GPR Investigation of Cobblestone Road Pavement Degradation

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Synopsis

Structural degradation of road pavements is a threat to traffic safety. Defects or damages in the road surface make driving unsmooth and uncomfortable and increase the likelihood of accidents.
Ground Penetrating Radar (GPR) has been successfully used in non-destructive investigation of road pavement degradation and identification of its causes.
The paper describes the results of a GPR study that was conducted on the cobblestone road pavements of the historical center of L'Aquila (Abruzzo, Italy). The investigation had the purpose of finding correlations between the following variables: type of stone surface; traffic load; road surface degradation; and results from GPR scans. Both qualitative analyses (anomalies on radar sections) and quantitative analyses (curves of radar signal attenuation with depth) were carried out. The investigation was conducted on 15 sites representing various combinations of the above-mentioned variables. Each site had a surface area of 3 x 3 m. The antenna arrays had a nominal frequency of 1,600 MHz (down to a depth of 1 m) and of 600 MHz (down to a depth of 4 m). The scans were performed on grids with a mesh of 1.5 and 0.5 m, respectively.
The investigated sites were grouped into classes of pavement surface degradation (PSD) and of traffic load (TL). The groups (no degradation, average and high) of the first index were established on the basis of direct observations of defects. Conversely, the groups of the second index were based on the number of passing vehicles per unit of time. Also in this case, three classes were defined: heavy, average and low. The cobblestones used in the investigated sites were made up of red porphyry from the Bolzano area, local limestone and leucititic lava from the Lazio Region.
Comparisons between radar attenuation curves (and related PSD and TL classes) and types of cobblestone elucidated some aspects concerning GPR calibration in the investigation of the cobblestone road pavements.
In terms of types of road pavement and PSD and TL classes, the porphyry pavement had a more marked electromagnetic wave reflection than the limestone or leucititic lava ones. This is due to the fact that porphyry has a high iron content, which amplifies incident radar signal reflection.
In terms of traffic on sites belonging to the same PSD class and with the same pavement, heavy-load roads had a more pronounced electromagnetic wave reflection than average- or low-load roads. This finding is justified by the more significant destructuring of the cobblestone road pavement and, ultimately, by increased porosity of the road embankment, whose internal voids induce the multiple reflections observed in the attenuation curves.
Sites with the same type of road pavement and the same TL class were also investigated under variable surface degradation conditions. The more degraded is the surface degradation of these sites, the more rapidly dampened are their attenuation curves with depth. This observation is due to the fact that a higher surface degradation (high PSD class) immediately dampens the reflected radar signal before it reaches the deeper layers of the road structure.

GPR Investigation of Cobblestone Road Pavement Degradation

The conditions of the road pavement, its roughness and evenness and its lack of localized or diffuse faults have a crucial impact on driving comfort and traffic safety. Consequently, the degradation of road pavements plays a dramatic role in road safety, directly or indirectly. If damages to road pavements are not prevented with adequate maintenance, they may significantly increase the likelihood of accidents and the severity of damages.

Thus, a correct approach to road management emphasizing safety and preventing accidents requires a comprehensive plan with the following key elements:

- identification and classification of road pavement degradation;
- analysis of the scenario of possible causes;
- definition of the methodology to be followed and of the Best Available Technology for identifying the causes of the pavement degradation;
- prediction of the evolution of degradation over time;
- analysis of the severity of road pavement damages and of their evolution over time in terms of road safety;
- identification of the most effective and efficient rehabilitation projects.

The paper addresses these problems with reference to cobblestone road pavements located in the historical center of L'Aquila. In view of the recent breakthroughs of research in this sector (Benedetto & Angiò, 2002a; Benedetto & De Blasiis, 2001; Chun-Lok & Scullion, 1992), the causes of degradation of these road pavements were investigated with advanced GPR techniques.

APPLICATION OF GPR TECHNIQUES TO ROAD PAVEMENTS

Getting an in-depth understanding of a road pavement means identifying its type, size, materials, as well as the thickness of its layers and the mechanical properties of its constituents. The study of road pavement composition may rely on conventional methods, such as boreholes, or on non-destructive geophysical techniques. Boring of holes into the road surface is a time-consuming and destructive approach, which interferes with road traffic.

In the past few years, Ground Penetrating Radar (GPR) techniques have been extensively used thanks to their high efficiency, fast speed, non-destructiveness and limited interference with pedestrian and vehicle circulation (Benedetto & Angiò, 2002b; Bucchi et al., 2002; Gatti & Liuzzi, 1998).

The GPR can emit radio frequency signals in the typical range of 10-2000 MHz and record the echoes radiated by the objects contained in the medium or by the layers of different type which make up road surfaces. A transmitter generates a pulse signal with a given pulse repetition frequency. These successive pulses produce a signal with a duration in the range of nanoseconds. The signal is radiated by a broad-band antenna. The energy pulse propagates to the road pavement at a given velocity: when the pulse meets a layer whose dielectric properties are different from the ones of the overlying layer, then part of the energy is reflected by the layer, while the remaining energy crosses it. At the surface, the antenna receives the reflected signals. The amplitudes of the reflected waves provide information on the dielectric properties of the investigated layers. Interface echoes and echo spacings (time intervals that the pulse takes to cross the layers) can be identified on the receiver-recorded trace. From these time intervals, layer thickness can be determined.

The choice of the antenna in GPR techniques is essential. Such choice should be based on the desirable depth of investigation, on the types of materials to be investigated and on the expected imaging resolution. Low-frequency antennas have high penetration (80 – 350 MHz). They are used for deep investigation of stratigraphic horizons, groundwater, caves, etc. Medium-frequency antennas (350 – 600 MHz) are suitable for shallow investigation of road pavements and underlying utility grids. High-frequency antennas (600 – 2000 MHz) offer high spatial resolution but shallow penetration.

In the study reported in this paper, use was made of a 1,600 MHz monostatic antenna to get information on the cobblestone road surface, and of a 600 MHz bistatic antenna to identify its underlying utility grids, if any. Both antennas and their data collection and processing software were developed by Ingegneria dei Sistemi SpA (Pisa, Italy).

COBBLESTONE ROAD PAVEMENTS

Undeniably, cobblestone road pavements have a high aesthetic and historical value In Italy, they are found in many historical centers of major towns, but also in a number of small villages. Due to their often ancient origin, they represent a heritage whose value is to be protected, preserved and enhanced.

These road pavements commonly consist of cube- or prism-shaped stones, which are quarried by means of a cutting machine provided with a bladed hammer. The upper part of the cobblestone is left rough, while its lateral walls (obtained by fracturing) are usually inclined towards the bed surface, so as to form an elongated pyramid trunk. Common types of stone arrangement are: contrasting arches, "redans", peacock's tail and regular courses. The contrasting-arch arrangement is the most widespread, especially for vehicle traffic. Indeed, arches have a unique capability of bearing heavy loads and thrusts; in the case of a cobblestone pavement, the loads and thrusts are horizontally transmitted as a result of the grip of tires on the road surface. Contrasting arches are defined as such because their position contrasts the one of their neighbors and of the road edges.

In the Italian area, the most frequent types of stone are: crystalline rock (gneiss, granitoids), lava (porphyry, leucitite, basalt, etc.) and sedimentary rock (limestone, sandstone, etc.). The size of the cube stones generally varies with the type of material and is usually in the range of 5-15 cm.

Cobblestones are laid on an about 5 cm-thick layer of rendering sand, according to the selected layout, leaving narrow (max 5 mm) and parallel joints between them. Then, the joints are carefully filled with washed sand and the cobblestones are rammed with vibrating rammers. The last step in the process is the sealing of the shallow portion of the joints between the stones with waterproof binders; the most commonly used materials are cement slurry, hot and cold bitumen mastic (Blanco, 1995).

The other layers of the structure have a significant impact on cobblestone pavement durability. These layers are placed between the subbase and the overlying sand bed surface accommodating the stones. In the past, use was made of a granular mix of variable thickness, depending on the load-bearing capacity of the subbase. In recent years, a concrete slab has also been used in order to maintain the evenness of the road surface and allow it to better withstand the load of traffic (in urban areas, mainly bus traffic). The concrete slab is appropriately sized, according to the characteristics of the underlying layers and of the traffic loads predicted throughout the useful lifetime of the road pavement. The upper part of the slab is generally reinforced with a steel wire net, so as to minimize shrinkage and cracking processes, which are typical of this type of road pavements. Figure 1 shows the typical cross-sections of a cobblestone road pavement of ordinary type and of a cobblestone road pavement incorporating a reinforced concrete slab.

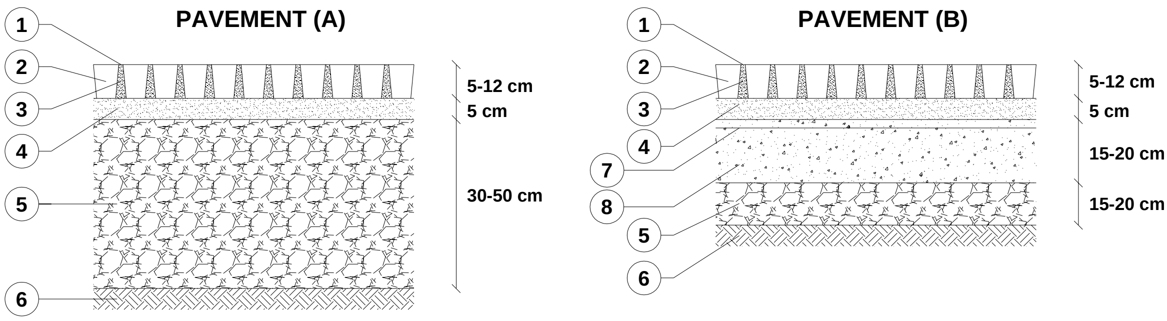

Figure 1: Typical cross-sections of a cobblestone road pavement of ordinary type (A) and of a cobblestone road pavement incorporating a reinforced concrete slab (B). 1- sealing bitumen; 2- stone paver; 3- washed sand; 4 bedding sand; 5- granular subbase; 6- subgrade; 7- reinforcing steel mesh; 8- concrete slab

At this stage, it is worth describing the factors which may trigger degradation of cobblestone road pavements. The main factor is the road surface deformation, which may originate from problems in both construction and operation of the road infrastructure. A common problem arising after road construction is the permanent deformation of the subbase and of the granular materials making up the pavement. This problem may be regarded as the combination of different factors, which are outlined below:

- unevenness of the subbase bed surface;
- poor workmanship in the placing of the layers;
- poor compaction;
- uneven compaction;
- incorrect finishing (water puddles); uneven surface;
- non-homogeneous thickness.

Conversely, the repeated-stress deformation due to traffic loads originates in the granular layers of the subbase and is caused by the use of unsuitable materials, such as:

- granular mixes with crushable aggregate;
- granular mixes with excess fines;

- granular mixes with plastic fines;
- mixes of inadequate grain size;
- plastic subbases;
- compressible subbases.

Furthermore, the seal of the joints between the cobblestones plays an important role; incorrect sealing of the joints may initiate degradation of the pavement, because the latter: i) does not ensure an even road surface; ii) does not prevent water from infiltrating into the underlying layers; iii) allows vehicle tires, rain and cleaning vehicle brushes to easily remove the sand fill from the joints.

Finally, it should be pointed out that, in most urban areas, damages to cobblestone road pavements depend above all on the underlying utility grids, which induce pavement instability upon their installation and maintenance.

THE INVESTIGATED ROAD PAVEMENTS

Analysis of Road Pavement Types, Traffic and Degradation

All the investigated road pavements consist of cobblestones and are located in the historical center of L'Aquila (Abruzzo Region – Italy) (Figure 2).

Figure 2: Investigated area and layout of the historical center of L'Aquila

All the cobblestone road pavements of the historical center of L'Aquila may be grouped into the following three types:

- porphyry: this is the most widespread type of pavement. Porphyry is an effusive eruptive rock with high content of silica (over 70%) and thus high resistance to stresses and external agents. Porphyries come especially from the area of Bolzano (95% of the total). The shape of the stones used in L'Aquila is a pyramid trunk with a square section at the top and a side of 5-8 cm;
- leucititic lava: this is a poorly widespread type of pavement. Leucititic lava is an effusive magmatic rock with 50-60% silica. It is very common in the volcanic areas of the Tyrrhenian margin of Lazio-Campania (especially in the Alban hills). The stones used in L'Aquila are prism-shaped; they may have a squared or rectangular section at the top and a side of 10-15 cm;
- limestone: this is a poorly widespread type of pavement. Limestone is a sedimentary rock with a calcium carbonate content exceeding 98%. It is very common in the Abruzzo Region and occurs in many varieties.The main problem of this stone is that it may be easily smoothed and worn by vehicle traffic; therefore, it does not ensure an adequate tire grip on the road surface. Its use is due to aesthetic reasons, i.e. the same material (generally, local limestone) for both road pavements and buildings of historical centers. The stones of L'Aquila are cube-shaped and their sides have a size of 10-12 cm.

The traffic load in the historical center of L'Aquila may be divided into three categories, depending on the importance of the related roads. In areas of traffic restraint, the number of passing vehicles is small; in dominantly residential areas, traffic load increases; on fast-traffic roads, traffic increases significantly and incorporates heavy vehicles (especially buses) which, however, never exceed 5% of the total passing vehicles.

For each road, the reference parameter, i.e. the Average Daily Traffic (ADT), was determined. After directly recording the Peak Hour Traffic (PHT), the ADT was calculated via the well-known formula ADT = (PHT /0.10). The PHT values were obtained by averaging the values recorded in different peak hours of the day and on different days of the week. To simplify the assessment of the ADT variable, three traffic load classes were identified on the basis of computed ADT values:

- Low Traffic with $0 < ADT \leq 800$
- Average Traffic with $800 < ADT \leq 2000$
- Heavy Traffic with $ADT > 2000$.

Based on direct observations of the road surface, the following three classes of pavement surface degradation were identified:

- no degradation = good pavement: cobblestones are unaltered; joints are intact and without gaps; the road surface has no dips;
- average degradation = fair pavement: loss of joints; some cobblestones are missing; the road surface has slight dips, but no ruts or potholes;
- high degradation = poor pavement: loss of joints; the road surface has ruts or potholes with exposed subbase material, marked dips and asphalt patch repairs.

With a view to finding correlations between all the investigated variables (type of stone pavement, traffic load and pavement surface degradation), 15 sites were taken into consideration, after a thorough analysis of all the roads in the historical center of L'Aquila. The 15 sites were selected in such a way as to represent of different combinations of the investigated variables. Figure 3 shows the images of the 15 sites, while Table 1 displays the identification data of all the sites, as well as the values assigned to the variables.

Table 1: Characteristics of the investigated sites

No.	Road	Cobblestone	Traffic	Degradation	Concrete slab	Utility grids	Radar discontinuities
1	Via Sant'Agostino	porphyry	heavy	no degr.	YES	YES (2)	NO
2	Via Bafile	porphyry	heavy	average	NO	YES (1)	NO
3	Via Roma	porphyry	heavy	high	NO	YES (5)	NO
4	Via delle Grazie 1	porphyry	average	no degr.	YES	YES (3)	NO
5	Via dell'Annunziata	porphyry	average	average	NO	YES (2)	NO
6	Via Sassa	porphyry	average	high	NO	YES (5)	YES
7	Via Borgo Rivera	porphyry	low	no degr.	NO	YES (2)	NO
8	Via Sallustio	porphyry	low	average	NO	YES (3)	NO
9	Via San Michele	limestone	heavy	no degr.	YES	YES (1)	NO
10	Via degli Alemanni	limestone	average	high	NO	YES (4)	YES
11	Via delle Grazie 2	limestone	low	no degr.	YES	YES (3)	NO
12	Via di Piscignola	limestone	low	average	NO	YES (1)	NO
13	Piazza San Pietro	leucititic lava	low	no degr.	NO	YES (3)	NO
14	Via Minicuccio d'Ugolino	leucititic lava	low	average	NO	YES (3)	NO
15	Via Santo Spirito	leucititic lava	low	high	NO	YES (5)	YES

Figure 3: The 15 investigated sites

To provide a comprehensive picture of the pavements under review, Table 1 also indicates: i) whether a concrete slab is interposed between the layers of the superstructure; ii) whether utility grids are placed beneath the superstructure and arranged parallelly with the road axis and, if so, their number; iii) whether the road surface has 2-3 m-deep discontinuities. These details were identified thanks to the use of the GPR.

GPR Data Acquisition Survey

The GPR survey had the purpose of identifying the types of layers making up the superstructures of the pavements and the presence of anomalies (e.g. utility grids) by processing the radar signals emitted by the targets encountered at depth.

Each of the investigated sites had a surface area of 3 x 3 m. The 1,600 MHz antenna was used for investigations to a depth of 1 m, while the 600 MHz antenna was used for investigations to a depth of 4 m; the scans were made on grids with a mesh of 1.5 and 0.5 m, respectively.

The goals of the 1,600 MHz antenna survey were as follows:

- determining the influence of the characteristics of the layers making up the road superstructures down to 1 m below the road surface;
- based on a statistical-descriptive analysis of the radargrams, establishing correlations between the indicators provided by the GPR technique (analysis of sweep mean and sweep power recorded on the curves of signal attenuation with depth) and the three investigated variables: pavement surface degradation, type of stone pavement and traffic load.

As to the first point, the most significant result was the identification of pavements where a reinforced concrete slab had been interposed between the layers of the superstructure (Table 1). All four pavements with a built-in slab (Via S. Agostino, Via delle Grazie 1, Via San Michele and Via delle Grazie 2) proved to have no degradation; therefore, they are good. This finding confirms the value of a rigid layer (reinforced concrete slab), which prevents differential settlements between the pavement areas exposed to traffic stress (tracks left by tires) and the remaining pavement areas.

As to the second point, three categories of correlations were established between the investigated variables.

In the first category of correlations, sites with the same type of stone pavement and the same traffic load were investigated on variable assumptions of pavement surface degradation. Five combinations were identified among the investigated roads (Table 2).

Table 2: Road pavements grouped by level of degradation

No.	Cobblestone	Traffic	Degradation	Road	Code figs 4-5
1	porphyry	heavy	no degradation	Via Sant'Agostino	a
			average	Via Bafile	b
			high	Via Roma	c
2	porphyry	average	no degradation	Via delle Grazie 1	a
			average	Via dell'Annunziata	b
			high	Via Sassa	c
3	porphyry	low	no degradation	Via Borgo Rivera	a
			average	Via Sallustio	b
4	limestone	low	no degradation	Via delle Grazie 2	a
			average	Via di Piscignola	b
5	leucititic lava	low	no degradation	Piazza San Pietro	a
			average	Via Minicuccio	b
			high	Via Santo Spirito	c

Figures 4 and 5 exhibit the sweep mean and sweep power diagrams of the five combinations shown in Table 2. In the table, each road is associated with an alphanumerical code, which is found also in the corresponding diagram.

Comparing the results of the sweep mean diagrams yields a recurrent sequence between the three levels of degradation (a: no degradation; b: average degradation; c: high degradation). In areas where the road is degraded, a reflected signal is almost always recorded. This signal, which is picked up by the receiver antenna, has higher values than the ones of less degraded roads. A single exception is combination n° 5 (between Via Santo Spirito and Piazza San Pietro), where signals are inverted. The analysis of sweep power diagrams shows that they are fairly consistent with the considerations made above for the sweep mean diagrams.

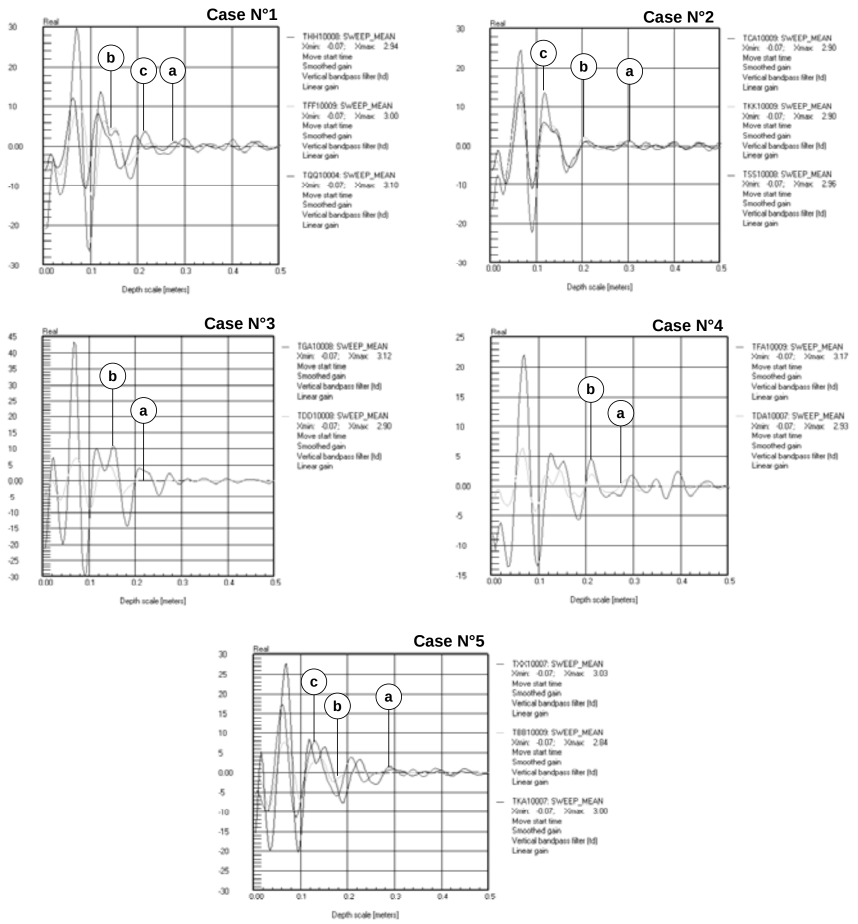

Figure 4: Sweep mean of pavements grouped by level of degradation

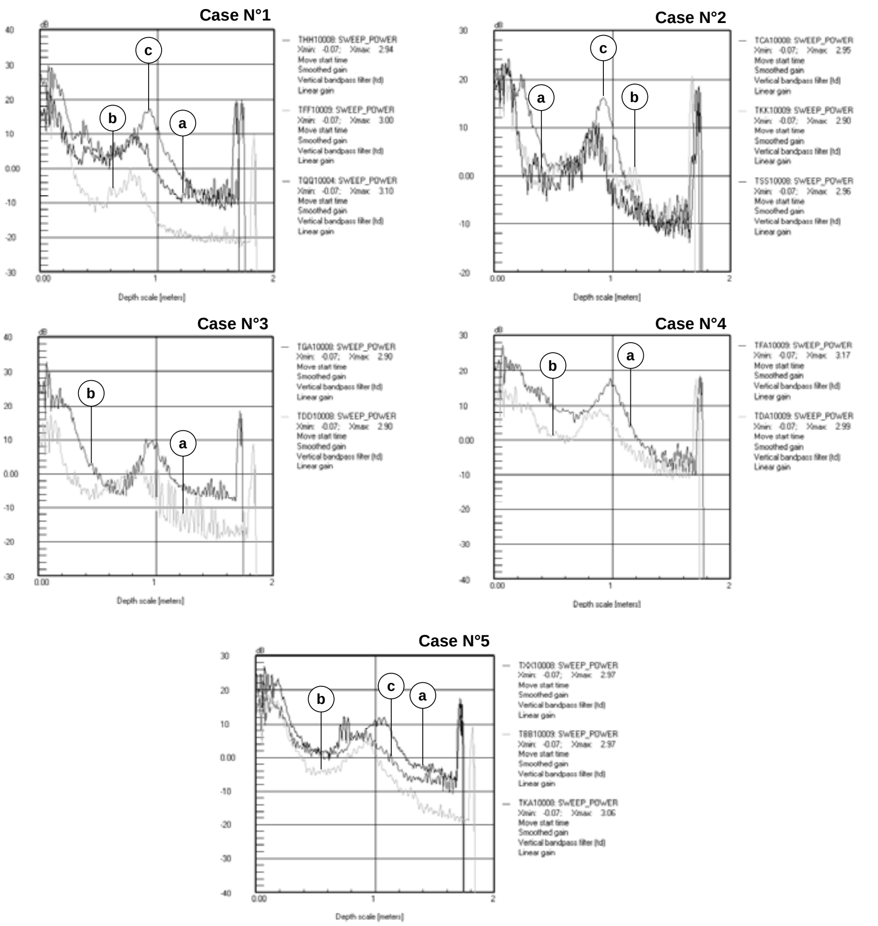

Figure 5: Sweep power of pavements grouped by level of degradation

In the second category of correlations, sites with the same level of degradation and the same traffic load were investigated on variable assumptions in terms of type of stone pavement. Three combinations were identified among the investigated roads (Table 3).

Table 3: Pavements grouped by type of stone pavement

No.	Degradation	Traffic	Cobblestone	Road	Code figs 6-7
1	no degradation	low	porphyry	Via Borgo Rivera	a
			limestone	Via delle Grazie 2	b
			leucititic lava	Piazza San Pietro	c
2	average	low	porphyry	Via Sallustio	a
			limestone	Via di Piscignola	b
			leucititic lava	Via Minicuccio	c
3	no degradation	heavy	porphyry	Via Sant'Agostino	a
			limestone	Via San Michele	b

Figures 6 and 7 display the sweep mean and sweep power diagrams, respectively, of the three combinations shown in Table 3. In the Table, each road is associated with an alphanumerical code, which is used also in the corresponding diagram.

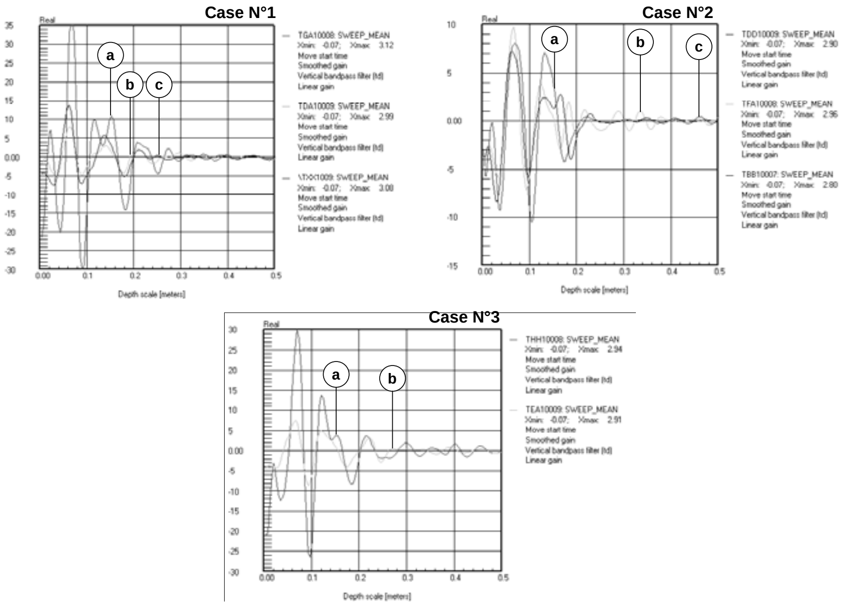

Figure 6: Sweep mean of pavements grouped by type of stone

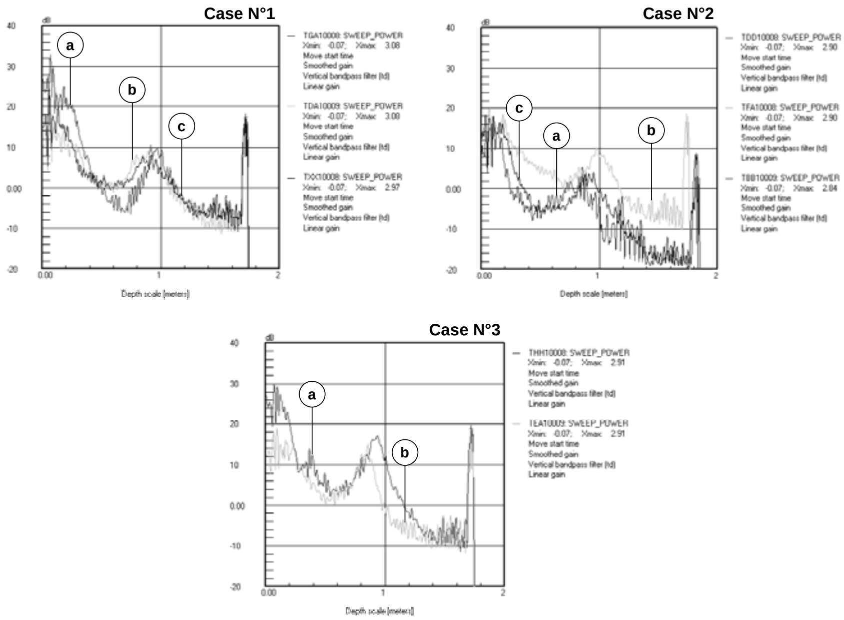

Figure 7: Sweep power of pavements grouped by type of stone

Comparing the results of the sweep mean diagrams gives a recurrent sequence between the three types of stone pavement (a: porphyry; b: limestone; c: leucititic lava). Porphyry pavements have a more marked reflection of electromagnetic waves than limestone and leucititic lava ones. This finding is less evident in combination n° 2, namely on Via Sallustio (porphyry pavement). The analysis of sweep power diagrams shows that they in fairly good agreement with the considerations made above for the sweep mean diagrams, and the anomaly detected in combination n° 2 is enhanced.
In the third category of correlations, sites with the same level of degradation and the same type of stone pavement were investigated on variable assumptions of traffic load. Among the investigated roads, three combinations were identified, as specified in Table 4.

Table 4: Pavements grouped by traffic load

N	Degradation	Cobblestone	Traffic	Road	Code figs 8-9
1	no degradation	porphyry	heavy	Via Sant'Agostino	a
			average	Via delle Grazie 1	b
			low	Via Borgo Rivera	c
2	average	porphyry	heavy	Via Bafile	a
			average	Via dell'Annunziata	b
			low	Via Sallustio	c
3	no degradation	limestone	heavy	Via San Michele	a
			low	Via delle Grazie 2	b

Figures 8 and 9 exhibit the sweep mean and sweep power diagrams, respectively, of the three combinations stated in Table 4. In the table, each road is associated with an alphanumerical code, which is found also in the corresponding diagram.
Comparing the results of the sweep mean diagrams gives a recurrent sequence between the three traffic loads (a: heavy; b: average; c: low). In almost all cases, pavements exposed to a heavy traffic load have a more pronounced reflection of electromagnetic waves than those where the traffic load is lower. This finding is less evident in combination n° 2, namely on Via Bafile (heavy traffic). The sweep power diagrams are fairly consistent with the considerations made above for the sweep mean diagrams, and the anomaly recorded in combination n° 2 is highly enhanced.
The goals of the 600 MHz antenna survey were as follows:

- identifying utility grids, if any, underlying the road superstructure (i.e. in the subbase at a depth of over 1 m from the road surface);
- identifying extensive and very deep discontinuities (i.e. at a depth of over 2 m from the road surface).

With regard to the first point, the investigation identified the number of utility grids located beneath the pavements (Table 1). This finding infers that all pavements with a high number of utility grids (Via Roma, Via Sassa, Via degli Alemanni and Via Santo Spirito) have a high level of degradation. This degradation depends on opening of trenches for installing or maintaining utility grids and consequent reworking of the shallow layers of the road superstructure. The settlement of the trench fills induces differential failures and ensuing deformation of the road surface and loosening of the joints between the stones (loss of interlocking effect). This process facilitates removal of some pavement stones by the tires of passing vehicles.

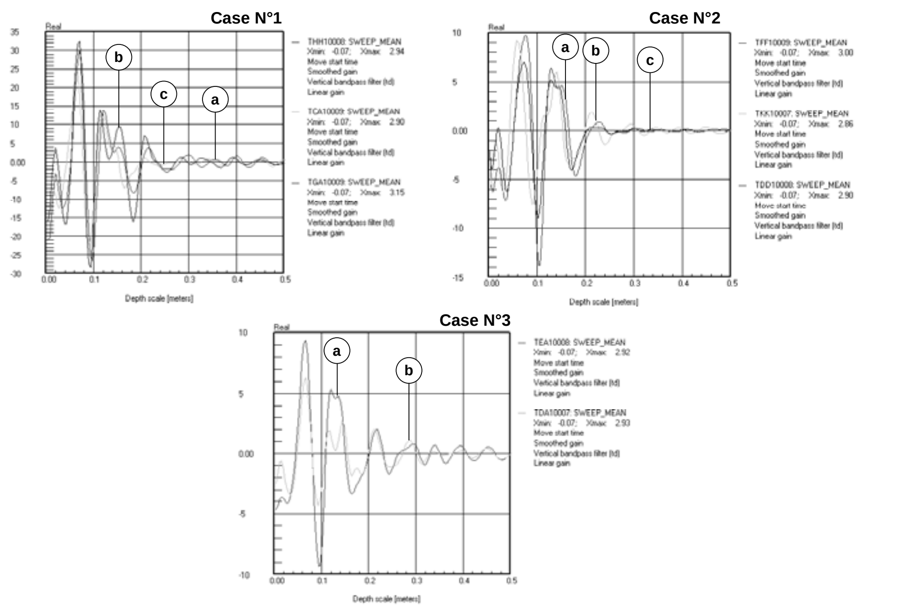

Figure 8: Sweep mean of pavements grouped by traffic load

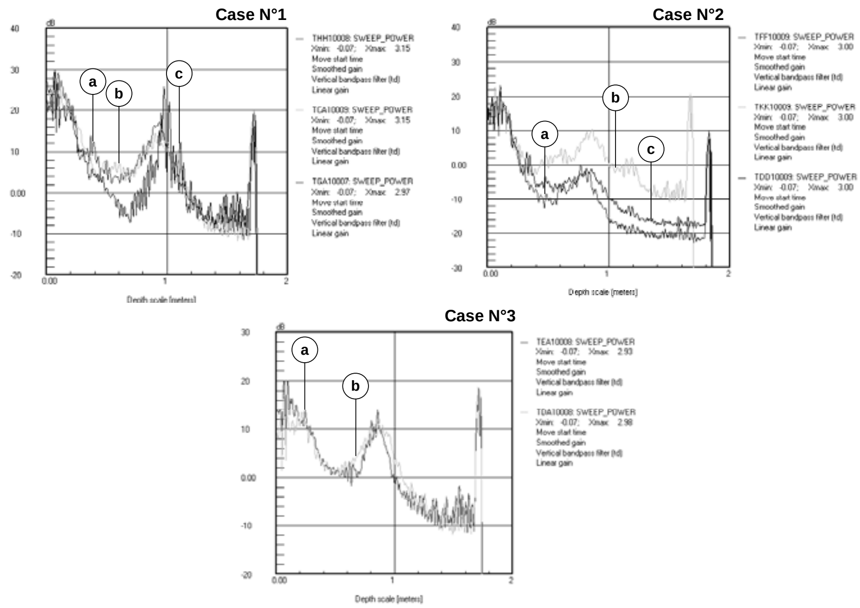

Figure 9: Sweep power of pavements grouped by traffic load

With regard to the second point, the investigation identified very deep discontinuities in the following three roads: Via Sassa, Via degli Alemanni and Via Santo Spirito. These roads are the same as those having a high number of underlying utility grids and a high level of degradation. Figures 10, 11 and 12 display the radargrams obtained from the above-mentioned three roads, whose discontinuities lie at a depth of 2-3 m from the road surface. Also in this instance, the high degradation of the road pavements depends on the lack of a homogeneous subbase and on inadequate compaction of the deep layers.

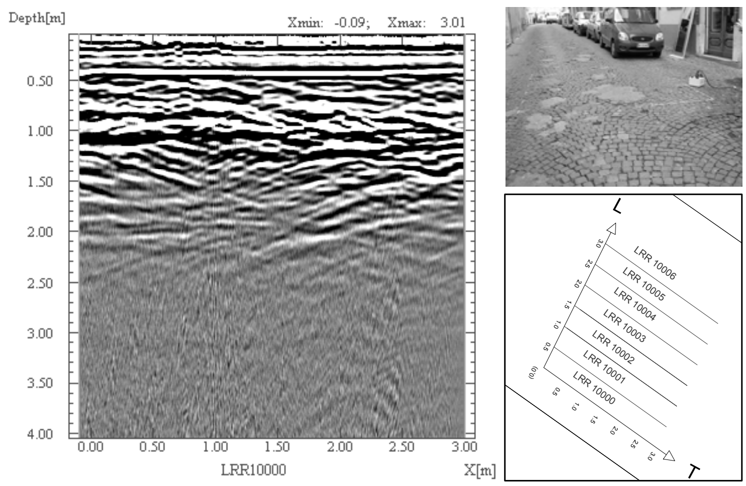

Figure 10: Deep radar discontinuity on Via Sassa

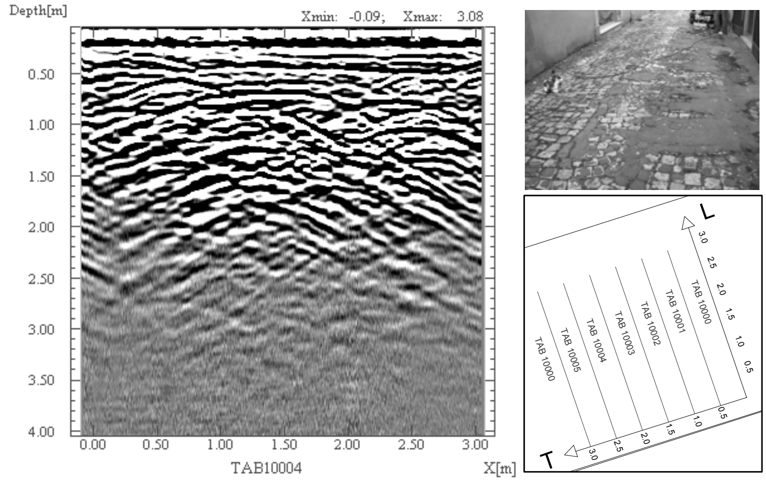

Figure 11: Deep radar discontinuity on Via degli Alemanni

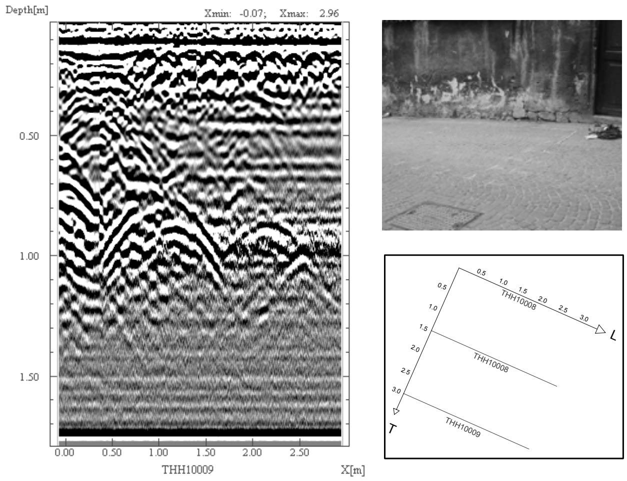

Figure 12: Deep radar discontinuity on Via Santo Spirito

CONCLUSIONS

The paper discusses the findings from a GPR investigation on cobblestone road pavements located in the historical center of L'Aquila (Abruzzo Region). The investigation was aimed at assessing the degradation of the pavements and their possible causal factors.

The GPR investigation used 1,600 MHz (down to a depth of 1 m) and 600 MHz (down to a depth of 4 m) antennas.

The goals of the investigation on the upper layers of the pavements (1,600 MHz antenna) were as follows:

- determining the influence of the characteristics of the road superstructure layers;
- finding correlations between the following variables: type of stone pavement, traffic load, pavement surface degradation and GPR scans.

As to the first point, the investigation showed no degradation in the pavements whose superstructure layers had an interposed reinforced concrete slab; thus, all these pavements are good.

As to the second point, the investigation established three correlations between the investigated variables.

In the first category of correlations, sites with the same type of stone pavement and the same traffic load were investigated on various assumptions of pavement surface degradation. Results show that in areas where the road is degraded, the reflected radar signal has higher values than the ones of less degraded roads.

In the second category of correlations, sites with the same level of degradation and the same traffic load were investigated on various assumptions of type of stone pavement. Results show that porphyry pavements have a more marked reflection of electromagnetic waves than limestone and leucititic lava pavements.

In the third category of correlations, sites with the same level of degradation and the same type of stone pavement were investigated on various assumptions of traffic load. Results shows that pavements exposed to a heavy traffic load have a more marked radar signal reflection than those where traffic load is lower.

The goals of the investigation on the deep layers of the pavements (600 MHz antenna) were as follows:

- identifying utility grids, if any, beneath the road superstructure (i.e. in the subbase at a depth of over 1 m from the road surface);
- detecting extensive and very deep discontinuities (at a depth of over 2 m from the road surface).

As to the first point, the investigation identified the number of utility grids underlying the pavements, indicating that all pavements with a high number of utility grids are affected by high degradation.

As to the second point, the investigation identified roads with very deep discontinuities; also in this instance, degradation is high.

The study reported in this paper established good statistical correlations between GPR signals and the characteristics of the investigated cobblestone road pavements.

In the future, these correlations will hopefully make it possible to develop all-GPR techniques for investigating road pavement degradation. Indeed, these techniques have the advantages of being non-destructive, easy and fast to use and cost-effective.

The results described in this paper substantiate the expected good performance of GPR techniques in the investigation of cobblestone road pavement degradation.

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