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Concrete Pavement Layers Investigation with GPR in the BR-101 Highway

Investigação de Camadas de Pavimento Rígido com GPR na Rodovia BR-101

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Abstract

In the construction project of a highway, some rules related to the materials and thicknesses of the layers must be followed to guarantee that the project is carried out properly. From denunciations accusing irregularities on the project of the highway BR-101, on Northeastern Brazil, we applied the Ground Penetrating Radar (GPR) method to investigate the depths of the base and subbase layers. It was used a 900 MHz shielded antenna, acquiring 45 km of data. The medium velocity was obtained indirectly through a hyperbolic fit and calibrated comparing it with the depth of a test trench. The results pointed out depth variations for both of the layers along the analyzed track, however the average depth only deviates from the original project for the base layer.
Keywords: GPR; concrete pavement; BR-101

Resumo

No projeto de construção de uma rodovia, algumas regras relacionadas aos materiais e espessuras das camadas devem ser seguidas para garantir que o projeto seja realizado adequadamente. A partir de denúncias acusando irregularidades no projeto da rodovia BR-101, no Nordeste do Brasil, aplicou-se o método Ground Penetrating Radar (GPR) para investigar as profundidades das camadas base e sub-base. Foi utilizada uma antena blindada de 900 MHz, adquirindo 45 km de dados. A velocidade do meio foi obtida indiretamente através de um ajuste hiperbólico e calibrada a partir da comparação com a profundidade de uma vala de teste. Os resultados apontaram variações de profundidade para ambas as camadas ao longo da trilha analisada, porém a profundidade média desvia do projeto original apenas na camada de base.
Palavras-Chave: GPR; pavimento rígido; BR-101

1 Introduction

Brazil presents a large road mesh over the country, however, just 14% of it is paved (CNT, 2014). According to National Transport and Logistics Plan of 2009, made by the Ministries of Transportation and Defense, the transport through highways stands for more than half of the total transportation, with a decreasing tendency in the long term. Still, there's a need for the expansion of the mesh and the paving of the existent roads and its conservation.

The pavement is organized in a conjunct of layers, horizontally orientated and vertically stacked. They are designed to resist the stress resulted from the traffic and provide better conditions. The Brazilian highways are mainly formed of flexible pavements, but as well made of rigid pavements on a minor scale. The flexible pavement is organized in surface course, base course, subbase, and subgrade. The rigid pavement is, on the other hand, organized in concrete slab, base course, subbase course and subgrade (CNT, 2014; Jain *et al*., 2013). The pavement projects are developed to maximize traffic conditions and minimize maintenance costs.

Among all the layers composing the pavement, this work focuses on the shallowest. On the rigid pavement, the external layer, the surface, is made of concrete united by tie bars and has the function to distribute the stress and resist degradation. Sequentially below is the base, which redistributes and is resistant to the stress, composed mainly of macadam. The subbase is complementary to the base and filled with aggregates with a quality inferior to the ones used in the base (DNIT, 2006).

The agencies have two options regarding verifying the pavement conditions and thickness: direct or indirect sampling. The direct requires the extraction of cores, digging test-pits or even the use of Dynamic Cone Penetrometer (DCP) measurements (Loizos & Plati, 2007). The disadvantage of the direct sampling is the interference and damage to the area. Indirect methods allow getting information without harming the pavement. However, the direct sampling can't represent all the extension of the pavement, once the samples are random, punctual and sparse, due to the damage they cause when extracted. Indirect methods can provide continuous information, thus an advantage to large investigations. One of the common methods used for indirect observation is the Ground Penetrating Radar (GPR).

The GPR method analyzes the propagation of high frequency, which can be between 25 and 5000 MHz (Jol, 2009), electromagnetic pulses on the studied environment. The electromagnetic signal is released by the equipment, reflected by the medium and received at another antenna. The registered signal allows the identification of the millimetric layers which form the pavement. Thereupon the GPR has been used in pavement studies since the mid-1970s (Morey, 1998).

At the pavement study, the GPR main objective is to find the thickness of the layers or any other structures as cavities or fissures, inside or below the coating; as well as the locations of the tie bars connecting concrete blocks in the case of rigid pavements. Regarding pavement thickness measurements with GPR, there were executed many studies with successful results (Leng & Al-Qadi, 2011; Liu & Sato, 2014; Loizos & Plati, 2007; Saarenketo & Roimela, 1998; Saarenketo & Scullion, 2000).

The extension of the highways coverage along the country dimensions difficult the government supervision. This work was executed in order to investigate the denunciation of illicit acts during the construction of the BR-101. This denounce was received in 2010 by the *Advocacia Geral da União* (AGU), the Brazilian equivalent to the Attorney General's Office.

The BR-101 is a federal highway that crosses twelve states, from Rio Grande do Norte till the Rio Grande do Sul, and extends over 4500 km. Due to its long extension, only the division 07, comprehending approximately 38.7 km and located on the state of Pernambuco, was analyzed. Therefore, this work presents the results of the determination of the thicknesses of the base and subbase layers at division 07 of the BR-101.

2 Methodology

The general radar system is formed by a pulse generator, a receiver antenna and a recording unit (Reynolds, 1997). The generated electromagnetic waves travel through the medium and part of the energy is reflected when they collide with an interface. The reflected wave is received through another antenna, and the signal converted. The resulting signal may be seen through a display unit (Figure 2).

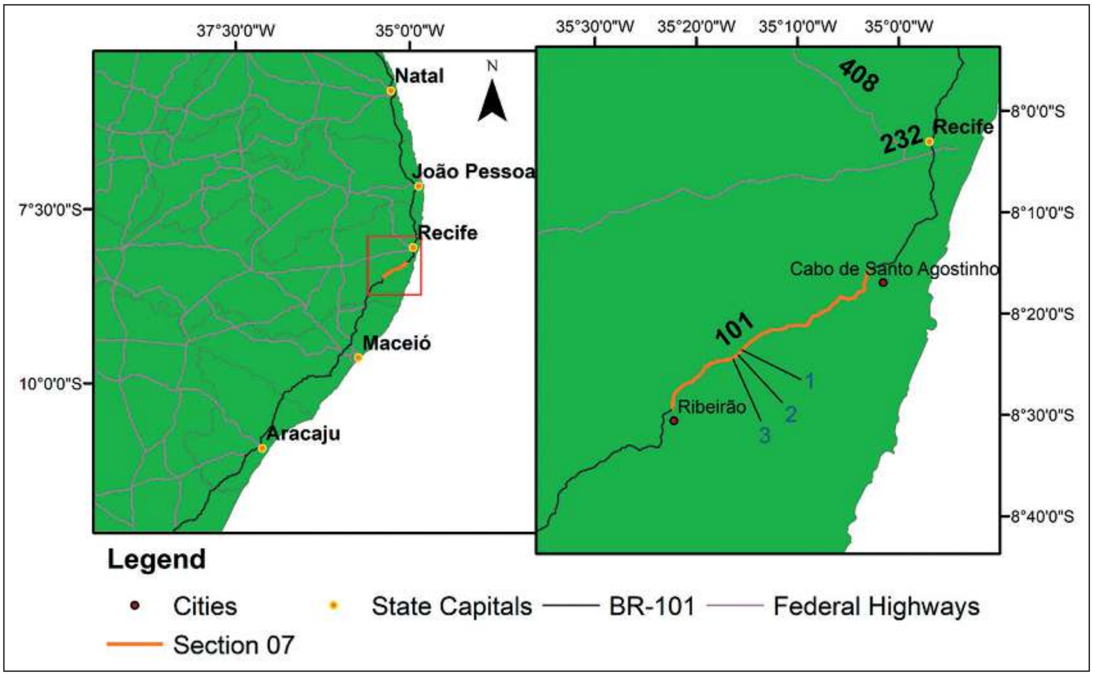

Figure 1 Localization of the BR-101 and the section 07. The section goes from the cities of Cabo de Santo Agostinho to Ribeirão. The numbers 1,2 and 3 are the locations for the sections in Figure 7.

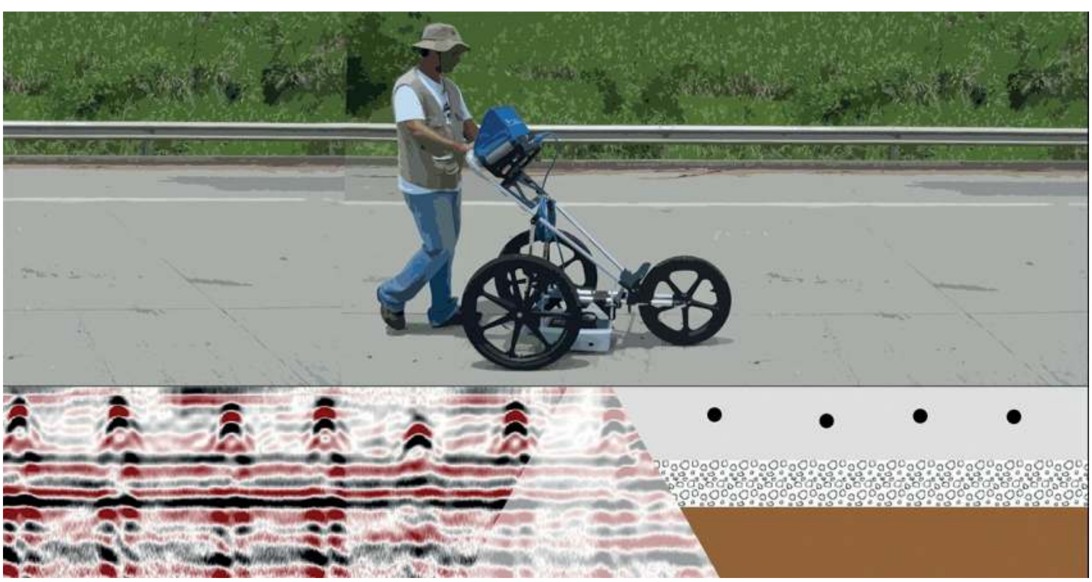

Figure 2 Illustrative GPR acquisition. The medium is the schematic representation of the shallowest layers of a rigid pavement. The wave travels in this medium and is reflected at the interfaces, because of the difference in the electromagnetic properties.

In order to the reflection occur at the interface, the two mediums need to have different electrical characteristics. The three main properties related are the magnetic permeability μ, the electric conductivity σ, and the dielectric permittivity ε (Beben *et al.*, 2012). The wave velocity V_m depends of dielectric permittivity and the speed of light in vacuum c (1).

$$V_m = \frac{c}{\sqrt{\varepsilon_r}} \quad (1)$$

The penetration depth of the equipment depends on the frequency content of the wave, and it is defined as the amplitude value attenuated by a factor of e^{-1} (Beben *et al.*, 2012). The waves have a frequency according to the generator antenna. The signal attenuation during the travel in the medium is mainly controlled by the spherical spreading, the energy partitioning at the interfaces, the conversion of electromagnetic energy into thermal energy (Beres & Haeni, 1991), the material composition and the amount of water present (Leucci, 2008).

The acquisition was executed with the SIR-3000, from Geophysical Survey System Inc. – GSSI, coupled with a shielded antenna of 900 MHz. The beginning and end of the profiles matched the concrete blocks limit. The acquisition followed the highway direction from the cities of Recife to Maceió (Figure 1).

As higher frequencies present smaller wavelengths, the higher the frequency the higher the accuracy of the investigation. The differentiation possibility of two signal measurements is the vertical resolution, which also depends of the frequency. According to Conyers (2004), objects can be distinguished if they have at least 25% of the wavelength size. Due to the small thickness of the investigated layers, it is required the use of a high frequency antenna. The average accuracy of base thickness measurement is ± 9.5% (Maser & Scullion, 1992; Willett *et al*., 2006).

The profiles were acquired in the common-offset antenna combination, trace interval of 0.01 m, each with 512 samples and time sampling interval of 0,058593 ns, 30 ns time window and sampling frequency of 17066 MHz. The acquired profiles extension varied from 500 to 600 m, to avoid large files and storage issues.

The processing workflow (Figure 4) was accomplished using the Reflex-Win 6.0.5, from Sandmeier Software. The first step of the processing consisted in the removal of the travel time between the antennas and the ground, because of the equipment design the antennas are suspended and don’t touch the ground directly. To remove broadband noise and interferences, it was applied a band-pass filter to keep the frequencies around the center of the designed frequency of the antenna (900 MHz). There are constant signals from external fonts that interfere with the GPR signal, and it presents a standardized response in the data. These constant signals were attenuated applying a background removal. As the amplitude attenuates according to the distance traveled by the wave, the header gain was removed in order to be applied a combination of a linear and an exponential gain, recovering the amplitudes at the desired interval. Lastly, a Kirchhoff Migration was applied to the data. The benefits of the migration include better definition of the diffracted and reflected energy, increasing thus the precision.

The velocity was measured with indirect and direct methods. The indirect method is executed with a hyperbola fitting into the diffractions caused by the tie bars at the pavement. The aperture of the hyperbola indicates the velocity of the medium (Fi-

Figure 3 GPR system. The equipment is a GSSI SIR-3000 coupled with a 900 MHz antenna. The same equipment is seen, laterally, in Figure 2.

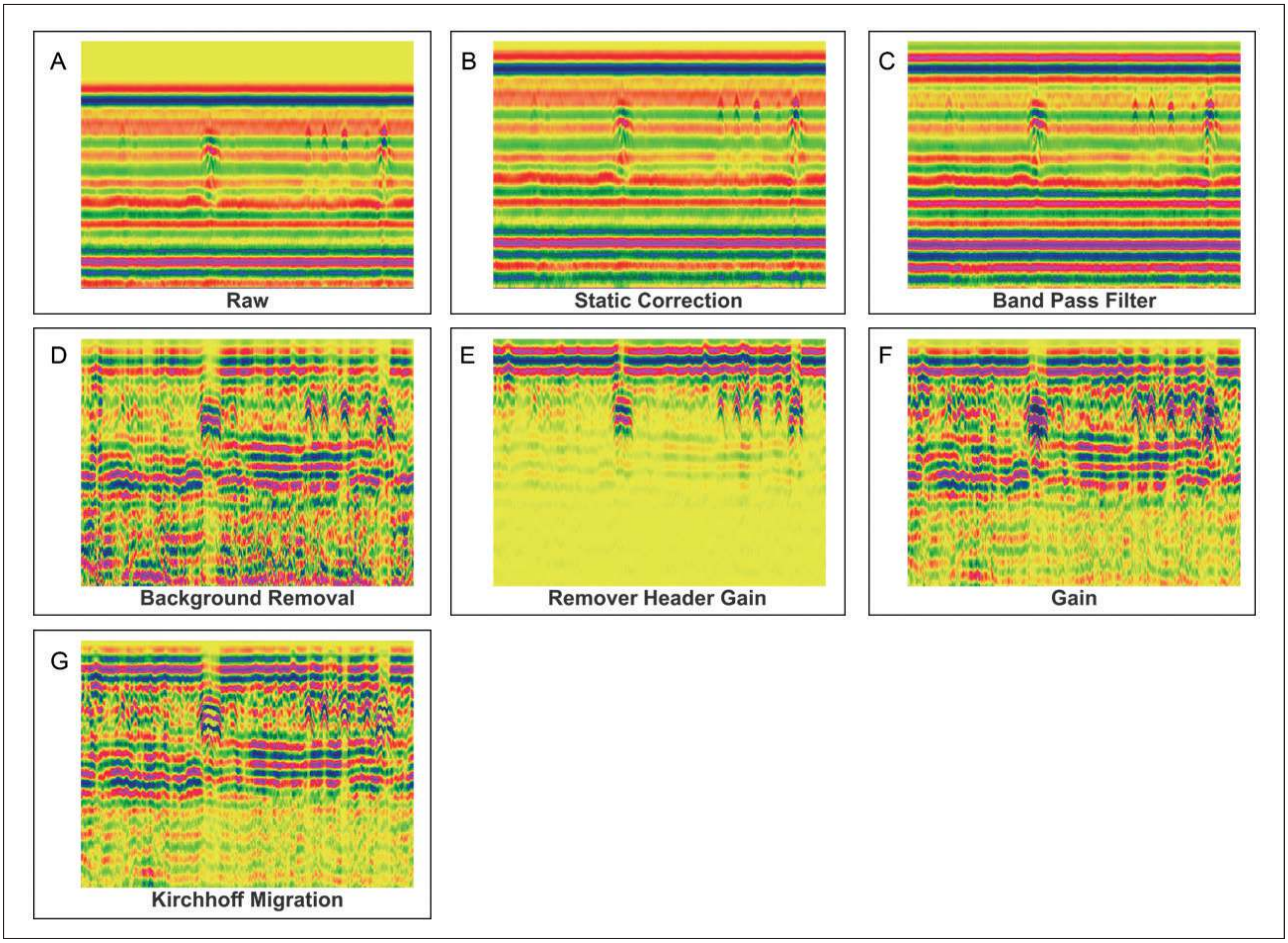

Figure 4 Flow chart of the processing steps applied to the dataset. The images from A to G show for the same section the data modification for every processing step. This small section of just a few meters was clipped out from a stored section, as an example of how the objective of the processing is to heighten the identification of the targets.

gure 5). The direct method is executed through the comparison of the real depth of the layers obtained from a trench and the travel time of the same layer in the radargram. The velocity is used either in the migration and in the time-depth conversion. The adjusted velocity was equal of 0.0720 m/ns.

After the processing, the top limits of the base and subbase layers were delimited for the dataset. The delimitation was made from amplitude analysis on the radargram and also based on the diffractions caused by the tie bars inside the concrete, besides observed horizontal continuation pattern of the interfaces between the layers. The interfaces can also be discriminated using a stacked conjunct of traces of a section (Figure 6), and also by the trace envelope (Figure 7).

3 Results and Discussion

According to construction project of the pavement of the BR-101, the top of the base layer should be at the depth of 0.22 m, and the top of the subbase at the depth of 0.32 m. The processed dataset was analyzed, and the interfaces between these layers marked with points (1 per trace). The statistics in Table 1 made from the points presented that the average depth values found for the base layer was 0.20 m, and 0.32 for the subbase layer.

Another analysis can be made using the trace envelope. The envelope contains the absolute value of the amplitude of the trace. The envelope analysis from an area of a section permitted to identify regions,

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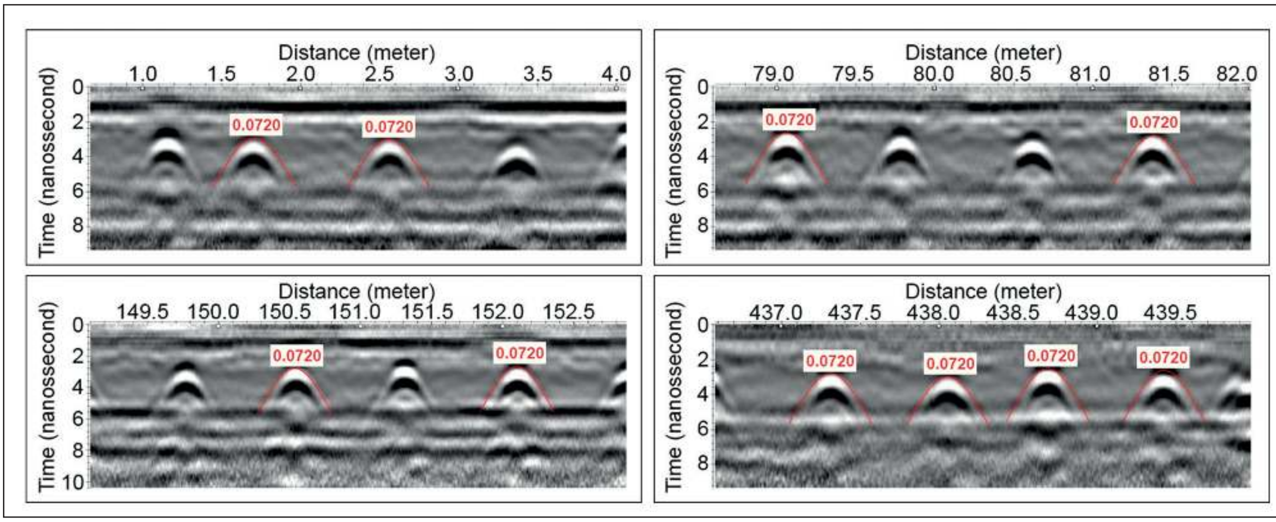

Figure 5 Hyperbolic curve fit on the tie bars caused diffractions. The images were taken from different linear tracks of the road. The velocities are the same, which indicates consistency of the fitting.

	Top Depth Base Layer	Top Depth Subbase Layer
Number of Points	7 754 470	7 728 686
Standard Deviation	0.0217	0.0194
Mean	0.2030	0.3203
Mode	0.2040	0.3118
Median	0.2029	0.3200
Maximum	0.2983	0.4540
Minimum	0.1098	0.2322
Above Project	21.24%	50.00%
Below Project	78.76%	50.00%

Table 1 Statistical results of the points delimitated as the interfaces of the concrete-base and base-subbase layers.

where the amplitude content is different (Figure 6). The layers depth provided similar results, 0.20 m and 0.32 m for the base and subbase layers, respectively. The direct measurement from the envelope (Figure 7) amplitude emphasize the base layer, distinguished by its continuity as a high amplitude body, and the tie bars diffractions. Nevertheless, there are smaller differences when compared to the common amplitude radargram, because of the absolute transformation of the amplitude in the envelope, medium amplitude values don't stand out as the bright colors of the bulk of the layer, leading to edge uncertainties.

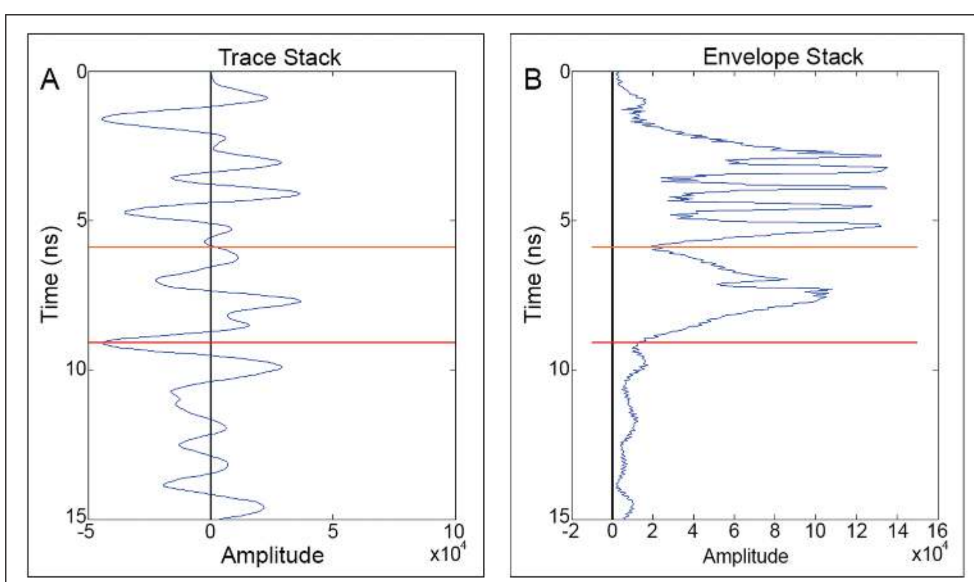

Figure 6 The trace stack A shows the amplitude stack of traces, while B shows the amplitude stack of the envelope of the traces. The envelope of the trace allows delimitating the regions correspondent to the layers. Although it is possible to identify the top and bottom of the interest layers, the lack of continuity makes it a harder task.

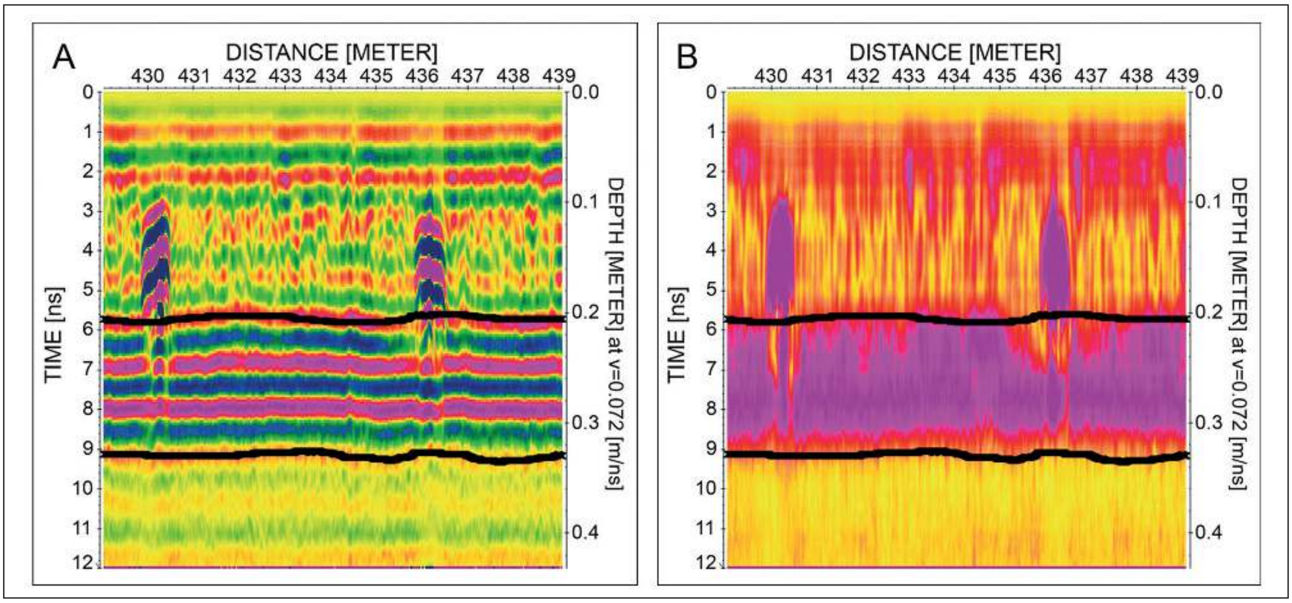

Figure 7 Comparison between the delimitation from an A average radargram and the B amplitude envelope.

Table 1 had already pointed the interface depth variation for the layers, but it is easier visualized in Figure 8. Both the base and subbase layers vary, and it is spread on the entire extension of the highway, where in some regions the variation is larger consisting in extremely irregular layers, and other regions that the layers are more regular. The base of the subbase layer cannot be seen due to the material which it is filled, that diffracts the energy.

The histograms (Figure 9) present the distribution of the depth points marked. The mean depth values presented before (0.20 for base and 0.32 for subbase) coincide or are very close to the mode value (0.20 for base and 0.31 for subbase) for each of the interfaces. Some depth intervals present a high number of samples, which pulls the mean towards these values. As the points are somewhat fairly distributed around the mean value, this indicates that although the mean is closer to the value specified on the project, still there is a large depth variation. For the top of the base layers, 78.76% of the points marked were below the specified depth, as for the top of the subbase layer, about 50% were below the planned depth.

4 Conclusion

The GPR has proven to be effective in the proposed study, assisting on the delimitation of the depths of the layers. The use of this method beneficial because of the easy data acquisition, especially on flat surfaces as a highway, also due to its simplicity comparing to other methods and the preservation of the studied area.

As seen in the presented data, the depth of the layers is very uncertain, due to a constant change of the depths. This result shows that there is a difference between the highway and the construction project, that specified that the top of the base and subbase layers should be at the depths of 0.22 m and 0.32 m, respectively; when the mean depth values for each of them was 0.20 and 0.32 m. Although the mean depth value for the subbase layer is the same as the project, there is a difference of 0.02 m for the base layer.

The constant change of depths in the base and subbase layers along the section 7 of the BR-101 could affect the highway durability or lifetime, thus the region is a potential location to perform studies about structural imperfections and its impact.

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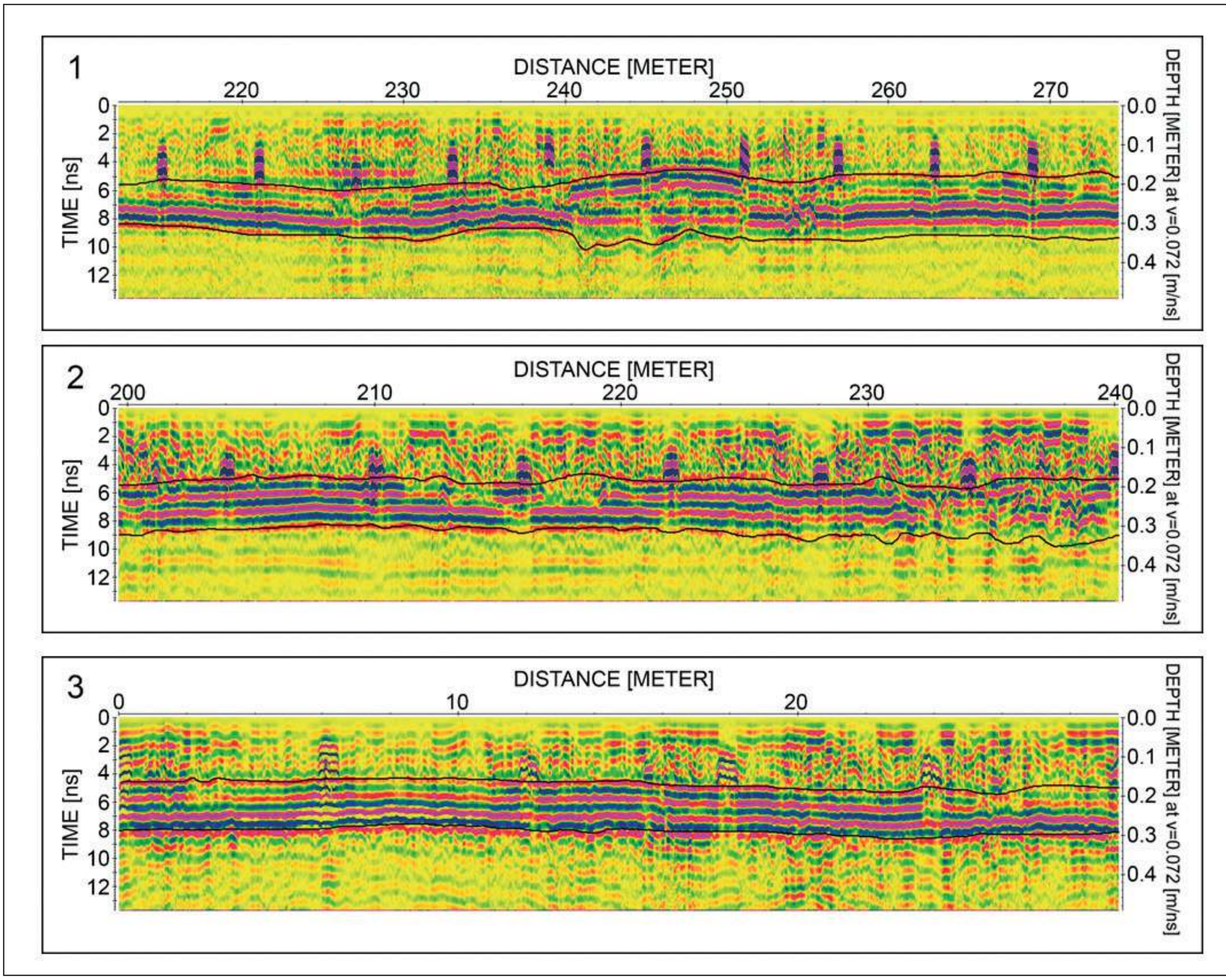

Figure 8 Compilation of sections presenting the layers studied. From these, it is possible to see the depth variation for each of the layers. They were extracted from different areas of the highway, as shown in Figure 1.

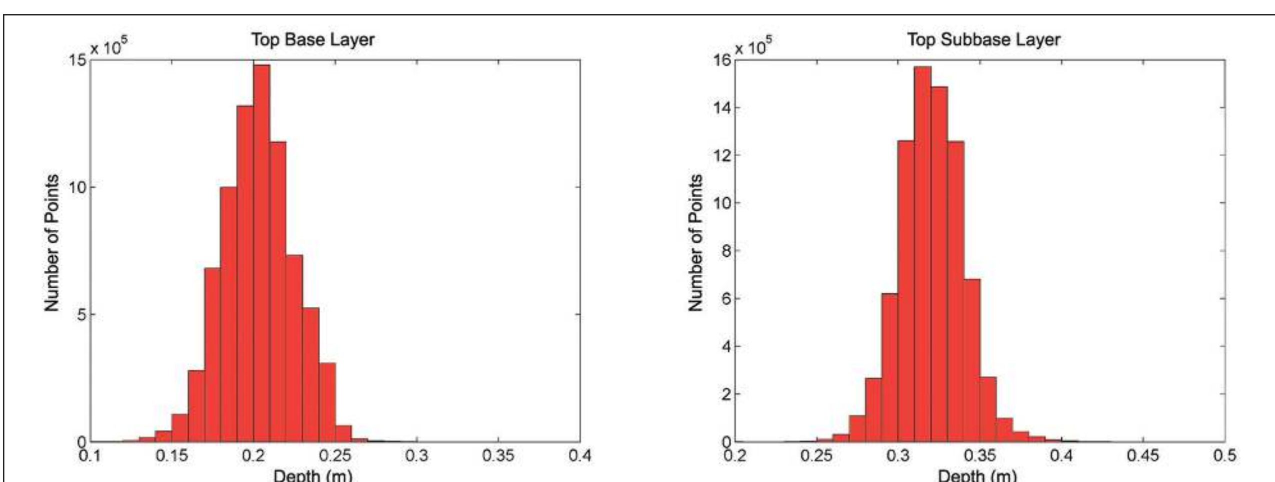

Figure 9 Histogram presenting the distribution of points for a depth interval of 0.01 m.

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