DEVELOPMENT OF THE STEEL ROD TECHNIQUE FOR THE ASSESSMENT OF AERATION IN URBAN SOILS

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Abstract. Diagnosis of poor performance in urban trees requires means of evaluating soil aeration. A technique using 60 cm long steel rods inserted into the ground has been developed into an effective and practical means of assessing the vertical and spatial distribution of soil aeration in urban soils; even those covered by hard surfaces. A laboratory study verified the interpretation of the four types of corrosion found on steel rods with respect to soil aeration, although the presence of uncorroded metal could not be clearly related to suitability for root growth. A field study indicated that the best numerical reflections of soil aeration are the total presence of corrosion types indicative of inhospitable soil conditions, and the contrast between inhospitable conditions in the top 30 cm and the bottom 30 cm of the rod.

Non-structural roots are composed of living cells which need oxygen to survive. For most tree species this oxygen must come from the soil. If the supply of soil oxygen is inadequate, roots cannot grow and will die. In order to diagnose poor amenity tree performance, means are required to assess soil aeration.

The most commonly used means of assessing soil aeration, or more specifically oxygen content, is an oxygen probe. A hollow probe is driven into the soil to the desired depth (usually 0.5 m maximum), and soil air extracted and analyzed for oxygen content. On urban sites stony or compacted soils, underground services and hard urban surfaces limit opportunities to use this method. In initial trials, where the probe could be inserted, oxygen content readings were often higher than expected bearing in mind the compacted nature of many of the sites. It is possible that, as the probe was driven into the ground, fissures and gaps were created around the probe so that the air extracted from the soil contained atmospheric air drawn down the outside of the probe. In addition, this method assesses oxygen content of air in the soil pores only, it takes no account of oxygen dissolved in soil water. The oxygen probe cannot be used in waterlogged soil.

Platinum microcathodes have been used to measure oxygen diffusion rate through soil (13) or oxygen flux over time (4). This method is not limited by the moisture content of the soil and is more indicative of the oxygen available to tree roots. However, the equipment required is expensive and complicated and the method is only practical for use on private ground as probes have to remain in the soil to allow monitoring over a number of days.

The rate and characteristics of the corrosion of iron in soil depends on a number of factors: soil resistivity, redox potential, moisture content, salt content, soil iron content, pH, organic matter content, oxygen diffusion rate and bulk density. However, for any given soil, oxygen diffusion rate is the factor that most affects corrosion rate (7,11,14). In the early 1980's Forestry Commission researchers demonstrated that the corrosion of steel rods inserted into the ground could reveal information about oxygen diffusion rate along a soil profile (5).

Since 1982 the steel rod technique has been successfully used for the determination of the depth of onset of waterlogged conditions in the soil, mainly for comparison with the depth of tree rooting (1,2,5,12) but also in a study of the fluctuation of a wetland water table (3). Carnell and Anderson (5) classified corrosion on steel rods into five categories (Table 1) and combined the shiny metal, smooth black and matt grey categories to indicate the presence of conditions inhospitable to root growth.

The form of interpretation adopted by Hunt et al (12) was simply to record the depth of predomi-

Table 1: The interpretation of steel rod corrosion patterns after Carnell & Anderson (1986).

Red/brown rust:	indicates a well aerated soil.
Raised black:	occurs where rusting has started but has been interrupted, or where rust has been knocked off during removal of the rod from the ground.
Shiny metal:	can indicate the presence of substances (usually polyphenols or oil products) which have protected the rods from rusting. These can arise from organic residues that are under anaerobic conditions, and the soil can be classed as inhospitable for root growth.
Smooth black:	occurs where anaerobic bacteria utilize soil sulphates producing hydrogen sulphide, which reacts with the surface of the metal.
Matt grey:	indicates totally anaerobic conditions.

nantly red rust, assuming this to be related to the zone of conditions conducive to root growth. Anderson and Durrant (2), working on forest soils, used two measurements; the depth of the first shiny, matt grey or smooth black patch over 3 mm across indicating the onset of anaerobic conditions and the depth at which almost continuous inhospitable conditions were indicated. The zone between these two measurements was interpreted as less favourable for rooting but not totally inhibiting to root growth.

Research using steel rods to evaluate aeration in urban soils was started in 1987 in England and initially compared steel rod corrosion patterns with the growth of nine species of urban trees on contrasting sites (6). This study showed the inadequacy of simple measures of steel rod evaluation with respect to urban soils. Urban soils are characterized by a high level of disturbance with no clear profile formation. Soil forming materials are often imported to the site; replacing, being mixed with, or put on top of the disturbed indigenous soils. This and the frequent presence of building materials and underground services means that the aeration status of urban soils cannot be so easily determined. Consequently, analysis of corrosion patterns was designed to utilize the full detail of information that could be derived from the rods throughout their depth.

Colderick & Hodge (6) found that many of the rods extracted from urban soils had a surprisingly high proportion of shiny metal remaining after three months in the soil. The reason for this was not clear. Great care was taken to remove the protective film of engineering oil before inserting the rods, and the top centimeter of rod exposed to the air above the surface level always showed an even covering of red/brown rust indicating that the rods had a normal propensity to corrode.

In order to further develop techniques for the use and interpretation of steel rods two further pieces of research were undertaken:

i. A laboratory study to aid interpretation of corrosion patterns and to help explain the presence of uncorroded metal on steel rods after three months in the ground.

ii. A field study using steel rods around semi-mature plane trees. The aims of the study were to investigate the relationship between urban site conditions and tree growth, and to further develop methods of assessing and quantifying urban soils.

Materials and Methods

Interpretation of corrosion patterns. This randomised block experiment was carried out in open topped pipes. Twenty cm diameter plastic pipe was cut into 70 cm sections, and a plastic plate bonded to seal one end of each section. 3 mm sheet plastic was inserted vertically to divide each pipe into two halves. The treatments were:

Soil: Sandy loam and clay loam. No organic horizon was included in the soil and no attempt was made to maintain an intact soil profile in the pipe. This approximates to the situation commonly encountered in urban soils.

Compaction: (A) 10 kg weight dropped from 20 cm above the soil surface 10 times onto each 15 cm layer of soil put into the pipe. Half of the soil in each pipe was compacted, the dividers separating the compacted and uncompacted soils. A purpose designed tool was constructed to ensure the application of even force over the surface of the soils to be compacted. (B) *No compaction.* Soil put into pipes loosely and allowed to settle by gravity as the pipe was shaken and tapped.

The dry bulk density resulting from the compac-

Table 2: Dry bulk density (g/cm^3) of soils used in the laboratory study of steel rod corrosion patterns.

	loose	compacted
sandy loam	1.44	1.59
clay loam	1.17	1.39

tion treatments were assessed (Table 2). The clay loam was well structured, with a gravel content that appeared to reduced the compacting effect of tamping.

Soil Moisture Regime:

- Waterlogged for three months. Standing water remained present on the soil surface throughout the period.
- Field capacity for three months. The field capacity treatment involved irrigating the soil twice a week and allowing excess water to drain away through holes drilled around the base of the pipes.
- Initial irrigation to field capacity followed by no further water.
- Waterlogged for six weeks followed by field capacity for six weeks.
- Field capacity for six weeks followed by waterlogging for six weeks.

Rods were inserted for a three month period into the pipes; four rods to each pipe half. The pipes were kept undercover in an unheated lean-to. After extraction and cleaning (described in 9) the corrosion pattern on each rod was evaluated along two lines down the rod, 180° apart. The presence of each corrosion type was recorded to the nearest 0.5 cm, in each 3 cm section. Using the total of the two scores for any 3 cm section, each corrosion type could have a score from 0 to 12.

Two principal component analyses were used to interpret the variation in corrosion patterns between treatments. The first analysis was of the combined presence of matt grey, smooth black and shiny metal, which Carnell and Anderson (5) interpreted as indicative of conditions hostile to root growth. The second analysis was on the red/brown rust and raised black, indicative of conditions suitable to rooting.

Rods around semi-mature plane trees. The site, methods and results of this study are described fully in (10). This paper focuses on aspects of the study relating to the development of the steel rod technique.

A group of 35 semi-mature London plane (*Platanus acerifolia*) was selected at each of three adjacent sites at Milton Keynes (Buckinghamshire, England). The underlying soil of the area is slightly stony calcareous clay. Trees 1 to 35 formed two parallel rows in the 5 m wide central reservation of an urban dual-carriageway, which was surfaced with a 25 cm layer of compacted "2 cm to dust" gravel. The underlying soil had a mean bulk density of 1.9 g/cm^3. Trees 36 to 70 were in a single row, planted in 0.5 m gaps between paving stones of a car park. The underlying soil had a mean bulk density of 1.8 g/cm^3. Trees 71 to 105 formed a single row on a turf area adjacent to the car park. The underlying soil also had a mean bulk density of 1.8 g/cm^3.

Steel rods were inserted for three month periods; spring, summer, autumn and winter, using the specification and technique described in Hodge & Knott (9). Three rods were inserted around each tree, one in the planting pit and two at one metre from the tree 180° from each other. Where possible, rod positions were moved at each insertion to avoid any influence of the hole left by previous insertions.

After extraction and cleaning the corrosion pattern on each rod was evaluated along two lines down the rod, 180° apart. During the first year of the study rods were assessed in 3 cm long sections and an anaerobism score of between 0 (no anaerobism) and 12 determined for each section. This score was derived from the proportion of the 3 cm sections occupied by grey, smooth black and shiny metal, which Carnell & Anderson (5) interpreted as indicative of conditions hostile to root growth. Using the mean of the two scores for any 3 cm section, each rod was represented by 20 data values. It was hoped that principal component analysis would indicate ways of combining parts of the data set allowing simplification of future rod assessments.

Results

Interpretation of corrosion patterns. The first stage in processing the data from rods inserted into the different water regimes, compaction levels and soil types was to undertake principal component analysis. Analysis of the combined presence of matt grey, smooth black and shiny metal combined was able to explain 54% of the variation in the steel rod corrosion patterns. The most important factor was the amount of matt grey between 9 and 36 cm. Second was the amount of shiny metal between 12 and 45 cm, and third was the contrast between the amount of shiny metal from 6 to 24 cm and that from 36 to 54 cm.

Principal component analysis of the occurrence of red/brown rust was able to explain 81% of the variation in steel rod corrosion patterns. The most important factor from this analysis was the total rusting score. Second was the contrast between rusting on the top 30 cm and bottom 30 cm of the rod, and third was the contrast between rusting on the top quarter of the rod and that in the middle.

Analysis of variance was undertaken using the six factors revealed by principal component analysis, in order to compare the corrosion patterns resulting from different treatments in the laboratory study. Significant water regime, compaction and soil type effects were found. The occurrence of the different corrosion types is shown in Figures 1 to 4.

The Effect of Water Regime. The waterlogged treatment resulted in rods with significantly more matt grey (from 9 to 36 cm) than other water regimes, particularly in the clay loam which had higher bulk densities than the sandy loam. This was accompanied by a significantly lower presence of red/brown rust. The presence of smooth black was largely restricted to well below the surface of the waterlogged zone. Smooth black was more prevalent in the rods from the clay loam (Figure 2) where sulphates were available in the soil to support the hydrogen sulphide producing anaerobic bacteria that cause this corrosion type.

The drought treatment resulted in rods with more shiny metal on the top than the bottom, and more red/brown rust (indicative of aerobic conditions) on the bottom than the top compared to the other treatments.

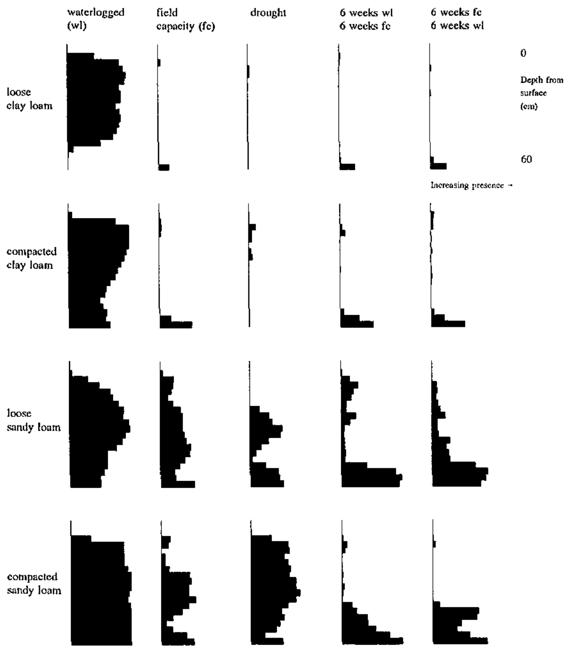

Figure 1: Presence of matt grey corrosion on steel rods after three months under five soil moisture regimes.

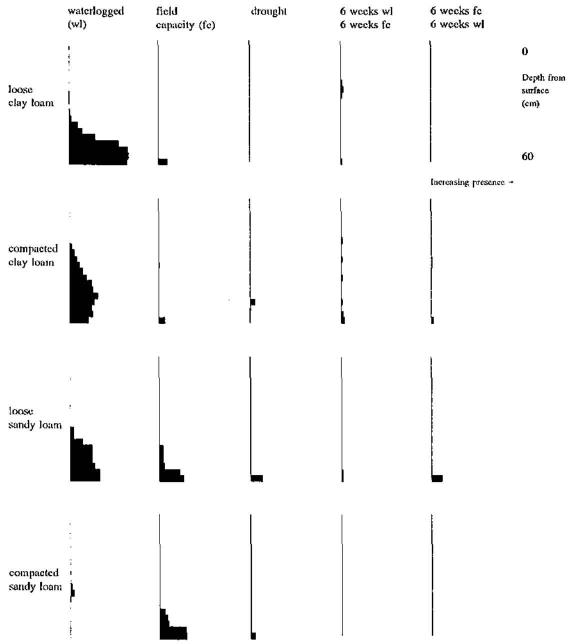

Figure 2: Presence of smooth black corrosion on steel rods after three months under five soil moisture regimes.

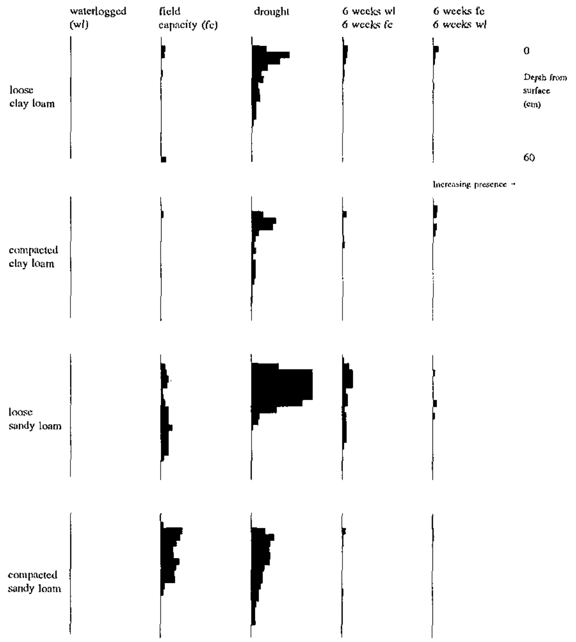

Figure 3: Presence of shiny metal on steel rods after three months under five soil moisture regimes.

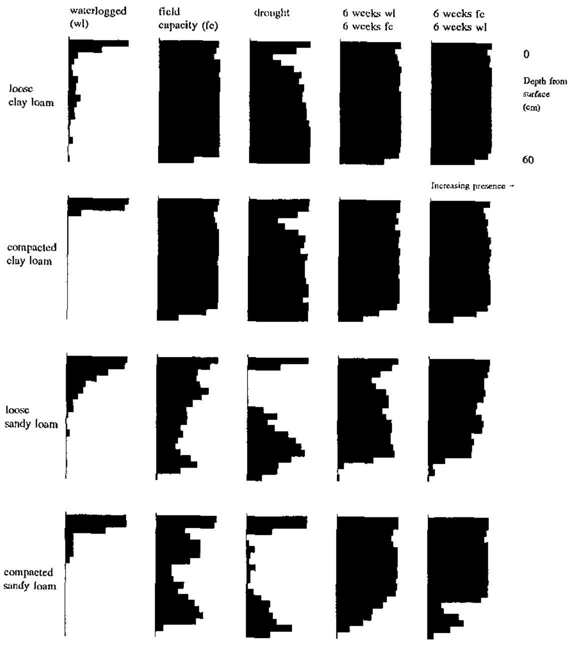

Figure 4: Presence of red/brown rust on steel rods after three months under five soil moisture regimes.

There were no clear distinctions between the field capacity, field capacity then waterlogged and waterlogged then field capacity treatments, all of which resulted in rods with a predominance of red/brown rust. However, there was a trend of an increasing presence of matt grey (indicative of anaerobic conditions) towards the bottom of rods in soils subjected to waterlogging for part of the time (Figure 1).

The Effect of Compaction. Rods from the compacted and droughted sandy loam had more matt grey than rods from the uncompacted, droughted sandy loam. Compacted soil had less red/brown rust below 30 cm than uncompacted soil, and, in the dry soil, less red/brown rust in the middle of the rod compared to the top. These factors indicate the interrupted diffusion of oxygen into the compacted soil.

The Effect of Soil Type. The sandy loam tended to show more evidence of inhospitable conditions than the clay loam, with more matt grey on rods in the field capacity and drought treatments and consequently less red/brown rust. With the field capacity then waterlogged treatment, rods in the clay loam tended to show more red/brown rust at the bottom than those in sand, and there was significantly more shiny metal on rods in the sandy loam. This result is probably due to the lower bulk density of the loose and compacted sandy loam over their clay loam counterparts.

Interpretation of Shiny Metal. A professional corrosion expert was consulted on the possible explanations for the presence of shiny metal on rods that had been in the soil for three months. The most likely reason is the action of 'differential aeration cells,' particularly in drought prone coarse textured soils. Local differences in the packing of the soil and in its moisture content may cause the development of these cells within which the area with the least oxygen in anodic and therefore relatively corrosive, whilst the areas of greater oxygen concentration are more cathodic than the metal of the rod and hence able protect the metal from corrosion.

Steel rods around semi-mature plane trees. Principal component analyses were carried out on the data from the steel rods inserted in three site types at Milton Keynes. The analysis showed that the patterns of anaerobism on both rods at 1 m from the tree were similar, but were very different from the rods removed from the planting pit. Subsequent analyses were thus based on the anaerobism scores from the two rods 1 m from the tree combined, and the scores for the individual rods in the planting pit. Subsequent analyses were carried out on each of six combinations of rod location (at 1 m or in the planting pit) and season (rods removed in spring, summer and autumn). A final analysis combined the data from all seasons for each rod location.

Principal component analysis of the presence of inhospitable conditions on rods 1 m from the tree was able to explain about 50% of the variation in steel rod corrosion patterns in each of the three seasons. The most important factor from this analysis was the total anaerobism score for each rod, and second was the contrast between the anaerobism scores on the top 30 cm and bottom 30 cm of each rod.

The amount and pattern of corrosion on rods in the planting pits varied considerably between sites and seasons. However, in the spring the most important feature was the anaerobism scores from the bottom 30 cm of each rod in the planting pit, and second was the anaerobism scores from 6 to 24 cm. In the summer the most important feature was the anaerobism scores from 21 to 45 cm, and second was the contrast between the anaerobism scores from 45 to 60 cm and that from 6 to 27 cm. In the autumn the most important factor was the anaerobism scores from 27 to 60 cm, and second was the anaerobism scores from 9 to 27 cm.

When undertaken with all of the rod data together the principal component analysis indicated that the most important factor overall was the total anaerobism score for each rod, and second was the contrast between the anaerobism scores on the top 30 cm and bottom 30 cm of each rod.

Discussion

The steel rod technique offers the potential to be a valuable tool for the assessment of aeration in urban soils. However, for the technique to be viable it must be both practical and reliable. The practical aspects of the technique are discussed in Hodge & Knott (9). The work reported here aimed to verify the reliability of the technique in the urban situation.

The laboratory study verified that the corrosion patterns on steel rods are reliable indicators of the difference between contrasting soil moisture and aeration regimes. However, differences between the field capacity treatment and treatments with a fluctuating water table were not apparent from analysis, all three treatments having a high proportion of red/brown rust. Whether this lack of ability of the technique to differentiate between these soil moisture regimes is of practical importance with respect to the performance of trees is debatable. For substantial amounts of red/brown rust to develop on the rods, oxygen must be available for a substantial part of the three month insertion period. Even in waterlogged conditions, there is enough oxygen dissolved in the soil water and in air pockets to cause some red/brown rust formation, and hence to be of some value to tree roots. In situations where rapidly changing soil moisture regimes are expected the period of rod insertion could be reduced to two months.

The reasons for the presence of uncorroded metal on extracted rods has been clarified by the laboratory study. Carnell & Anderson (5) worked in upland gley soils which had a substantial organic horizon. The presence of uncorroded metal on extracted rods related well to this horizon and justified the interpretation that the metal was protected from corrosion by organic compounds (Table 1). No other significant occurrences of shiny metal were noted, presumably because conditions in the upland soil were not conducive to the operation of differential aeration cells, which the laboratory study found to be most prevalent in dry, coarse textured soils. In the urban situation the presence of shiny metal on extracted rods is not a good indicator of suitability for root growth and substantial occurrence must be interpreted with caution. Hodge & Knott (9) gives procedures for analysis of rods with a substantial presence of shiny metal.

Whilst the laboratory study aimed to confirm the interpretation of corrosion types, the field study sought to refine the method of steel rod evaluation.

In the field study the most important factor for interpreting the steel rod corrosion patterns tended to be the total anaerobism score for the whole rod, and second was a contrast between the top 30 cm and the bottom 30 cm of the rod. However, in some instances contrasts involving shorter sections of rod were also important. Consequently, it appears that the collection of corrosion data for statistical analysis in 15 cm sections rather than 3 cm sections does not result in a significant reduction in the amount of information obtained from the rods, whilst allowing considerable time savings in the collection of data to be made. This simplification was verified by principal component analysis of the steel rod data from the laboratory study, and was subsequently adopted in the field study.

The field study also indicated that the total anaerobism score for each rod and an expression of contrast between the total anaerobism score on the top and bottom halves of the rod (for example: the anaerobism score from 0 to 30 cm minus the score from 31 to 60 cm for each rod) could be used as values expressing the aeration status of the soil in regression comparisons. This approach was validated by the laboratory study which highlighted the same two factors. The applicability of this approach was confirmed in the field study where these expressions of soil aeration status were related to annual shoot extension, leaf size, leaf colour and crown density of 105 London plane trees over two years (10).

Colderick & Hodge (6) found the comparison of rusting profiles of rods inserted for three month periods, corresponding to the spring, summer, autumn and winter, made it possible to determine whether anaerobic conditions were due principally to waterlogging (extent of anaerobism high in the winter and lower in the summer) or compaction (extent of anaerobism high all year). On some sites distinct compacted pans could be discerned using the steel rod technique in this way (8). The Milton Keynes field study indicated that, if monitoring over a whole year is not possible, rods inserted for three months over the spring yielded data most closely related to tree performance (under English climatic conditions) (10). During the spring new root growth is susceptible to adverse soil moisture conditions and such conditions, be it soil drying or waterlogging, can quickly develop, particularly in compacted urban soils. Adverse conditions for rooting in the spring are likely to affect the condition of the above ground parts of the tree during the summer.

Conclusions

The assessment and interpretation of soil aeration is notoriously difficult. The conventional methods using an oxygen probe or platinum micro-cathodes each have severe limitations. The steel rod technique was initially used to investigate forest soils and the only assessment undertaken was the depth to the onset of waterlogged conditions. Colderick & Hodge (6) found that such simple measures were not adequate in evaluating the aeration status of disturbed urban soils and more comprehensive procedures were developed.

The technique has now been further refined into an reliable and effective method of assessing the vertical and spatial distribution of soil aeration in urban soils; even those covered by hard surfaces.

The laboratory study confirmed the interpretation of the four corrosion types and clarified the reasons for the presence of uncorroded areas on some extracted rods. If shiny metal occurs in association with soils containing undecomposed organic matter, it is indicative of conditions hostile to rooting. In other soils, particularly drought prone coarse textured soils, the presence of substantial amounts of shiny metal cannot be used as an indicator of suitability for root growth.

Evaluation and analysis of steel rod corrosion patterns from the field study showed that data can be collected in four 15 cm sections down the rod without significantly reducing the amount of information obtained from the rods compared to data collection in 3 cm sections. For statistical analysis the total anaerobism score for each rod and the total anaerobism score from 0 to 30 cm minus total score from 31 to 60 cm for each rod can be used as values expressing the aeration status of the soil.

The information derived from steel rods is maximised if a comparison of results can be made between seasons. If this is not possible, rods should be inserted for the spring.

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Résumé. Les études sur les arbres en milieu urbain nécessitent des méthodes pour évaluer les conditions physiques du sol, parfois sous la couche durcie de la surface. La technique de la tige d'acier a été développée afin d'évaluer le degré d'aération du sol. Le développement de cette technique et des procédures analytiques sont discutées. La principale composante d'analyse a démontré que la meilleure image des patrons de corrosion se constitue de la somme des marques de celles indiquant des conditions inhospitalières ainsi que du contraste des conditions inhospitalières entre les 30 premiers centimètres de sol et les 30 inférieurs suivants. Les résultats d'une étude sur une situation de corrosion contrôlée sont reportés et les caractéristiques de corrosion pour divers degrés d'humidité du sol sont spécifiées.

Zusammenfassung. Studien an Strassenbäumen erfordern Mittel und Wege, um die physikalischen Bodenbeschaffenheiten manchmal auch unter harten Strassenbelägen zu bewerten. Die Stahlstangentechnik wurde entwickelt, um die Bodenbelüftung zu untersuchen. Die Entwicklung der Technik und das analytische Vorgehen sind umstritten. Eine grundsätzliche Analyse der Komponenten ergab, daß die beste numerische Wiedergabe der Korrosionserscheinungen die totale Erfassung derjenigen ist, die unwirtliche Bedingungen zeigen und der Kontrast zwischen den unwirtlichen Bedingungen in den oberen 30 cm und den unteren 30 cm. Die Ergebnisse einer kontrollierten Erosionsstudie sind wiedergegeben und die Korrosionscharakteristiken von verschiedenen Bodenfeuchtigkeitsbereichen angezeigt.