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Multidisciplinary investigation of tree falling risk: a case study of Pau-Ferro, in São Paulo City / SP

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Abstract

Objective: Diagnose and analyze the falling risk of the pau-ferro tree using a methodology developed by the authors, described in the form of a conceptual flowchart, which includes results of the phytosanitary diagnosis, eventual soil movement, trunk inclination, as well as geophysical methods for risk evaluation and management.
Methodology: Application of procedures to analyze the risk of falling trees considering external and internal aspects, using non-destructive equipment, along with trunk inclination control, vertical soil displacement, tree root outcrop and subsoil characterization integrating geophysical methods.
Originality/Relevance: This study applied civil engineering and geophysical techniques to analyze tree falling risk in urban areas.
Results: The tree specimen used in this study had an apparent cavity and intense wood rotting, as well as, a bent and detached root, making it impossible for the tree to anchor and support itself. The concentration of roots, below the surface of the ground, did not provide stability due to the evolution of the vertical displacement of the surface and inclination of the trunk towards an avenue, and its suppression was recommended due to the risk of falling.
Social/Management Contributions: Trees offer numerous benefits and obtaining these depends on proper management and monitoring. Decision making regarding the risk of falling should be preferably based on several analyses, and non-destructive methods, reducing uncertainties so that trees are not removed unnecessarily.

Keywords: Tree. Falling risk. Soil. Geophysics.

Investigação multidisciplinar do risco de queda de árvore: estudo de caso em Pau-Ferro, na Cidade de São Paulo / SP

Resumo

Objetivo: Diagnosticar e analisar o risco de queda da árvore de pau-ferro a partir de uma metodologia desenvolvida pelos autores, descrita na forma de um fluxograma conceitual, e que integra resultados do diagnóstico fitossanitário, de eventuais movimentações do solo, da inclinação do tronco e, também, de métodos geofísicos para a tomada de decisão do risco e manejo.

Metodologia: Aplicação de procedimentos para análise do risco de queda da árvore considerando aspectos externos e internos, utilizando equipamentos não destrutivos, em paralelo ao controle da inclinação do tronco, dos deslocamentos verticais do solo e da raiz aflorada da árvore, além da caracterização do subsolo integrando métodos geofísicos.

Originalidade/Relevância: Este trabalho mostra a utilização de técnicas da engenharia civil e da geofísica para a análise do risco de queda de árvore no ambiente urbano.

Resultados: O exemplar arbóreo utilizado como estudo de caso apresentava cavidade aparente e apodrecimento intenso do lenho, além de raiz dobrada e descolada do solo, o que impossibilitava sua ancoragem e sustentação. A concentração de raízes abaixo da superfície do terreno não garantia a estabilidade devido a evolução dos deslocamentos verticais de superfície e inclinação do tronco para a avenida, sendo indicada sua supressão por apresentar risco de queda.

Contribuições sociais/para a gestão: As árvores oferecem inúmeros benefícios e a obtenção destes privilégios depende de uma gestão adequada que considere o seu manejo e monitoramento correto. A tomada de decisão do risco de queda deve estar pautada em diversas análises, preferencialmente baseadas em métodos não destrutivos, diminuindo as incertezas para que árvores não sejam suprimidas sem necessidade.

Palavras-chave: Árvore. Risco de queda. Solo. Geofísica.

Investigación multidisciplinaria del riesgo de caída de árboles: un estudio de caso en Pau-Ferro, en la ciudad de São Paulo / SP

Resumen

Objetivo: Diagnosticar y analizar el riesgo de caída de árboles de pau-ferro utilizando una metodología desarrollada por los autores, descrita en forma de diagrama de flujo conceptual, que incluye resultados del diagnóstico fitosanitario, eventuales movimientos de suelo, inclinación del tronco y, así como métodos geofísicos para la decisión de riesgo y manejo.

Metodología: Aplicación de procedimientos para analizar el riesgo de caída de árboles considerando aspectos externos e internos, utilizando equipos no destructivos, en paralelo al control de la inclinación del tronco, desplazamientos verticales del suelo y afloramiento radicular del árbol, además de la caracterización de los métodos geofísicos de integración del subsuelo.

Originalidad/Relevancia: Este trabajo muestra el uso de ingeniería civil y técnicas geofísicas para analizar el riesgo de caída de árboles en el entorno urbano.

Resultados: El ejemplar de árbol utilizado como caso de estudio presentaba una aparente cavidad y una pudrición intensa de la madera, así como una raíz torcida y desprendida del suelo, lo que imposibilitaba su anclaje y apoyo. La concentración de raíces, por debajo de la superficie del terreno, no garantizaba la estabilidad debido a la evolución de los desplazamientos verticales de la superficie e inclinación del tronco hacia la avenida, y se indica su supresión por presentar riesgo de caída.

Contribuciones sociales/de gestión: Los árboles ofrecen numerosos beneficios y la obtención de estos privilegios depende de una adecuada gestión que considere su adecuado manejo y seguimiento. La toma de decisiones sobre el riesgo de caída debe basarse en varios análisis, preferentemente basados en métodos no destructivos, reduciendo incertidumbres para que no se eliminen árboles innecesariamente.

Palabras clave: Árbol. Riesgo de caída. Suelo. Geofísica.

Introduction

The Associação Brasileira de Normas Técnicas (2019) norm number 16246-3, establishes requirements for tree risk assessment along with structural integrity and other factors that affect the level of risk for people, property and public services in order to orient proper tree risk management.

The question of integrity and the risks associated with trees has been the focus of much research in the past. Since the 1960s there has been an increasing increase in the number of tree stability studies. However, there are still many uncertainties and limitations concerning risk analysis of falling trees, thus difficulting decisions on appropriate management (Amaral, 2002, 2014; Brazolin, 2009; Bobrowski, 2016; Rodrigues, 2019). Rollo (2009) states that desirable falling tree risk assessment should include stages of both external visual and internal analysis, criteria for assessing rupture and decision-making management. However, in many cases, only external visual analysis is used to assess risk and this does not consider possible internal damage (Carvalho, 2019). The importance of internal evaluation methods is that it allows an examination of the conditions of each individual tree and the degree of resistance to such factors as flexion, torsion, shear and transverse forces (Bobrowski, 2010).

Due to this, the Instituto de Pesquisas Tecnológicas do Estado de São Paulo (2003), IPT, initially developed a methodology to diagnose the presence of *xylophagous* organisms, which considers external visual analysis and non-destructive internal analysis of the trunk and improved the fall risk analysis based on the biomechanics of trees (Niklas, 1992; Mattheck & Breloer, 1997; Instituto de Pesquisas Tecnológicas do Estado de São Paulo, 2004; Brazolin, 2009; Amaral, 2014). Then, in mid-2019, the IPT expanded its studies to include the influence of local soil and the tree root analysis that which are rarely considered in tree falling risk analyzes carried out in Brazil. The adoption of these activities in the analysis of a living organism constitutes an innovation, as it brings added and important information for tree falling risk management and decision-making, based on the analysis of the non-apparent, root system, the understanding of soil behavior and its influence on tree inclination.

In the present study, an innovative approach is discussed through a case study of an ironwood tree, for decision-making in the management of the tree specimen.

Methodology

Study area characterization

The present study applied the developed methodology in an ironwood tree of the botanical species *Libidibia ferrea*, family fabaceae, located in the garden of the *Adriano Marchini* Building, at Institute of Technological Research of the State of São Paulo (IPT), at the main campus of the University of São Paulo (USP), in São Paulo City (Figure 1A).

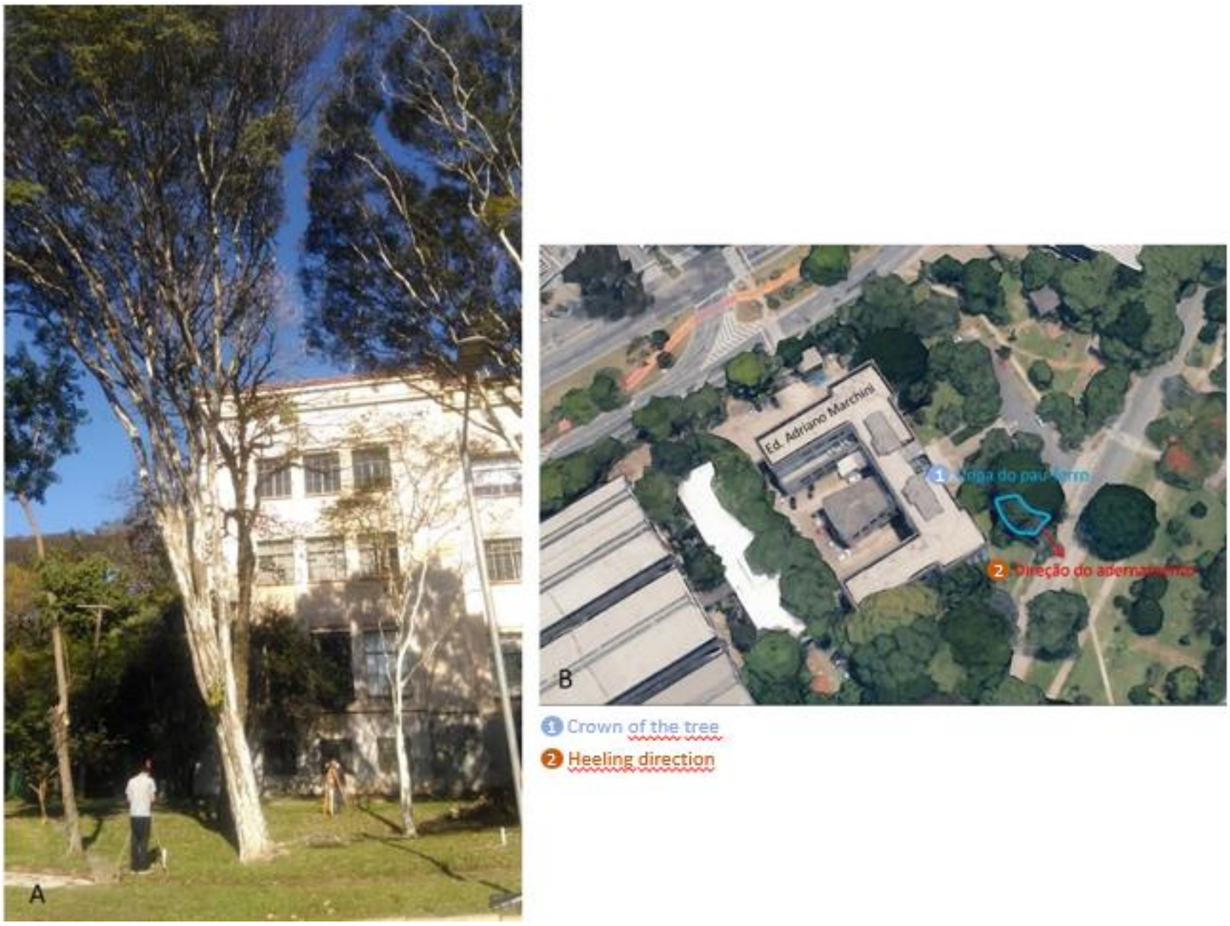
The predominant climate of the region is tropical, characterized by hot, rainy summers and a dry, slightly cold winter (*Climatologia de São Paulo*, 2022). The topography of the location is flat and given the proximity to an important waterway, the ground water level is high. The surface layers of the soil have organic matter and high deformability.

The tree was located in a landscaped area, with permeable soil, with no obstructions for full development. Other trees were sparsely distributed at the site. The specimen had a total height of approximately 18 m, diameter at breast height (DBH) of 58 cm and crown area of 22 m². As there is no precise information about the age of the tree, estimated calculations put this tree to be 20 years old, based on the average size of adult trees (São Paulo, 2015).

IPT has an urban forest management plan on its campus and this tree was diagnosed with an apparent cavity and trunk inclination - a fact rarely observed empirically in trees of this species, and therefore the need for specific monitoring, especially due to the fact that its eventual fall would reach the *Professor Almeida Prado* Avenue, a high-density traffic avenue and the main connection to the University of São Paulo bus terminal.

Figure 1

(A): Picture of the ironwood tree located in the garden of the Adriano Marchini Building - IPT, at the USP main campus in São Paulo City; and (B): Location of the pau-ferro in relation to local roads, with a tendency to tip over towards Prof. Almeida Prado Avenue



Source: Author elaboration.

Methodological procedures and application assumptions

Monitoring this tree specimen involved carrying out periodic inspections to: I) verify the progression of biodeterioration (xylophagous termites and rotting fungi) and to categorize the tree according to its risk of falling into low, medium or high for trunk rupture; II) control the inclination of the trunk; III) evaluate the geotechnical action of the subsoil in terms of its long-term resistance and deformability; and IV) analyze the root system that was found below the ground surface next to the tree and the main physical and lithological characteristics of the subsoil to complement the geotechnical investigations.

In order to analyze the risk of falling of the pau-ferro tree - especially in cases where the categorization of the risk of rupture in the trunk results in a low or medium level - and to make management decisions, such as pruning or suppression, some conceptual premises were admitted to integrate all the methods used, namely:

a. Tree under study was located in an urban environment;
b. The root depth up to 0.7m;
c. Ironwood trees usually do not have a leaning trunk or exposed roots;
d. Although it is a living being, the tree can be associated with a cantilevered beam - type structural element, with a double link (rotation is allowed), in analogy to civil engineering studies;
e. The biomechanics axiom of equivalence and uniformity of resistance between the tree trunk and root hold true;
f. There were no nearby excavations that could compromise the tree;
g. There was no underground construction work near the tree location;
h. Soil Mechanic concepts and laws of are valid in characterizing the massif in which the tree under study is found;
i. Invasive (non-harmful) and non-invasive (geophysical) tests can be carried out to investigate the soil mass characteristics where the tree is located;
j. The terrain surface may be paved, vegetated or exposed but in paved areas it may be more difficult to perform geophysical tests, with the exception of GPR.

1 Biodeterioration progression

Biodeterioration progression verification was carried out by means of periodic inspections, every three months, during a period of nine months, using the IPT patented tree inspection technology, a method established in a (Instituto de Pesquisas Tecnológicas do Estado de São Paulo, 2003), and the Arbio software (Viríssimo et al., 2013) for the registration of external analysis methodologies, internal analysis of the stem and fall risk simulations for trunk rupture. The evaluation of the tree was carried out at ground level, with no work being carried out at heights, according to ABT norm NR 35 - Work at Heights.

1.1 External analysis

For this analysis, six items were considered: botanical identification; dendrometry; density; general state; surrounding conditions; and phytosanitary status. The complete description of each is reported below, regardless of whether it was observed in the ironwood tree of the case study:

a. Botanical identification - carried out at the possible taxonomic level, according to the vegetative material (flower, fruit and leaves) available at the time of analysis;

b. Dendrometry - with the aid of a forestry tape and a hypsometer, the following tree characteristics were surveyed: total height, height of the 1st bifurcation, crown area, approximate trunk eccentricity and inclination angle, diameter at breast height - DBH and collar diameter – DC when the first fork was less than 1.30 m;

c. Apparent tree density to provide information on the mechanical properties of the wood - determined from the identification of the tree species and by consulting the available literature classification (Lorenzi, 1992; Silva et al., 2021);

d. General condition - initially classified as: dead (no sap flow); declining (showing signs of disease, such as loose bark, dry branches or dead tree parts or vigorous (with no signs of disease or pests). For the apparent roots, the occurrence of bending or coiling, wound/pruning and physical barrier were evaluated. For trunk evaluation, the existence of multiple trunks, accentuated inclination, ingrown bark, wounds, cracks and apparent cavity, up to a height of two meters, were observed. The evaluation of the general condition of the crown consisted of visual observation of epiphytes and parasites (*mata pau* fig tree, mistletoe and egg threads), unbalanced crown (displacement of the center of gravity), dry or deteriorated branches, tree stumps, pruning, epicormic branches, inadequate pruning (a pronounced “V”, drastic, lateral and with deterioration) and rotten 1st bifurcation, insect attack or cracks, along with observable positive aspects of adapted growth or self-optimization of the tree (biomechanics) was verified to overcome defects, such as longitudinal thickening ("ribs"), thickening/protuberance in the trunk and tabular roots. The occurrence of anthropic actions, such as girdling, strangulation, whitewashing/painting, vehicle collision, buried neck, filling cavities, poisoning and attached objects, were also verified;

e. Surrounding conditions – refer to aspects of the built environment that could affect the development of the tree and its exposure to wind. The analyzed attributes were:

interferences with overhead electric power lines (primary network, secondary network, home, electrical branch, cable and transformer), inspection box, tree species, building façades, underground installations (water, sewage, river, gas and electrical cables), street furniture and poles. If the tree was located on the street, information on the sidewalk (width and free lane for pedestrians) and the construction site (adaptation of the permeable area and dimensions) were also collected. In regard to tree wind exposure, the layout of the buildings and other surrounding trees that could offer some form of protection barrier to the tree under were also noted;

f. Phytosanitary status - the occurrence of rotting fungi, xylophagous termites and wood borers were verified in the root system (when exposed), in the trunk and crown (1st bifurcation), up to a height of two meters.

The presence of rotting fungi was characterized by the observation of fruiting bodies or by wood attack classified by the following intensity categories: superficial; moderate, when it reached the sapwood; or intense, when it progressed to the core.

In the case of termites, the identification was based on nesting habits (underground, arboreal or wood), on the occurrence of nest structure, tunnels or vestiges, on wood attack, on soil dispersion and on the presence of residues (feces). and activity (live insects). The occurrence of wood borers was observed by the attack on the wood (holes, residues or exudate) or by the presence of the insect.

When present, termites and wood borers were collected with tweezers and placed in jars with 70% alcohol and the fruiting bodies of rotting fungi in paper bags. The identification of these organisms was carried out by the IPT.

1.2 Internal analysis

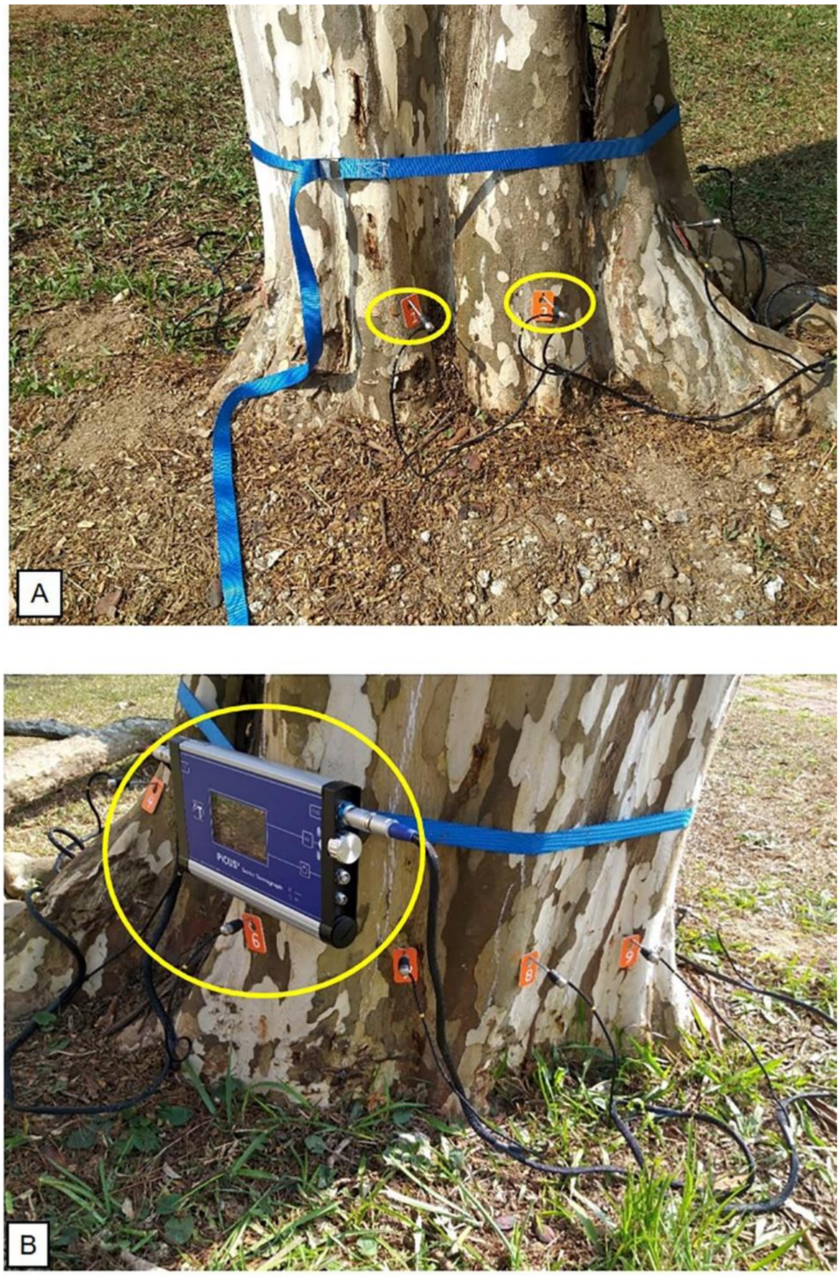
The tree was internally analyzed for deterioration and quantification of healthy wood (sapwood or heartwood). This analysis was carried out through non-destructive prospecting, with the use of a penetrograph-type device, with a 1.5 mm diameter drill. Analyzes with this equipment are based on the information that during the wood deterioration process, there is a decrease drilling resistance. It should be noted that the penetrograph only records the data that are found at the spot where the drill passes. The surveys were carried out in the collar (root and trunk transition), at an approximate height of 10 cm from the ground, as tensions are concentrated at this location due to wind forces on the crown and the weight of the tree, which can lead to a rupture.

To complement the data obtained from prospecting, a more detailed inspection of the entire cross-section of the tree was carried out using a mechanical impulse tomograph (Figure

2) which, by propagating sonic waves through the interior of the tree, creates a map of traversed velocities in the wood that represent alteration processes. With these two analyses, the internal condition tree was diagnosed as healthy or deteriorated by xylophagous organisms. When the existence of internal deterioration was verified, the approximate percentage of the deteriorated area was calculated in relation to the cross-sectional area of the trunk, establishing the following deterioration classes: small, from 1.0 to 11.0%; average, from 11.1% to 44.0%; and large, above 44.1%, according to the classification proposed by Brazolin (2009).

Figure 2

(A): Tomographic sensor modules; and (B) mechanical wave calculation processing unit



Source: Author elaboration.

1.3. Trunk rupture risk analysis

Trunk rupture risk analysis was based on external and internal analysis of the trunk and was restricted to the possibility of the tree rupture in the trunk, up to a height of two meters, when external evidence of problems was observed. Branch breaking was not evaluated, which would require work at height, nor the pivoting of the root system, as there is still no mathematical model in Brazil that considers the analysis of pivoting or pulling out of the root system (clod). For this analysis, we took into account the information obtained in the external evaluations, related to the biological condition, general state and aspects of biomechanics (adapted growth or self-optimization), and internal (healthy and deteriorated), for categorization of the tree in terms of its fall risk at: low, without any significant defects; medium, with defects associated with rupture, but still with self-optimization processes and signs of maintenance of structural stability; or high, defects that pose an imminent risk of trunk rupture.

For the risk of trunk rupture, up to two meters high, the “1/3 rule” was used, that is, any internal deterioration cannot exceed 2/3 of the radius, with at least 1/3 of the radius remaining healthy wood from the surface of the trunk. This parameter is valid as long as there are no other factors, such as: wounds, hollows, crown imbalance or accentuated trunk inclination (Mattheck & Breloer, 1997).

The relationship between the total height of the tree (H) and the diameter of the trunk (D), also known as the slenderness model, was considered, with rupture risk being indicated when $H/D > 50$, for trees in areas of low strong wind incidence or protected by buildings and other trees, as in the case of the tree under study or $H/D>30$, for trees exposed to significant wind stress. This model is not valid for young trees or trees with low bifurcation in relation to the total height of the tree (Mattheck, 2007).

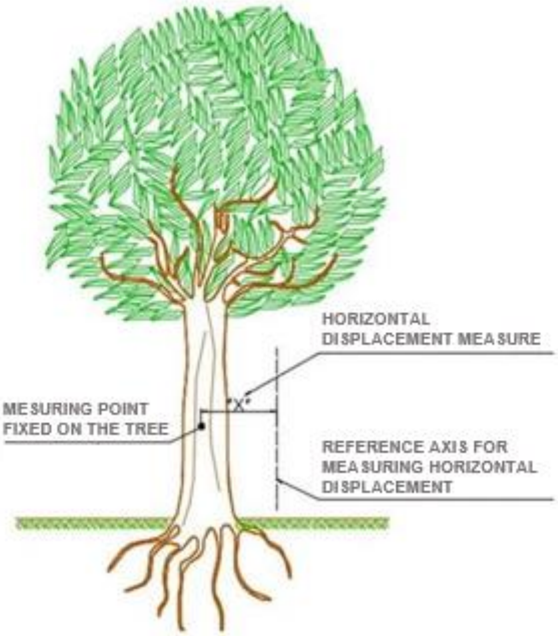
A probabilistic dynamic model was also used to assess the tree's risk of trunk rupture based on the prediction of ruin at 12 different wind speeds (Beaufort scale) (Universidade Estadual Paulista Júlio de Mesquita Filho, 2021). This model uses data from dendrometry, apparent density, internal analysis of the bole and barrier factor (surrounding conditions that indicate exposure of the tree to winds).

2 Trunk inclination control

The monitoring of the inclination of the ironwood was carried out over a period of 11 months, through two-month maximum interval readings with shorter time intervals during the rainy season. Monitoring work was carried out using topographic techniques, with the use of theodolite, millimeter ruler and steel nails to mark the reference and measurement points. The study was limited to measurements on a two-dimensional plane, measuring the horizontal displacement (x axis) of a point (Figure 3), in order to associate the measurements taken with an eventual tendency for tree inclination or leaning.

Figure 3

Slope measurement schematic drawing



Source: Author elaboration.

3 Subsoil Geotechnical Characterization

The characterization of the subsoil was carried out by monitoring the vertical displacements of the terrain surface and geophysical tests, described below:

3.1 Displacements monitoring

The monitoring of the displacements of the surface soil and the outcropped root of the pau-ferro tree was carried out over a period of seven months and its periodicity occurred according to the discussions between the teams, with a greater number of readings during rainy season period.

The objective of this study was to monitor, using specific instrumentation, the possible occurrence surface soil settlement and in the outcropped root of the ironwood tree, and their effects on the stability of the tree. The instrumentation consisted of repression pins, surface markers, nails fixed to the apparent roots and a fixed reference in the Adriano Marchini Building, with readings by means of a precision topographic level and an Invar ruler.

In parallel with field monitoring, a theoretical study of the behavior of the local soil was carried out in regard to long-term settlement development and soil support capacity for correlation with the behavior indicated by the instrumentation.

3.2. Geophysical tests

The subsurface characterization was carried out over a period of three months, based on the integration of the results of different non-invasive geophysical methods: electro resistivity (electrical imaging), seismic refraction, surface wave testing (MASW) and Ground Penetrating Radar (GPR). These techniques were applied mainly to evaluate the presence and distribution of roots that were below the soil surface, soil properties (porosity and moisture content), in addition to verifying possible underground interference to confirm the information contained in the terrain maps provided by USP.

The electro resistivity method measures the electrical resistivity distribution of the soil by injecting an electric current using electrodes fixed on the soil surface. Electrical resistivity is the ability of the medium to oppose the passage of this current, with more sandy media, for example, presenting higher resistivity values, while media with higher water content, presenting lower values. Refraction seismic and MASW measure the travel time of an acoustic wave generated by an artificial source (hammer) that travels through the layers of the soil. The speed of propagation of these waves is linked to the physical properties of the medium, such as density, water content and specifically with MASW, the stiffness of the material. GPR is a method of reflecting high frequency electromagnetic waves (10 MHz to 2600 MHz), emitted by an antenna on the surface, in which it is possible to obtain a high-resolution image of the subsoil, where the depth of investigation varies according to the frequency used and the properties of the medium.

In order to contribute to the interpretation of the results of the (indirect) geophysical tests and to obtain more reliable data, a manual drill was carried out (invasive mechanical test) for the tactile-visual characterization of the existing soil horizons in the surface layers (up to 4 m deep) of the ground.

In this geophysical analysis, an attempt was made to characterize the subsurface and relate the results to the structural behavior of the tree, together with analyzes of soil settlement, in order to assist in the analysis of the risk of falls and in decisions regarding correct management.

For the investigation of the characteristics of the subsoil, a profile was established (24 m long line) on which electro resistivity tests (electrical imaging), refractive seismic and MASW tests were carried out, as well as direct drilling with an auger hole. For electro resistivity, an array of dipole-dipole electrodes was used, with multiple spacing of 1 m and 2 m. For refraction seismic, a 24-channel seismograph and 8 Hz geophones (4 Hz for MASW) were used, in addition to a sledgehammer as a seismic source. For the characterization of the root system that was below the ground surface, an 800 MHz GPR antenna was used, with an acquisition area of 5.0 m x 5.0 m around the pau-ferro tree, with profiles in the X and Y directions spaced

0.2 m apart. The calculation of porosity and moisture content were obtained from classic models found in the literature (Topp et al., 1980; Ledieu et al., 1986) that relate the dielectric constant parameter, measured by GPR, with soil properties.

4 Fall risk flowchart analysis

From the developed studies, conceptual principles were elaborated for the organization of a flowchart that contextualized the decision-making process to evaluate the risk of falling of the ironwood tree and its management, or any other tree to be analyzed, considering the integration of all the results of the methods used, namely: classification of the trunk risk rupture, the control of the bole inclination, the evaluation of the geotechnical subsoil characteristics and the analysis of the root system that was found below the soil surface.

In the flowchart presented, the following management practices were also considered: adequacy of the construction site, permeable strip, buildings or urban equipment; target removal or restriction of occupation or movement of people; specialized technical assessment for diseases and other pests; installation of support systems, such as cabling or struts; transplanting; branch pruning; phytosanitary treatment; monitoring of the tree specimen; and suppression.

Results and discussion

The results obtained in each phase of the study are presented and discussed separately followed by an integrated analysis of the collected information allowing a consolidation of the developed methodology in the form of a guiding flowchart for decisions regarding the management of the trees in urban environments.

Biodeterioration progression

During the nine-month monitoring period of the pau-ferro tree, there was no change in dendrometry or in the progression of wood biodeterioration. The pau-ferro tree had a total height of approximately 18 m, a diameter at breast height (DBH) of 58 cm, height of the 1st bifurcation of 1.5 m, trunk inclination of 20 degrees, eccentricity and canopy area of 2 m and 22 m^2, respectively.

The tree was vigorous, located in a landscaped area, with permeable soil, and with the presence of a landfill (unconsolidated material).

The root system presented a bent and detached root from the ground (Figure 4A), making anchorage and force distribution for trunk support impossible. This root also presented some thickening; however, it was located on the traction side of the inclination of the stem (Figure 4B), which meant significant loss of anchorage.

The trunk had an apparent cavity measuring 40 cm high × 16 cm wide (Figure 4A) located on the sheared side. On both sides of the cavity, the adapted growth of "ribs" was observed, which are structural reinforcements that can structurally compensate this fragile region (cavity), however, in one of the points, it was verified the detachment/fracture of part of the wood, which may have been caused by traction stresses, due to trunk heeling.

Figure 4

A: Detached bent root and cavity site; and B: Trunk inclination with root lift

Source: Author elaboration.

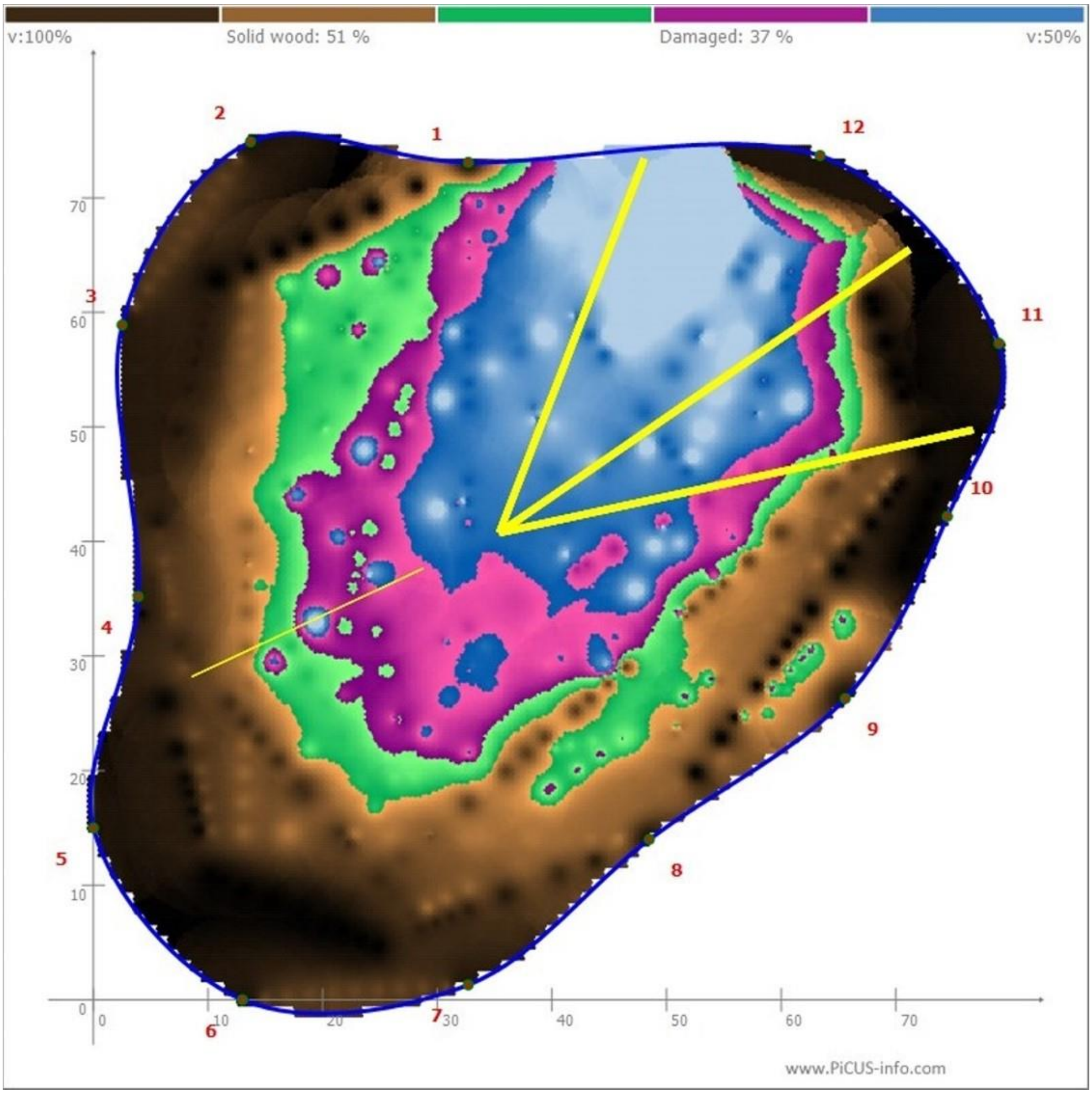
In the last crown inspection few leaves were found, compared to the other Ironwoods in the vicinity, and a slight imbalance, due to its eccentricity. Also observed were dry and senile branches, pruning stumps and epicormic shoots.

In the phytosanitary evaluation, rotting fungi of superficial intensity in the canopy, moderate in the apparent roots and intense, caused by white rot, inside the trunk cavity were found.

The Mechanical impulse tomography internal diagnosis carried out by means of (Figure 5) and prospecting (Figure 6) showed that the pau-ferro tree presented an average deterioration in the trunk region. In Figure 5, the cavity located between points 3 and 4, did not appear in the tomography probably because it was performed above this region.

Figure 5

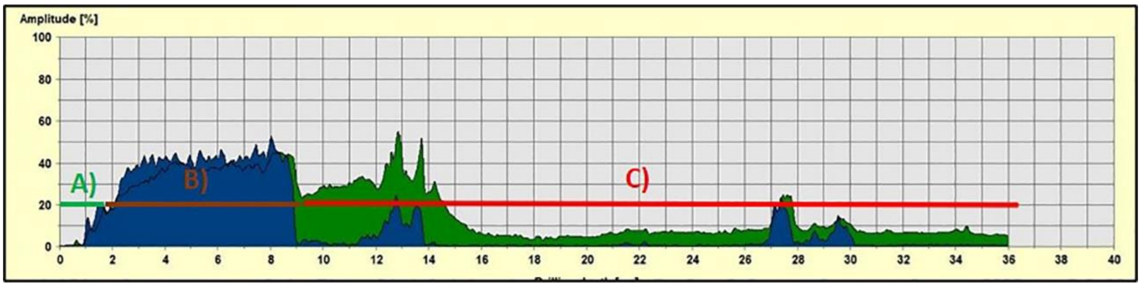
Tomographic image of the cross-section of the trunk region. The numbers on the X and Y axes indicate the approximate diameter of the analyzed section. The numbering around the geometry represents the measurement sensor points; and the yellow lines, where the wood tends to crack. The black and brown colors indicate healthy wood, with high speed of the mechanical wave; the lilac and blue colors indicate wood with intense deterioration or absence of wood (cavity), that is, low speed of the mechanical wave. The green color, wood with alteration in its mechanical properties, but still with resistance



Source: Author elaboration.

Figure 6

Reading of one of the graphs of tree trunk prospection, between points 1 and 12 (Figure 5). Indication of the wood's mechanical resistance to drill penetration (Y axis) and depth of penetration (X axis). (A): Green line represents the bark/sapwood region; (B) brown line represents healthy wood; and (C): Red line represents wood with deterioration



Source: Author elaboration.

The deterioration found in the trunk region was stable throughout the monitoring period, with little evolution, retaining its medium deterioration classification. The “1/3” rule could not be applied as the tree had an apparent cavity. The analysis of the slenderness model (H/D=19) indicated low risk, as well as the probabilistic dynamic model with a low probability of rupture, even in high winds.

Given the above, it can be concluded that the categorization of the pau-ferro tree in terms of its risk of falling and breaking the trunk, considering only the results of the external and internal analysis, can be considered as average; with defects associated with rupture, but still with self-optimization processes and signs of structural stability maintenance.

Trunk inclination control

As with soil settlement, inclination measurements indicated movement tendency, with low development.

Subsoil Geotechnical Characteristics

A) Soil displacements

Topographical measurements indicated some movement of small magnitude, confirming the presence of compressible soils in the surface layers of the terrain, where the support roots of the Ironwood were located, as indicated by the GPR results, below. It should be noted that the monitoring period was relatively short for the quantitative assessment of shifts, but long enough to confirm a behavioral trend.

B) Geophysical methods

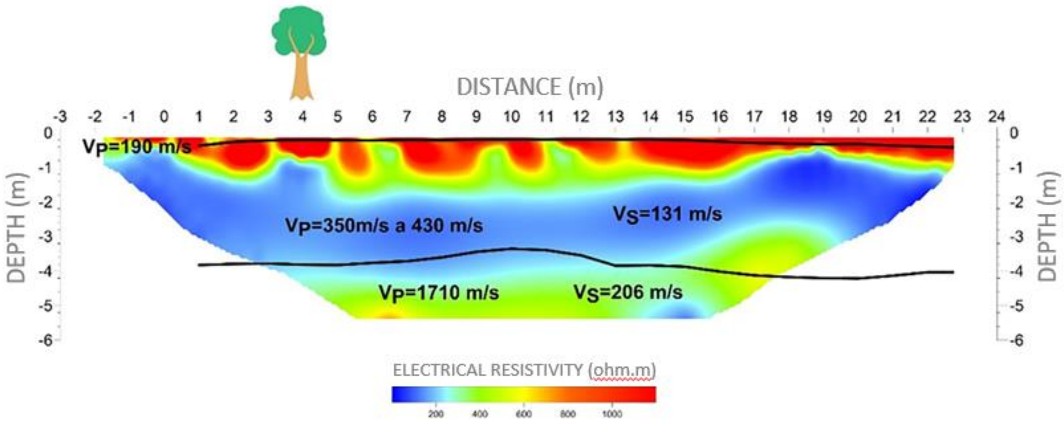
Figure 7 shows the results of the geophysical survey, in the form of a 2D section, representing the subsurface around the tree that was located at the 4 m position. The colors of the section correspond to the distribution of electrical resistivity in the subsoil, a parameter that has a strong relationship with the moisture content of the soil.

A shallower region with high resistivity values (warm colors) was observed, superimposed on a layer of low resistivity (shades in blue).

In this 2D section, additionally, interface (lines in black) and velocity value of the seismic waves, VP (compressional wave) and VS (shear wave) are marked. The parameters were obtained by the seismic refraction method and by the MASW test, respectively.

Figure 7

Modeled 2D section, with integrated results of the geophysical tests (electro resistivity, seismic refraction and MASW)

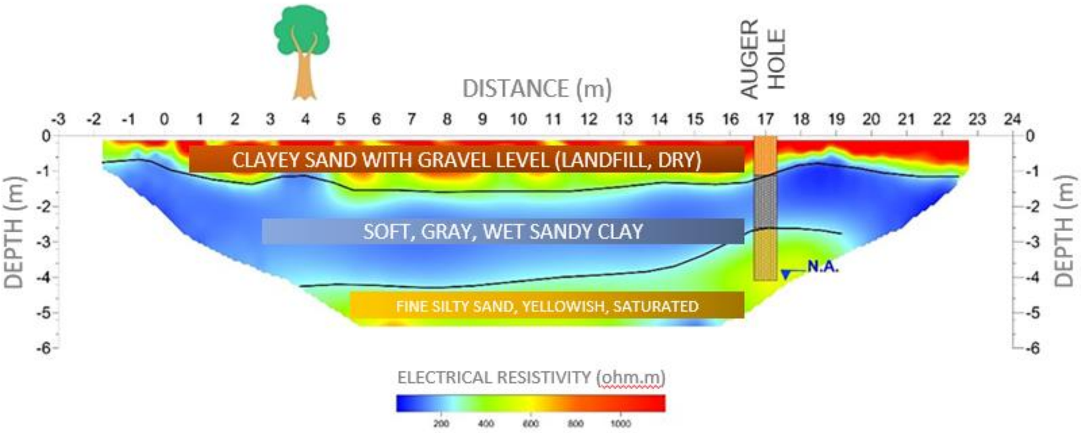


Source: Author elaboration.

By aggregating direct information obtained from drilling the auger, a correlation between the results of the geophysical tests and the identified lithologies was established. This result is shown in the same 2D section shown in Figure 7 and the respective lithologies that occur at the site (Figure 8).

Figure 8

Subsurface model interpreted based on geophysical test results, (indirect) and direct information obtained with the auger hole, showing occurring lithologies in the area and their conditions in relation to water content in the subsoil

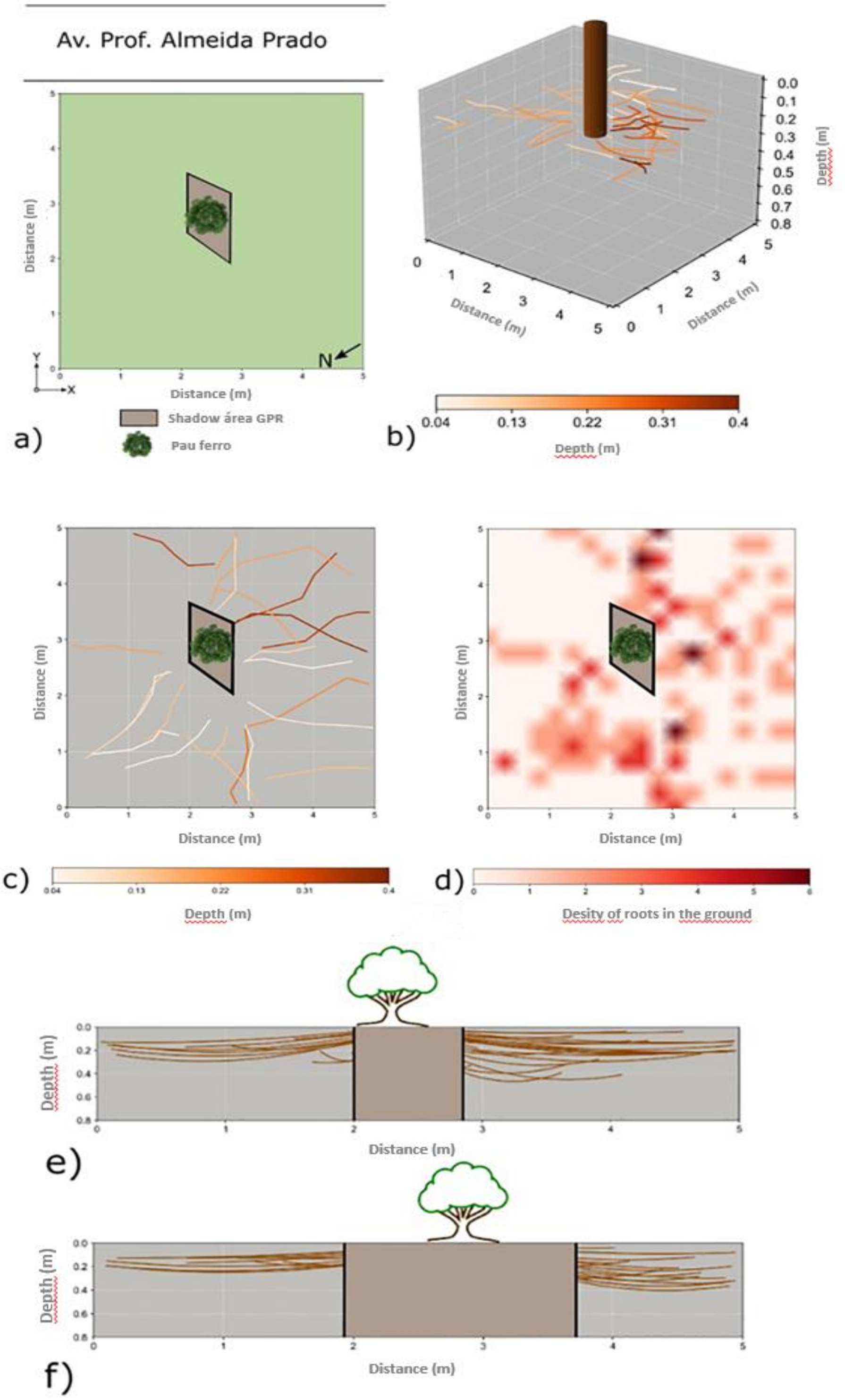


Source: Author elaboration.

Figure 9 presents the root system obtained processed GPR data. In Figure 9a we have the schematics of the acquisition area, with the Pau Ferro tree in the center and the two acquisition directions X and Y. The maximum depth to map the roots was 0.4 m, in fine clayey sandy soil and landfill. Roots were distributed throughout the study region, and no preferential direction was observed when examined in 3D, in Figure 9b as a function of depth (2D), in the subsoil root count map and in the profiles in the two acquisition directions (Figures 9b, 9c, 9d, 9d, 9e and 9f, respectively), indicating good disposition and no barrier for development. With a resolution (minimum dimension of detection by GPR) of 3.1 cm, the diameter of the roots varied from 3.5 cm and 8.9 cm. The surface soil (up to 1.3 m) has a porosity of 23% and water content of 29%, revealing a compact and dry soil, in addition to confirming the absence of other occurrences in the soil (pipes or electrical cables), as analyzed in the available maps of the area.

Figura 9

Representation of the pau-ferro root system obtained by the GPR method. a) Schematic sketch of the acquisition area. b) Three-dimensional distribution of the root system. c) Spatial distribution varying with the depth of the root system. d) Map of occurrence of roots in the subsoil. e) Profile in the X direction with the distribution of the roots. f) Profile in the Y direction with the distribution of the roots

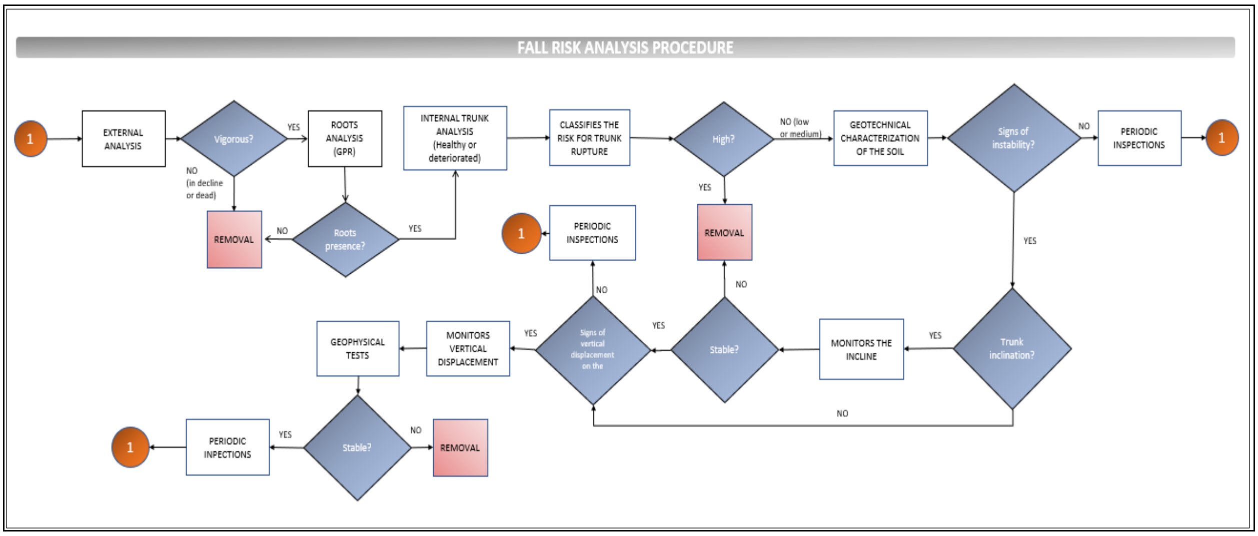


Source: Author elaboration.

The flowchart (Figure 10) integrates the assumptions and results of the phytosanitary diagnosis, soil displacement, control of trunk inclination and geophysical methods for decision-making on tree management.

Figure 10

Procedure flowchart for risk falling analysis of the Ironwood tree



Source: Author elaboration.

Using the proposed flowchart for risk decision, the target assessment was verified considering the area around the tree, circumscribed in a radius of 1.5 times the total height of the tree specimen, in the event that the tree fell. In this analysis, possible risks to material goods and human life were evaluated, based on the frequency of movement of people and vehicles in the vicinity of the tree and type of street. Target analysis helps in prioritizing management actions, especially when there is no possibility of removing the target or isolating the area to be affected by the possible fall of the tree.

Although the Pau Ferro tree has an established root system, objective evidence of a risk of falling was found due to the evolution of surface settlement - that is, the bulging of the surface of the ground around the tree, and the consequent inclination of the trunk towards the Professor Almeida Prado Avenue, a street with high traffic volume. In view of the above, the removal of the tree was recommended.

Conclusions

The conclusions of the analysis of the risk of falling of the *Pau Ferro* tree are presented below, based on the integration of data from the results of the set of tests, measurements and monitoring carried out, according to the proposed methodology:

- The Ironwood has shallow roots, arranged in concentrated planes a few centimeters below the soil surface and is thus susceptible to eventual interference and deformability of the surface layer of the soil;
- The local subsoil has a surface layer of landfill, in which the Ironwood roots are found, overlying highly compressible, saturated soil, subject to settlements when subjected to increased loads;
- Vertical surface displacements evolve slowly over time, as well as the inclination of the *Pau Ferro* trunk;
- The inclination of the trunk changes the eccentricity of the crown and allows the change of the axis of gravity, favoring the fall;
- Despite the apparent cavity in the trunk, concentrations of roots were found in this area.

In view of the results obtained with the application of the proposed methodology, which extends the concept of the risk of falling beyond that which involves merely the rupture of the trunk, it can be said that the Ironwood tree analyzed was at risk of falling, and should suppressed, so as not to endanger infrastructure, material goods and human lives.

The *Pau Ferro* tree was vigorous, located in a landscaped area, with permeable soil, and with the presence of a landfill (unconsolidated material) on layers of soil. The specimen presented an apparent cavity and intense rotting of the wood in its trunk. A large-diameter root was bent and detached from the ground, making it impossible to anchor and distribute security forces to support the trunk. The concentrations of roots observed below the ground surface could not guarantee the stability of the tree due to the evolution of vertical displacements and the inclination of the trunk towards *the Professor Almeida Prado* Avenue. In view of the above, the tree was flagged for suppression as objective evidence indicated a risk of falling.

It should be understood that the analysis performed considered factors of the moment of diagnosis. Each tree, according to the characteristics of its species (wood mass density and natural durability), dendrometric measurements (total height, crown area), age, location planted and its general condition, reacts in specific ways to injury or attack suffered by biological agents and the action of wind and rain.

Based on a project developed in partnership with the Municipality of São Paulo (Instituto de Pesquisas Tecnológicas do Estado de São Paulo, 2004), in general, it is recommended, that trees with termites and xylophagous fungi (deterioration external or internal), be inspected every two years between. Exceptions made for trees classified with medium risk, annual inspections are recommended. Healthy trees can be inspected every three to five years.

There is, however, no guarantee that problems will not occur before the inspection times, due to unforeseen uncertainties such as intense weather events.

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