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GPR research on damaged road pavements built in cut and fill sections

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Abstract

We present the GPR (Ground Penetrating Radar) results dealing with flexible road pavements located on cut and fill sections. The aim is to evaluate the road damage (particularly the ramified cracks) taking into consideration also the cut and fill sections height and the traffic load. GPR evaluation was carried out on 14 sites selected in the secondary non-urban road network of L'Aquila, a medium-size urban area of Central Italy. Stress induced by traffic load generally affects a road section thickness of about 1.5 m. A monostatic 1600 MHz GPR antenna was used because it is quite high-resolution when inspecting road damage. GPR acquisition was carried out in damaged and adjoining undamaged road sites, to compare GPR data of the two areas. GPR data analysis was based on the sweep-rectified power approach to evaluate the radar signal attenuation curve vs. depth, which permitted to single out different road types of damage and to discuss the factors which caused them.

Keywords: 1600 MHz GPR antenna; flexible road pavements; cut and fill sections; ramified cracks

1. Introduction

We report the results carried out by using GPR (Ground Penetrating Radar) technique on flexible road pavements built in cut and fill sections. The goal was to find correlations between the type of paving deterioration, (only ramified cracks), the cut and fill section with a height about 4-8 m and the low traffic load (average daily traffic < 1000) and the results obtained from the GPR survey. Previous studies have always evaluated different types of paving deterioration with a reduced number of GPR scans. The results were interesting but not definite, due to their extremely small number (Colagrande et al. 2007).

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During the current research, to increase our data we acquired fourteen GPR measurements for the variable evaluated (cut and fill section with height of about 4-8 m and low traffic load).

With regards to the type of deterioration inspected, the survey was conducted only on the ramified cracks (also called spider or alligator cracking) that represent one of the five types of bearing capacity structural defects regarding flexible road pavements (SHRP-P-338 1993; Lahour and Al-Qadi 2008).

2. Materials and methodology

The research goals were to carry out a survey with the GPR technique of degraded road pavements with a single type of deterioration, carried out on the cut and fill sections. The ramified cracks (RC) deterioration analyzed were selected to represent the worst conditions. Longer fractures measuring 5 m and wider than 5 mm were identified and, regarding the extension of degraded areas, more than 5 m^2 extended pavements were identified.

Regarding the influence of the height of the cut and fill sections and the intensity of the traffic, were considered pavements consisting of high cut and fill sections (HCF), a height of > 4 m, and pavements subject to low traffic load (LT), with average daily traffic < 1000. Once again dealing with traffic loads, a further verification was performed which took into consideration the diversity of the fleet of vehicles in transit on the roads surveyed, in order not to neglect the effect of heavy traffic. This verification was not focused on the average daily traffic load, but rather on the equivalent standard axle loads (ESALs - each of the 120 KN) per year. The evaluation confirms the results obtained in the first study and identified the following traffic load classes: low traffic loads (LT) with < 4,000 ESALs/yr.

Therefore, the inquiry was performed on fourteen sites (Figs. 1a, 1b) chosen to be representative of the combination of the variables analyzed. The same sites were identified on the non-urban road network located close to L'Aquila (central Italy). Be informed that the studied area is placed at an altitude of 700 m above sea level and is characterized by cold winters.

Fig. 1a. L'Aquila location.

Fig. 1b. Non-urban roads of L'Aquila investigated with GPR (red color).

The superstructures of the evaluated roads are constituted by flexible road pavements which have similar layers, with the following thicknesses: layer of foundation in granular mixture: 30 cm, base layer in bitumen mixture: 10 cm, binder layer: 6 cm and surface layer: 4 cm, both consisting of a bituminous concrete. Therefore, the superstructures on average have a total thickness of 50 cm.

The GPR surveys were carried out to perform a quantitative analysis through the examination of the GPR signal attenuation curves with the depth (the rectified power method). An antenna module with a nominal frequency of 1600 MHz was used, which is a type of evaluation that is quite reliable if directed at a depth of up to 1.5 m. This choice was made based on the effect, due to the stresses induced by traffic on cut and fill sections, to a maximum depth of about 1.5 m, developing, however, in the most accentuated form on an average in the first 50 cm of the superstructure (Huang and Su 2004).

In this current study, we used a 1600 MHz butterfly antenna manufactured by Systems Engineering - IDS (Pisa). It is a portable, monostatic type, non-dispersive antenna and is characterized by linear polarization, low directivity and limited bandwidth.

3. State of the art

As it is known, the propagation of an electromagnetic field is described by the Maxwell equations, in which the constant of attenuation α appears, which expresses the amount of energy that is absorbed by the intersected layers. Please remember that the larger the void ratio of the evaluated material the greater the attenuation of the radar signal and the lower the attenuation constant is α (Benedetto 2004). Therefore, by determining precisely the α attenuation constant, it is possible to obtain a positive evaluation of the depth of the signal penetration itself.

Since the goal of our study is to evaluate the importance of structural defects, we decided to focus the evaluation on a maximum depth of 1.0 m from the road pavement. This choice was made because the effect, due to the stresses induced by traffic on cut and fill sections, to a maximum depth of about 1.5 m, developing. However, in the most accentuated form on an average in the first 50 cm of the superstructure and spreading, with a still evident and easily seen result, for an additional 50 cm. Therefore, the theoretical reference road section was schematized in two portions: the first, 50 cm (S1), representing the superstructure and the second, an additional 50 cm (S2) representative of the portion of cut and fill section laid on soil which is affected by the traffic (Benedetto et al. 2012). This choice was in line with the demands that the antenna resolution of GPR had adopted (1600 MHz). Another fundamental assumption adopted in the model was that layers S1 (road pavement) and S2 (subgrade) are considered homogeneous on average. This assumption does not accurately reflect the reality, especially for the S1 layer, given the granulometric variety, specific weight and form that characterize the materials used in road pavements. The sweep rectified power analysis was carried out in our study by using software created by IDSGred (© 2004 IDS Ingegneria Dei Sistemi SpA, Pisa) and represents the average trend (straight line attenuation) energy absorbed by the ground portion of the cut and fill sections placed between 50 and 100 cm (S2).

Through this interpretation of the rectified power diagrams, you can trace the α attenuation angle that graphically represents the angle that envelopes the R^2 regression line of power, forms with the x-axis which, in turn, indicates the depth from the road surface.

Regarding the surveys carried out in our study, please note that the analysis was carried out considering two contiguous stretches in length equal to 1.5 m belonging respectively to a damaged area and an undamaged area from degradation and as not to present specific abnormalities, such as vitiating the comparison.

The relative diagrams for the two contiguous sections surveyed (both damaged and undamaged area) were included in the same graph to highlight their differences. The red colored diagrams are related to the degraded road sections; while those of green colored diagrams belong to the intact portions (Colagrande et al. 2011). By making comparisons between attenuation corners of damaged areas (α_d) and undamaged (α_u), it is expected that if the difference between these values ($\Delta\alpha = \alpha_d$-α_u) tends to zero, then the probable cause that generated the deterioration of paving is attributable to phenomena of fatigue or thermal shrinkage. These phenomena are due to horizontal tensile stresses that develop in the S1 layer of the road pavement (Figure 2a). In fact, in this case, in the S2 layer the energy curves are almost coincident, which means that the subgrade terrain relating to the two examined road sections, display the same degree of densification and there are no compactions in place (Figure 3).

If instead, $\Delta\alpha \neq 0$ the probable cause that triggers the degradation of the road pavement is attributable to the change of soil compaction portion of the cut and fill section present in the S2 layer due to the action exerted by vehicular traffic. In this circumstance, we must make a further distinction between the case in which $\Delta\alpha > 0$ and the case in which $\Delta\alpha < 0$ (Benedetto and Benedetto 2002). In the first, the energy curves for the damaged areas (red) are at a lower energy content than those undamaged (green). This means that the deteriorated areas are more compacted of the not deteriorated areas. More precisely, the energy curves for the damaged areas (red) are positioned beneath those undamaged (green), and this confirms the fact that a lower power consumption level corresponds to an index of lesser void ratios (Figure 4).

Therefore, the degradation process is no longer in place in the deteriorated area, while the areas that are not deteriorated will tend, over time, to assume the same level of densification of damaged areas; then the entity of degradation will tend to not remain confined in the deteriorated area but to expand in the neighboring areas (Figure 2b).

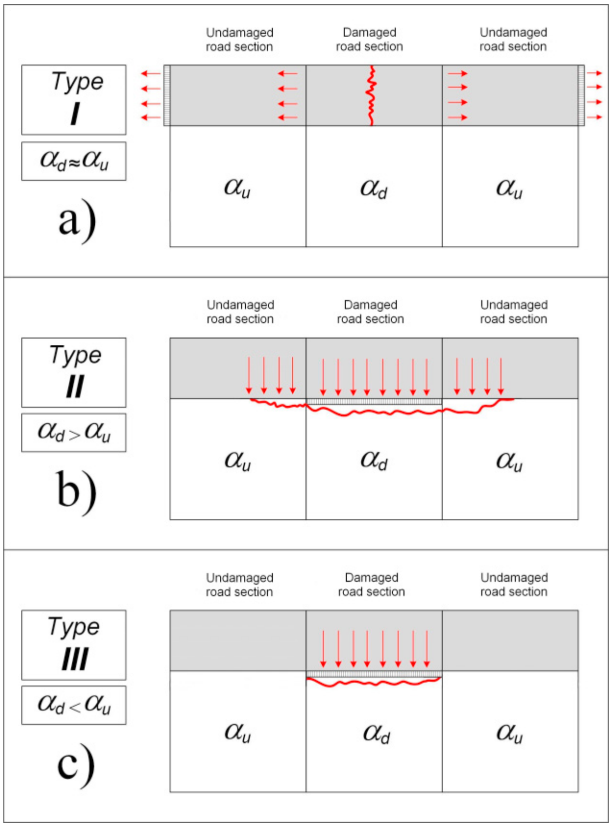

Fig. 2. Diagram illustrating the three types of road deterioration.

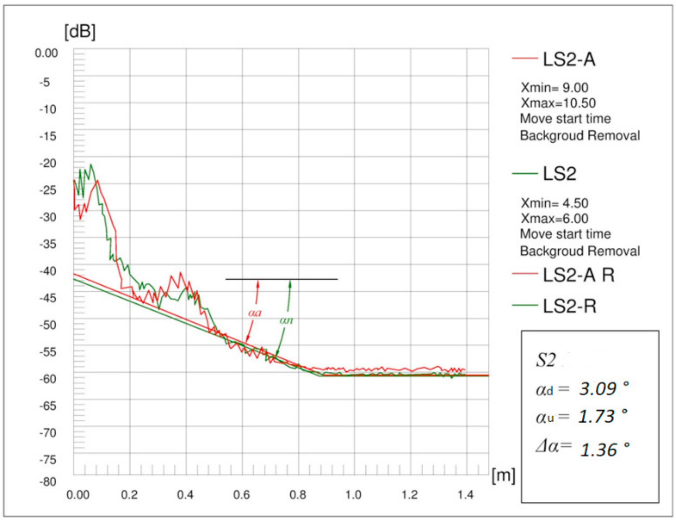

Fig. 3. Example of the $\Delta\alpha \cong 0$ case.

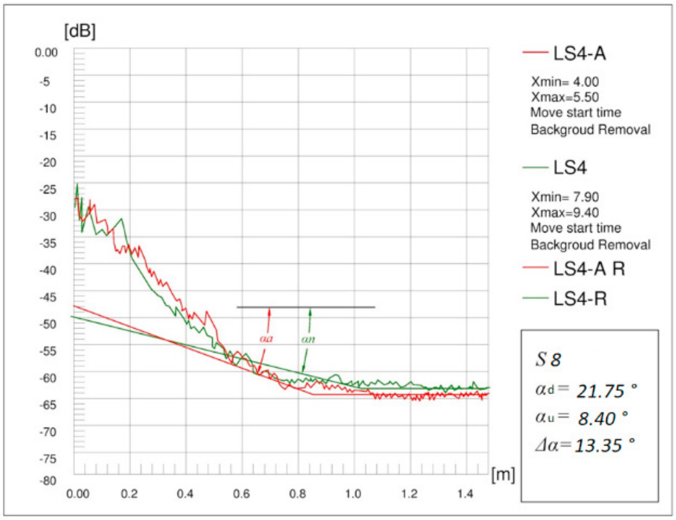

Fig. 4. Example of the $\Delta\alpha > 0$ case.

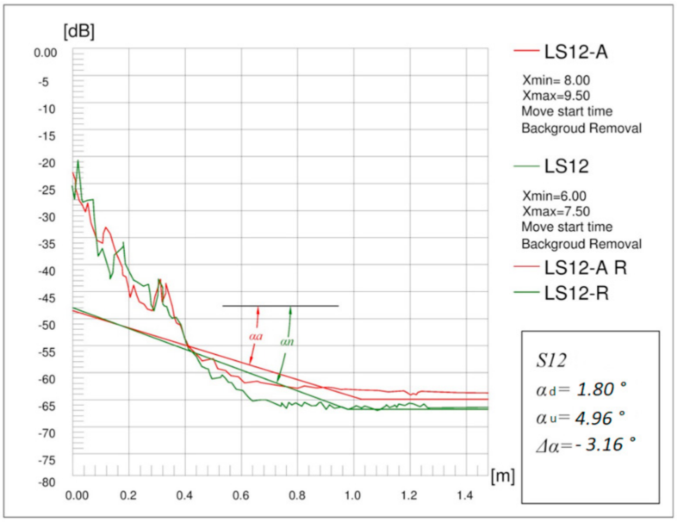

Fig. 5. Example of the $\Delta\alpha < 0$ case.

In the second, the energy curves for the damaged area (red) are at a higher energy content than those which are undamaged (green), and that the deteriorated areas are less non-deteriorated compacted areas.

More precisely, the energy curves for the damaged areas (red) are positioned above those undamaged (green), and this confirms the fact that at a power level absorbed corresponds a higher void ratio greater (Figure 5).

Therefore, the degradation process is still going on in the deteriorated area and continues until it reaches the level of densification of the area not deteriorated; for this, the degradation will remain confined in the area affected by deterioration (Figure 2c).

4. Results

We present the results of the GPR surveys carried out on fourteen sites representative of the combinations of the variables analyzed.

In this regard, it is noted that the accuracy in the interpretation of radargrams is a function of the antenna resolution and sampling the electromagnetic signal; in our case they are respectively of 1 cm and of 1024 samples per second. Furthermore, the resolution in the power sweep diagrams is of 1 dB for the signal attenuation (y-axis), and of 4 cm from the road surface to the depth (x-axis). This approach provides a detailed resolution to be able to evaluate areas up to 1 cm^2 in a thickness of road pavement/cut and fill section up to the depth of 1.5 m (Figures 3, 4 and 5).

With the assistance of the sweep rectified power analysis, we proceeded to the evaluation of signal attenuation angles is in damaged sections (α_d), and in those undamaged (α_u), to which was followed by the evaluation of the variation of the attenuation ($\Delta\alpha$). In Table 1 are reported, the combinations tested, the values of the attenuation constant α and the index $\Delta\alpha$ calculated.

The analysis of the results made it possible to divide the types of degradation in two categories: the first consists of the resulting deterioration due to problems inherent in the road pavement layer (layer S1), and the second consists of the interesting deterioration of the subgrade layers (layer S2).

The deterioration in the first category (breaking in S1 layer) have provided values of $\Delta\alpha$ content in a range, respectively, of $-2 < \Delta\alpha < +2$.

In this regard, the analysis of the values reported in Table 1, it was found that the first seven sections are characterized by the same types of results concerning the rupture in layer S1.

For the findings, we can state that, in the light of the considerations set out in the preceding paragraph, the deterioration caused in the S1 layer (Figures 2a, 3) are normally generated by horizontal tensile stresses due to fatigue or thermal shrinkage affecting the surface layers of the road pavement. Generally, the rupture of the road pavements depends from the undersize of layers respect to traffic loads. Moreover, the breaking of the surface layers in S1 may depend on deep settlement, which originate at the base of the detecting portion of the embankment of the cut and fill section (Figure 6).

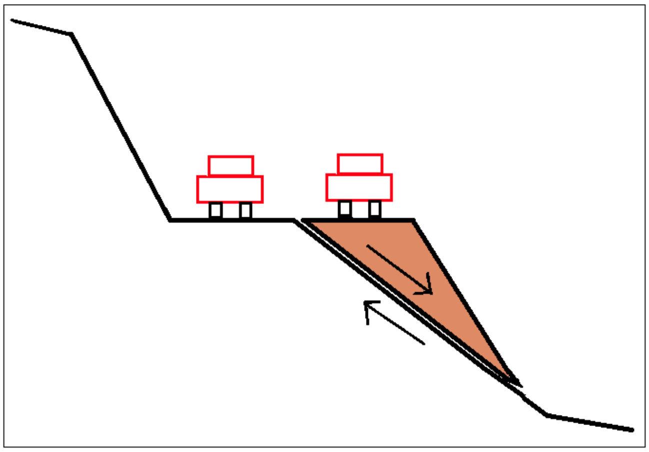

Fig. 6. Example of high height cut and fill section with traffic.

As said, we can deduce that the soils present in the cut and fill sections (up to 1.5 m deep) are not, in this case, the cause of no damage of the cracking type.

From the analysis of the results in the first category (breaking in S1 layer), it is clear a high repeatability resulted from the values obtained from the measurements with the GPR (50% of total), demonstrating that GPR is reliable for evaluation of deteriorated road surfaces and provides consistent results.

Regarding the deterioration of paving in the second category (rupture in the S2 layer), however, they were recorded values of $\Delta\alpha$ included in an interval of $-5 < \Delta\alpha < +15$.

Table 1. The different values of α_d and α_u measured and the index $\Delta\alpha$ calculated.

Number	α_d	α_u	$\Delta\alpha$	Damaged layer
1	2.13	0.15	1.98	S1
2	3.09	1.73	1.36	S1
3	0.64	0.80	-0.16	S1
4	2.83	3.22	-0.39	S1
5	2.98	1.69	1.29	S1
6	1.30	0.20	1.10	S1
7	2.78	3.52	-0.74	S1
8	21.75	8.40	13.35	S2
9	9.63	3.26	6.37	S2
10	14.95	0.95	14.00	S2
11	6.71	0.50	6.21	S2
12	1.80	4.96	-3.16	S2
13	1.90	4.46	-2,56	S2
14	5.61	2.78	2.83	S2

As found, it can be said that the deterioration regarding the layer (S2) are generated by the sudden change in density from the subgrade terrain produced by natural settling and the action exerted by the vehicle traffic (soil compaction). It is noted that, for 5 sections of 7 were recorded the highest values of $\Delta\alpha$ with a positive sign. This means that the problems inherent in the compaction are not limited to the layers close to the substrate but extend throughout in the neighboring damaged area of the cut and fill sections. For 2 sections of 7 were recorded the highest value of $\Delta\alpha$ with negative sign. This means that the problems of compaction are limited to the layers close to the substrate and remain confined in the already deteriorated areas. This means that generally, the rupture depends from landslides that interest the subgrade terrain of the roadway.

The results obtained also in this case show a high repeatability with 50% of total, showing that it is a reliable methodology for evaluation of road pavements deteriorated.

5. Conclusions

The results of a GPR survey conducted on degraded road pavements built on cut and fill sections (height: 4-8 m) and characterized by low traffic load (average daily traffic < 1000) is presented. It was evaluated only one type of deterioration (ramified cracks) and was carried out a survey on a large sample (fourteen surveys sites). These pavements have been identified on secondary roads of the non-urban area of the city of L'Aquila (central Italy).

The evaluation of the attenuation curves of the radar signal detected from the road pavement, performed by the sweep rectified power method, allowed us to determine the attenuation constant α.

Through the comparison of the attenuation of constant α, detected on two adjacent longitudinal sections belonging respectively to a damaged portion (α_d) and to an undamaged stretch (α_u), made it possible to trace the causes of the degradation of the analyzed pavements.

The results, taken from a large sample, showed high repeatability to demonstrate that the methodology can be trusted to evaluate deteriorated road pavements characterized by cut and fill sections.

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