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When the Crime Scene Is the Road: Forensic Geoscience Indicators Applied to Road Infrastructure and Urban Greening

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Abstract: Common to most cities with tree-lined roads, streets, and sidewalks is damage to paved surfaces caused by the growth of roots over time. Sub-surface root growth creates potential hazards for people driving motor vehicles and pedestrian traffic. In large urban centers like Rome (Italy), roads are vital infrastructure ensuring the mobility of citizens, commercial goods, and information. This infrastructure can become a crime scene when serious injuries or deaths result from the poor monitoring and management of urban trees. Sustainable management of road infrastructure and the associated urban greening is supported by a forensic geoscientific approach. In particular, the use of the GPR (Ground Penetrating Radar) technique allows (i) to control and detect anomalies in the root architecture beneath asphalt in a non-destructive way; and (ii) to plan actions to repair and avoid the possibility of further catastrophic scenarios and need for forensic investigations.

Keywords: forensic geosciences; GPR; urban greening; asphalt; tree roots; Rome

1. Introduction

In many urban areas, trees are commonly grown in paved areas along streets in isolation from other green spaces such as parks and riparian corridors. Along roads, trees and other plants face a significant challenge because paved surfaces, such as asphalt, are hot environments with the absence of evaporative cooling resulting in high sub-surface temperatures.

Landscaping with trees and other vegetation improves the appearance of roads, prevents soil erosion, and reduces greenhouse gas emissions. Planted areas also reduce storm water drainage problems, reduce the detrimental effects of wind and noise, enhance human comfort by providing heat-reducing shade [1–9], and provide habitat for a variety of insects, birds, and mammals. An aspect of urban trees that has not been examined is the relationship between tree shade and pavement performance. Performance relates to the ability of pavement to maintain its design standards and intended functional and structural condition [10].

Many of the challenges that urban trees bring about begin with the construction process. At the beginning of road construction, topsoil is generally removed. The subsoil is then compacted, and layers of crush and run-stone are added before asphalt or concrete is finally spread and compacted. If municipal compaction specifications are adhered to, the resulting anthropogenic soil mix under the pavement is generally impenetrable to roots due to mechanical impediment. The compacted soil also limits root growth because of low levels of available oxygen [11,12].

Trees planted near paved surfaces often suffer due to root damage and soil volume restriction. The lateral growth of shallow tree roots causes pavements to crack and heave, creating "lips" or "stub-toe" spots because of an uneven displacement of adjoining sections of concrete. This "root-versus-pavement" conflict is one of the most pervasive problems in urban greening. The removal and replacement of trees, and the repair of paved surfaces, can strain limited municipal funds. Besides, city governments may be found liable in civil or penal law suits where injuries or deaths occur as a result of pavement hazards [13].

In particular, when roots encounter dense soil and pavement, they change direction, stop growing, or adapt by remaining abnormally close to the surface. Damage occurs mostly on streets with thin asphalt layers, especially in the upper part of the pavement structure. Investigations of the growth characteristics have shown that tree roots penetrate the road structure mostly between the gravel sublayer and the asphalt layer since these layers do not allow a penetration because of their high compaction and penetration resistance [14]. Furthermore, roots seem to be attracted to condensed water collecting on the underside of the asphalt layer. This superficial rooting makes urban trees more vulnerable to drought and can cause instability and pavement heaving. However, if a dense soil is waterlogged, tree roots can also rot from lack of oxygen [15,16].

Tree roots growing under urban roads are known to cause cracking or lifting of the pavement [15–17], which may create a tripping hazard for pedestrians. In the United States, the cost of repairing this type of damage is more than $100 million per year [18,19].

Although trees are an integral part of the urban landscape, they can also be dangerous if not properly maintained. Fallen tree limbs, cracked asphalt, or exposed tree roots in eroded soil can all cause traffic accidents. For example, the first car accident on American soil occurred in Ohio in 1891 and involved automobile legend John William Lambert. The accident was the result of Lambert hitting a tree root, which caused the car to careen out of control and smash into a hitching post. Fortunately, injuries from this accident were minor [20,21].

In recent years, with the increasing number of cars, motorbikes, and bicycles circulating in the cities, vehicle accidents and injuries attributed to cracks in asphalt caused by root growth and fallen trees are now on the rise. An example is the Italian capital city of Rome. Data derived primarily from the Italian National Institute of Statistics (Istat) [22] shows that the number of car and motorbike accidents on municipal roads increased from 2001 to 2014 in Rome. A recent official report from the Municipality of Rome [23] identifies the most dangerous roads. In particular, there is a significant trend for the number of accidents with injured and deceased victims that involved trees falling along the roadside, and where roots have cracked or lifted the asphalt pavement (Figure 1).

Figure 1. Upward trend of serious accidents where tree root cracking or lifting of asphalt pavement resulted in injured and deceased victims in the city of Rome from 2001 to 2014 [22].

To this end, the city and its roads can potentially become a dramatic crime scene involving victims harmed by trees and their roots, poor urban arboreal management practices, and a lack of diagnostic regulations.

To avoid the rising number of such accidents, a forensic geoscientific approach is often adopted to investigate the tree root architecture beneath the roads and to diagnose the risk level. This method can be useful both before and after an accident, thereby preventing further injuries or deaths.

In particular, one of the most suitable forensic geoscientific techniques is the application of ground penetrating radar (GPR), a geophysical method that detects anomalies beneath the soil in a non-destructive way ([24,25] and literature therein).

In this paper, we discuss the results of several GPR measurements collected in the city of Rome along the tree-lined roads that have harmed the most people. This forensic tool provides different visualizations of tree root architecture beneath vital infrastructure and helps to verify the health condition of urban trees.

2. Materials and Methods

Forensic geoscience is the application of different branches of earth science (e.g., geophysics, geology, and geomorphology) to criminal investigation. A forensic geoscientist supports the investigation by means of the search and analysis of geological evidence at the crime scene and elsewhere for comparison [26].

This approach is particularly appropriate if the crime scene is considered to be a municipal road where property damage, injury, or death has occurred, involving, for example, a tree root breaking through the asphalt surface or a tree limb falling across a road or footpath (Figure 2).

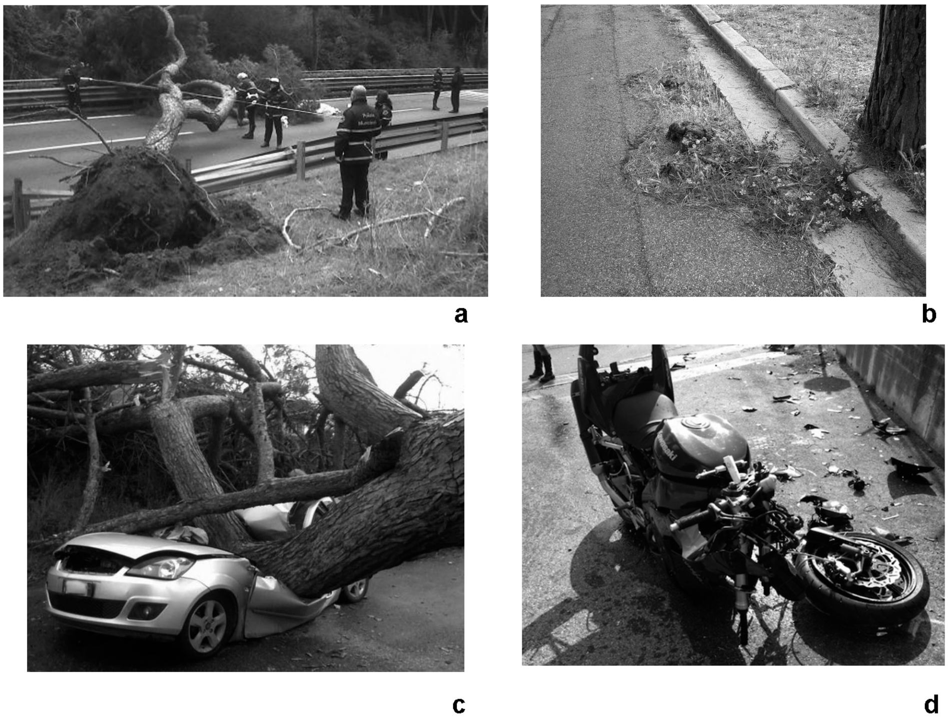

Figure 2. Recent examples of serious crashes with victims where falling trees (**a**) or root cracks (**b**) have been the responsible agent of injury, death, or vehicle damage (**c**,**d**) on the roads of Rome.

Given this background, the use of a specific forensic geoscientific method, specifically GPR, is particularly recommended. Ground penetrating radar operates primarily in the 1–3000 MHz frequency range [27] and is one of the newer geophysical methods. By exploiting the wave propagation characteristics of electromagnetic fields, GPR proves to be a very high-resolution sub-surface mapping method. In many respects, GPR is the electromagnetic counterpart of seismic reflection.

Reflection GPR maps subsurface features by detecting electromagnetic waves that are reflected. By taking measurements at a number of positions, the location and the depth of subsurface objects can be inferred. Reflections are caused by changes in electrical character between the reflector and the surrounding host material. Even very minor changes in material composition or in water content give rise to changes in electromagnetic impedance, which in turn causes radar reflections [28].

GPR data are collected along a single profile or in a grid of profiles to obtain 2D or pseudo 3D information on structures in the ground. The data can also be acquired along lines so densely spaced that the line spacing equals the step size along the line. This leads to a 3D data cube where data also can be displayed as time or depth slices (Figure 3). A detailed description of the GPR method can be found in [29–31].

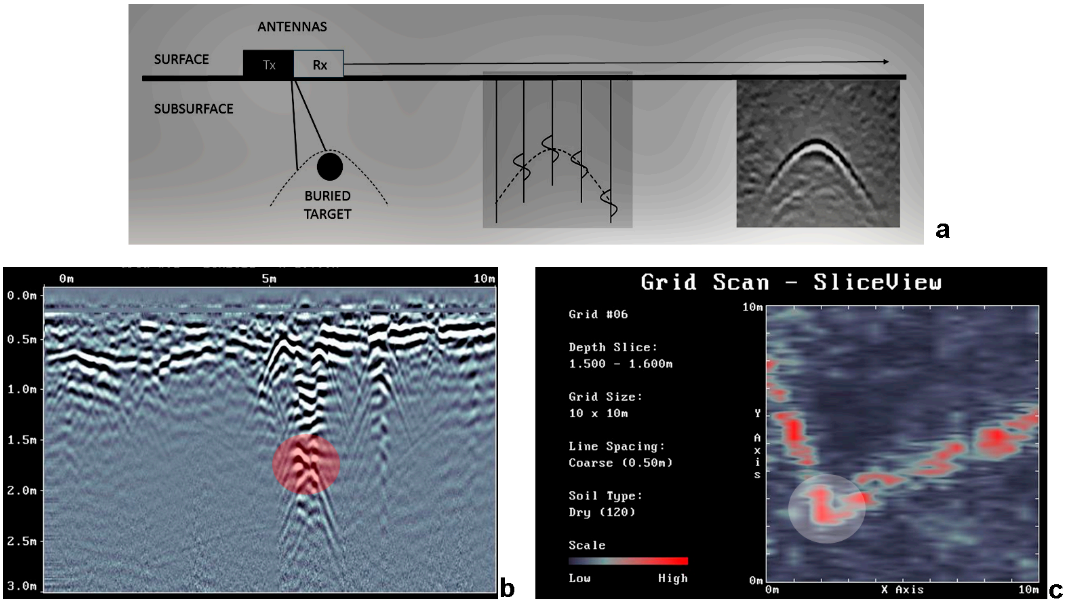

Figure 3. The upper image shows geometry of the most common mode of GPR data acquisition, referred to as "reflection mode" coverage. In (**a**), single transmitter (Tx) and receiver (Rx) antennae are transported over the ground surface in a fixed configuration above a buried target, resulting in hyperbolic time-distance behavior. The lower images show, in (**b**), a typical radargram (B-scan or GPR section). In (**c**), the relative depth map (C-scan or GPR depth-slice).

In recent years, GPR has gained popularity in forestry because of its application to water content estimation, root stress evaluation, root biomass modeling, and the ability to locate roots ([32] and literature therein). Since GPR can detect sub-surface features without disturbing the soil mass and overlying infrastructure, this geophysical method is the most suitable to apply in an urban setting where root cracks and tree falls are harming victims and damaging road surfaces.

In this work, the GPR system used was a FINDAR unit (Sensors & Software, Inc., Mississauga, ON, Canada) equipped with 500 MHz bi-static antennae and an odometer. Several grids with various dimensions were collected with a line spacing of 0.5 m, following only the Y-orientation. To identify the different targets present at depth, we first analyzed each radar section, applying the basic Dewow time filter and automatic gain control. To convert the two-way travel time into depth, we performed a velocity analysis using the hyperbola calibration technique [31] on all radar sections in which the hyperbolic events were detected.

To define the lateral continuity and geometry of the buried targets, we interpolated the grid data and generated a series of migrated depth-slice maps, applying the average envelope amplitude algorithm to each trace, and using the computed average signal velocity to estimate the target depths [29].

It is worth noting that all of the above-mentioned processes were performed directly on-site and in real time immediately after the acquisition of the GPR data.

3. Results and Discussion

Figure 4 illustrates the results of a GPR investigation along one of the most congested and dangerous main roads in the city of Rome: the SS8bis. As shown in Figure 4, mature pine trees are growing in close proximity to the road infrastructure, creating a critical condition for root development. As a consequence, the asphalt surface is cracking and bulging, creating uneven surfaces that are very unsafe for cars, motorbikes, bicycles, and pedestrians.

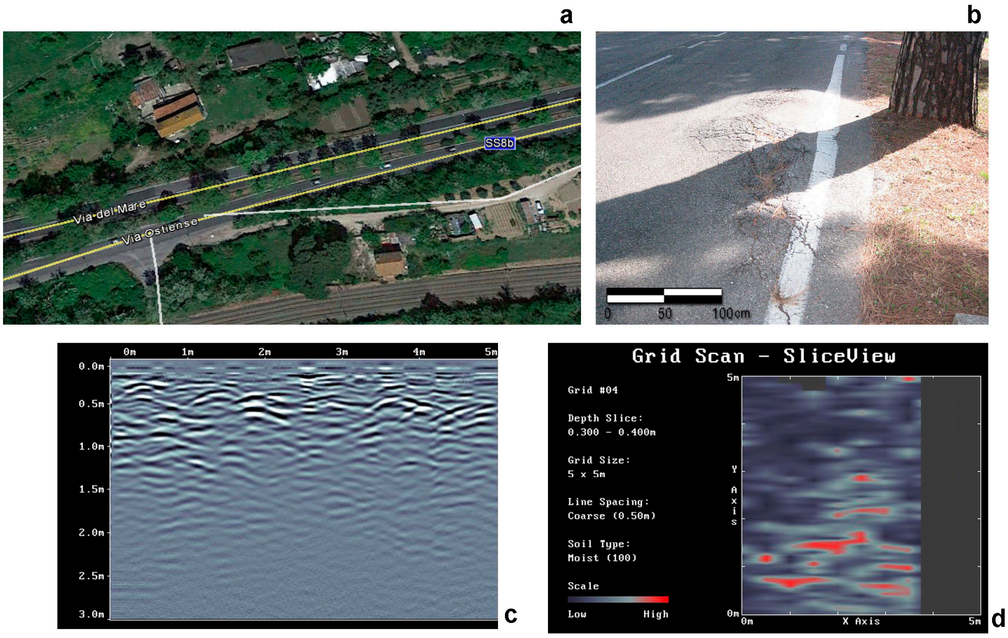

Figure 4. This figure shows the area of investigation along the SS8bis (**a**), with damage to asphalt due to the pine root growth and pavement uplifting (**b**). Several hyperbolic events and red elongated anomalies within the first 0.4 m on both the radargram (**c**) and depth slide map (**d**) are due to the root architecture beneath the asphalt.

The GPR survey revealed the pine root architecture beneath the asphalt not only in the area of uplift but also where the asphalt surface is still intact. Both the radargram and the depth slice image show the presence of upward root growth starting from about 0.35 m from the curbside.

Figures 5 and 6 highlight two cases where historical urban greening plans have created problems for a modern city [33]. For many Italian cities, the large streets decorated with pine trees constructed during the Fascism Period (1930s and 1940s) are now a serious risk to the safety of motor vehicles and their drivers in the 2000s.

Figure 5, in particular, illustrates the condition of the asphalt road surface close to one of these decorative pine trees along the Via delle Terme di Caracalla. Root lifting and asphalt cracks are clearly visible, creating a potentially dangerous situation. The GPR survey in this area shows anomalies at a depth of about 0.35 m, where the root architecture will create asphalt damage in a more central part of the pavement in the near future.

Figure 6 demonstrates how GPR can potentially prevent injuries and death along tree-lined roads. Via Cristoforo Colombo, connecting the city center of Rome with the coast, is also lined by pine trees. The GPR survey recognized roots at a depth of 0.25 m beneath the pavement, verifying the presence of risks beneath the asphalt related to tree roots. Both the radargram and depth-slice collected close to one of these trees suggest root lifting will become a problem in the near future.

Lastly, Figure 7 shows the GPR investigation into the stability of a plane tree along Lungotevere Street. This road, parallel to the Tiber River and created above its embankments, is lined by large plane trees. With very limited space between the road and the embankment, the roots of these trees cannot grow symmetrically. This creates not only an enormous problem of stability clearly visible in the figure, but also a grave risk for the safety of both motor vehicles and pedestrians passing by. The GPR data shows the presence of several anomalies at a depth of approximately 0.30 m on one side of the tree, demonstrating the asymmetrical growth of the roots.

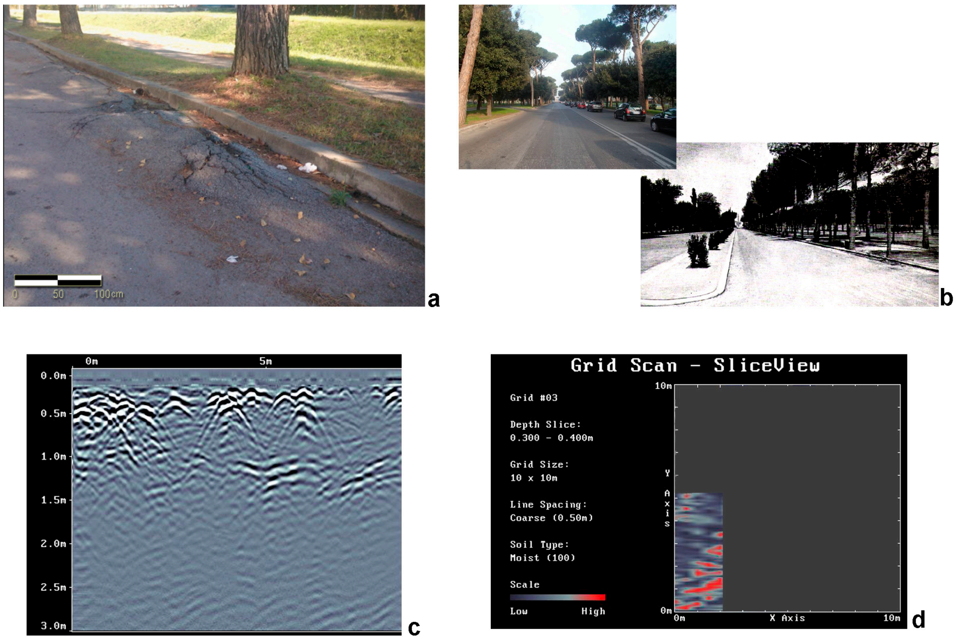

Figure 5. In (**a**), damaged asphalt along Viale delle Terme di Caracalla is shown. This tree-lined street was constructed in 1940s, as shown in (**b**). Strong hyperbolic events and red elongated anomalies in the first 0.4 m, observed on both the radargram (**c**) and depth map (**d**) image the root architecture beneath the asphalt.

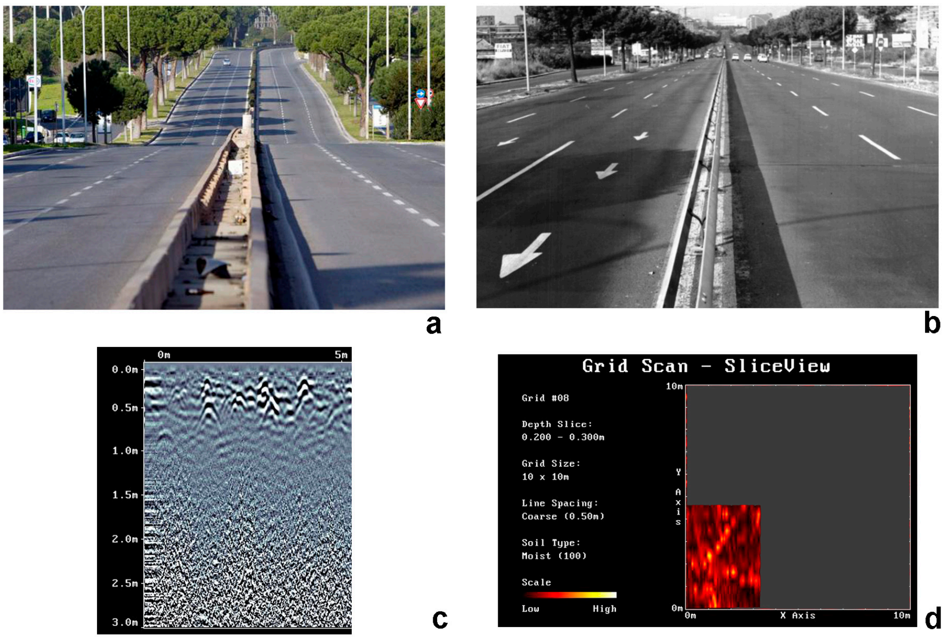

Figure 6. The upper images show Via Cristoforo Colombo in recent times (**a**) and during the 1950s (**b**). The lower images clearly show the very shallow root architecture of the pine trees beneath the asphalt road surface (hyperbolic events in (**c**) and yellow elongated anomalies in (**d**). Note, however, that the asphalt surface is not yet damaged by root growth.

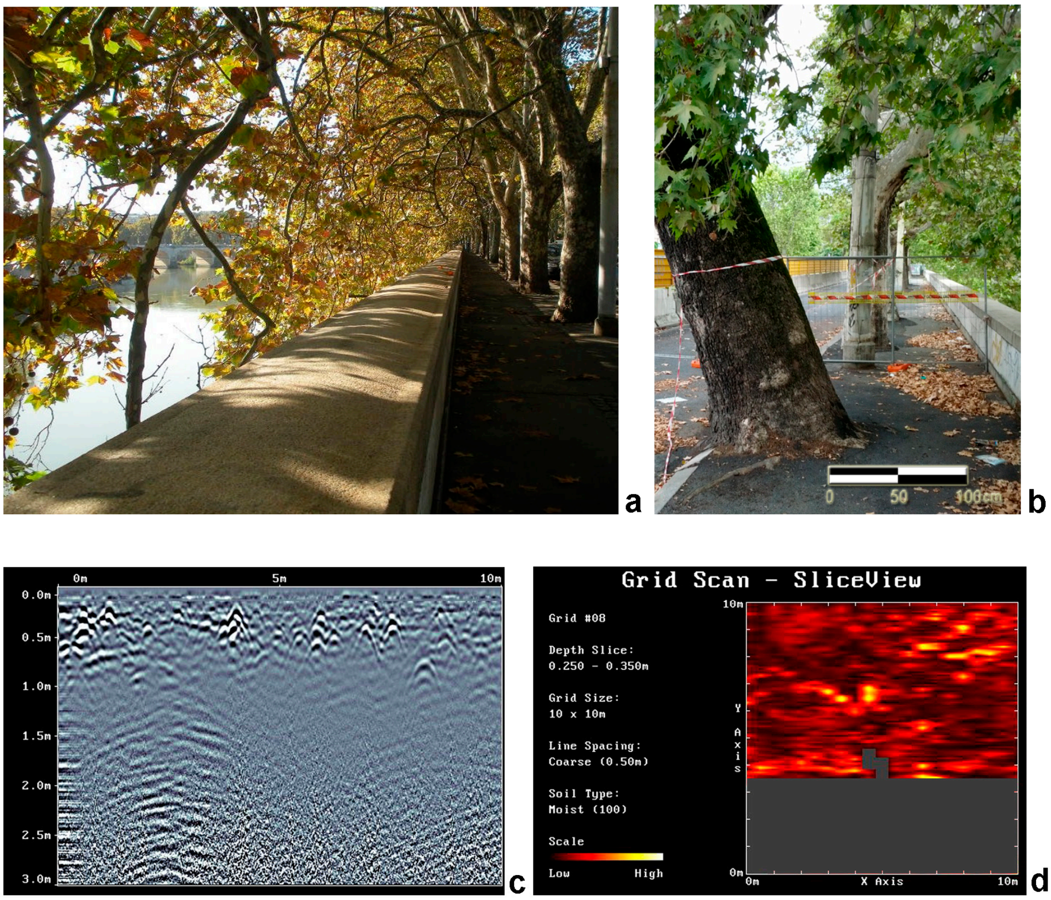

Figure 7. The upper images illustrate the critical situation of the plane trees between the embankments of the Tiber River and Lungotevere Street (**a**,**b**). The lower images illustrate the GPR results collected around the leaning tree (**c**,**d**) and highlight critical conditions in the first 0.3 m beneath the pavement. Note that the grey area in (d) represents the area with no GPR data parallel to the embankment.

The GPR results presented above demonstrate not only how urban tree-lined roads are a risk to the safety and security of citizens and property if tree roots are not monitored, but also how GPR investigations can be used to inspect the condition of asphalt in proximity to problem trees. It is also clear that, if asphalt is replaced and trees are retained, the likelihood of repeated road surface failure is very high for most sites investigated. Moreover, if the asphalt is replaced and trees are required to have many roots pruned, their health will decline, in turn creating the potential for falling branches. If trees over 15 years old have to be removed prematurely, there are significant losses in the benefits and services that trees provide (e.g., CO_2 reservoirs and urban wildlife habitats).

The forensic approach outlined above has several important benefits for cities like Rome. Firstly, the number of injuries and deaths related to tree root-related damage to asphalt surfaces will be reduced. Second, there are urban economic and environmental benefits to safe infrastructure and healthy trees.

4. Conclusions

The forensic geoscience approach using GPR can be enormously valuable if the crime scene is a major urban center like Rome, if the victims have been injured or killed in an accident involving tree-damaged road surfaces, or if the culprits are municipalities and landowners who, often due to a lack of diagnostic regulations, are failing to manage trees that were once planted to embellish but now threaten critical infrastructure and public safety. If more effort is placed into monitoring the extent of urban tree root structures, growth, and resulting damage, then the numbers of deaths and injuries related to this problem will quickly decrease. This multi-tasking approach to monitoring will also help by saving money and time from unnecessary replacement of infrastructure and loss of urban green space.

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