Replacement

Benefits are foregone when a large tree is prematurely removed because of a conflict with the infrastructure. The value of annual benefits produced by a large street tree in Modesto, Calif., can exceed \$100 (McPherson et al. 1999a). On the other hand, cities like Modesto spend \$20–\$40 per year to maintain a street tree of this size, so benefits can exceed costs by a factor of 2 or more (McPherson et al. 1999b). Replacement trees are a net cost for the first 5–10 years because establishment costs are greater than benefits from the relatively small tree crown. Therefore, premature removal and replacement of large trees results in considerable payment for work performed (\$691 per tree on average) and a substantial loss of net benefits formerly produced by the tree (approximately \$70 per tree).

Inspection and Repair Program Administration

Ninety-two percent of all Danish cities used closed-circuit TV inspection to implement annual or biannual inspection (17%) or to remediate acute intrusion (75%). Cullen (1982) stated that it would not be economical to inspect the entire pipe system at the frequencies necessary to anticipate and prevent all collapses. According to the DEPA (1992), the Danish cities had inspected 16% of all sewer systems, with 70% of these inspections conducted from 1987 to 1992. Eleven percent of the cities conducted closed-circuit TV inspection of all pipes, whereas 31% inspected their main pipes only. No specific costs have been reported on this issue.

RESEARCH NEEDS

Considering the worldwide scope of root damage in sewer systems, it is surprising that more research has not been conducted. There is a need for comprehensive damage surveys, methods to prevent damage, and costs associated with root intrusion for residents as well as municipalities. Also, "hidden costs" associated with tree removal, legal actions, and mitigation/prevention need to be better understood.

More in-depth information is needed concerning the relations between sewers (type, size, age, and structural condition), trees (species and root distribution), and urban soils. In addition, there is a need for studies that will assist policymakers to efficiently allocate funds among repair, mitigation, prevention, and legal remedies.

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