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Assessing the pavement subgrade by combining different non-destructive methods

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HIGHLIGHTS

- Air-coupled antennas are more suitable for measuring layer continuity.
- Ground-coupled antennas had better signal to noise ratio and better resolution.
- LWD is more suitable for the evaluation of the surface layer.
- FWD is more appropriate for the structural evaluation of the overall pavement.
- NDT techniques combined proved to be a useful approach to access the subgrade.

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ABSTRACT

The subgrade provides support to the pavement system and assures an effective distribution of traffic loads in depth. Therefore, a failure in the subgrade will have consequences on the entire pavement behaviour.

This work presents an integrated approach for the analysis of the road subgrade condition by combining different Non-Destructive Testing (NDT) techniques. Different Ground Penetrating Radar (GPR) systems, both antennas configuration and frequencies, were tested in order to achieve the best methodology for subgrade cracking detection. Additionally, NDT load tests were performed with two deflectometers, Falling Weight Deflectometer (FWD) and Light Weight Deflectometer (LWD), aiming to determine the elastic modulus of the subgrade and consequently detect damaged areas.

The tests were conducted at a real scale test section built to simulate pavement foundation layers consisting of clay soil subgrade, frequently used in African countries. The main tests performed are presented and analysed in this paper. Troubleshooting's are referred mainly related with GPR wave propagation on clayey materials, due to high absorption. Recommendations are made regarding the use of GPR antennas as air-coupled antennas lead to a better identification of pavement layer interfaces while ground-coupled antennas were preferable to detect anomalous areas, namely cracking and debonding. The results showed good agreement between both NDT methods (GPR and load tests) in the identification of the anomalous areas and were validated with some in-situ cores extracted.

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1. Introduction

The road transportation system has an important role in today's society with a direct influence in its economic development. The effect of vehicle loads is the lead cause of pavement deterioration

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over time, followed by the influence of the weather conditions and errors in design or construction that can intensify those effects resulting in a quicker decrease of the pavement condition [1]. With increasing demands in terms of traffic volumes and vehicle loads together with limited resources (time, money and personnel) to intervene in the road, pavement asset management has therefore become a vital activity at the network level [2].

Road inspections normally imply visual inspection, to evaluate cracks and delamination and also functional evaluation of

pavements, by assessing the surface parameters such as roughness and skid resistance [3]. However, it is also important to look beyond the surface as deficiencies in thickness, lack of interlock between bound and unbound layers and the loss of structural support have a significant impact on the reduction of pavements life-time [2]. Therefore, it is more and more important to perform a structural evaluation of the pavement for a complete diagnosis of its condition.

The subgrade provides support to the entire pavement system and assures an effective distribution of traffic loads in depth. Thus, proper pavement behaviour is directly related to the subgrade integrity. In the case of low-volume traffic pavements (with thinner asphalt layers), the subgrade is particularly relevant, as the stress magnitude from the traffic loads can be significant at subgrade level. In addition, the subgrade is more sensitive to environmental conditions variations.

Non-destructive testing (NDT) methods are preferable over time-consuming, unsafe and costly traditional destructive methods. Ground Penetrating Radar (GPR) is one of the most efficient NDT for subsurface monitoring [4]. GPR provides continuous monitoring along pavements with the advantage of operation at traffic speed, without causing disruption to traffic. The main applications in pavement engineering are the layer thickness measurement and detection of changes in structure [5] but also the assessment of moisture and air void content [6,7], detection of subsurface defects [8–10] and, at the experimental level, the estimation of the mechanical characteristics of the pavement layers [11]. The most common GPR systems are based on impulse frequencies which apply a single electromagnetic wave at a selected frequency [5]. The wave travels from the antenna into the pavement and is reflected when it meets an interface between two materials that present different dielectric constants [5,12]. Two different antennas setups can be used in roads inspections: ground-coupled antennas, that require contact with the pavement surface, and air-coupled horn antennas, that operate suspended, generally 40–50 cm above the pavement surface. The ground-coupled antennas can provide higher penetration depth for the same frequency, whereas air-coupled horn antennas, as they work suspended over the pavement, allow higher acquisition speeds [1].

Additionally, Falling Weight Deflectometer (FWD) is considered to be the most effective NDT device for pavement deflection measurements worldwide, realistically simulating the pavement responses under traffic loading [13] and consequently, it is generally used for bearing capacity evaluation [14–16]. The FWD applies an impulse load that consists of a mass dropped onto a damped spring system mounted on a loading plate and measures the shape of the deflection bowl resulted with a series of geophones located at different distances from the load. Using the deflection values obtained in-situ, elastic modulus can be estimated for each layer throughout back-calculation when the thicknesses of the pavement layers are known. The FWD is nowadays used in combination with GPR to determine elastic modulus of pavement layers [14,15] and, more recently, in subsurface cracking detection [17]. Moreover, Light Weight Deflectometers (LWD) are portable devices traditionally used for quick quality control of unbound layers at subgrade and subbase level. LWD provides a direct estimation of the elastic modulus for such layers [18]. However, the measuring depth (normally twice the plate diameter) is lower than the FWD because it uses lower loads, so the LWD modulus characterises only the upper part of the pavement structure condition. Also, the LWD only measures the deflections on three points up to 0.60 m from the load, compared with the FWD that can measure deflections on nine points, with the farthest located at 2.10 m from the application of the load.

This work presents an integrated approach by combining different NDT techniques focused on the analysis of the road subgrade

condition. Different GPR systems and Load test equipment were used in order to define the best methodology. Thus, the GPR data allowed for cracking detection, while the deflectometers provided the elastic modulus of the subgrade. Apart from other structural deficiencies such as moisture and delamination, the existence of subsurface cracking decreases the elastic modulus of the layer. The tests were performed on an experimental test section, built to simulate pavement subgrade layers consisting of clay soil materials, generally used in African countries for low-volume roads foundations. This paper covers the construction period and intents to characterize the pavement before the beginning of the service life. Nevertheless, this methodology combining NDT techniques can be used to access in service pavements over climate changes, time and traffic.

2. Materials and methods

2.1. Experimental area

An experimental test section was constructed in order to simulate a pavement subgrade and evaluate the feasibility of the use of different NDT methods to analyse its behaviour.

The physical model was built in a concrete pit section with a maximum depth of 1.97 m and a total area of 3.07 m wide and 31.5 m long. The test section was implemented in an area of approximately 36.0 m² limited transversally by concrete walls and below by a concrete floor (Fig. 1).

The test section structure comprises the foundation of the pavement constituted by a 0.15 m capping layer of improved subgrade with a soil with 95% compaction, a 0.90 m layer of compacted subgrade of the same soil with a compaction of 93% applied in four layers of 0.15 m and one layer of 0.30 m (Fig. 1). Above the concrete slab, a 0.48 m layer of soil was applied to install the drainage of the test section. This layer was built with the same soil and compaction values as the compacted subgrade above.

The soil used in the subgrade layers is classified by the Unified Soil Classification System (USCS) as clay of low plasticity, lean clay and by the AASHTO Soil Classification System as A-7-6, clay material with general rating as a subgrade fair to poor.

Physical properties were evaluated such as grading, Atterberg limits, linear shrinkage and optimum water content, correspondent maximum dry density, as well as mechanical properties like Californian Bearing Ratio. The properties of the soil obtained are presented in Table 1 and the grading curve is shown in Fig. 2. The grading curve was obtained using two methods: hydrometer for the finest particles and sieving for the rest.

From the properties of the soil used in the subgrade layers (Table 1), we may conclude that its behaviour is highly influenced by the water content. It should be mentioned that the swelling values obtained (about 5%) for a compaction degree of 96% and 98% can be a problem with moisture changes and the consequent increase of volume. The effective stiffness of this soil highly depends on its saturation degree.

As previously referred, the foundation of the pavement was constructed in layers. For construction quality control, different tests were performed immediately after compaction on the top of each layer (Fig. 3). Water content, dry density and the compaction degree were determined by the nuclear density test method and these results were calibrated with the measurement obtained by the sand-cone method. The surface moduli (E_{LWD}) of the subgrade layers were calculated using the Light Weight Deflectometer (LWD).

Fig. 3a shows some deviations in compaction values between layers at different positions of the whole test section. This can partially be explained by some limitations during the compaction of

Fig. 3. Construction quality control summary properties.

optimum value, this soil presents higher strength, higher compressibility and lower potential for swelling. However, it reveals greater potential for shrinkage [19].

During the construction, several metal sheets were installed at selected locations, to be used as references for GPR data interpretation. As shown in Fig. 4, the metal sheets vary from 0.30 m to 0.50 m wide and were disposed perpendicularly to the survey alignments at different depths (0.15, 0.45, 0.75 and 1.05 m).

2.2. Methods: data acquisition and processing

2.2.1. Ground Penetrating Radar

Different GPR systems were employed using both ground- and air-coupled antennas (Fig. 5a). The ground-coupled system used

was from Malå Geoscience and it was composed by a Proex control unit and two bistatic antennas of 1.0 and 2.3 GHz. The air-coupled system consisted of two pairs of bistatic antennas with central frequencies of 1.0 and 1.8 GHz; and a SIR 20 acquisition unit, all from GSSI.

The tests were performed on the top of the subgrade layers along three longitudinal lines: through the middle and on both sides of the track (Fig. 4).

The GPR data from the ground-coupled antennas was collected by time, whereas for the air-coupled antennas the acquisition was carried out by distance. The surveys were performed at a constant speed and marks were taken at the beginning and at the end of each section in order to allow for the correlation of the data gathered by both systems. Prior to the tests, for the air-coupled

Fig. 4. Configuration of the metal sheets placed between layers and the location of the NDT tests alignments.

Fig. 5. Ground Penetrating Radar system: (a) ground-coupled and (b) air-coupled antennas; (c) calibration of air-coupled antennas with metal plate.

Table 2

GPR acquisition setup.

Antennas		Ground-coupled		Air-coupled	
Frequency	[GHz]	1.0	2.3	1.0	1.8
Time Window	[ns]	43	14	20	12
Samples/scan		500	292	1024	1024
Trace interval	[scan/s]	100	100	–	–
	[scan/m]	–	–	200	50

antennas, a calibration file was collected using a metal plate (Fig. 5b). For this calibration, the air-coupled antennas were positioned at the same height above the surface as they were during the survey and then were bounced while the amplitude of the reflected wave on the metal plate (considered as a perfect reflector) was recorded [20]. These records were used to correct the reflection amplitude as a function of the antennas height above the surface and also to calculate the dielectric value through the surface reflection method. Table 2 describes the setup used for the data acquisition.

Before the interpretation of the GPR images, some processing was applied. The data from the ground-coupled antennas was processed with ReflexW v6.1 software [21], applying the following sequence: time-zero correction, temporal filtering (dewow), gain application (gain function with linear and exponential part), spatial filtering (subtracting average) and a band-pass (butterworth) filter. The objective was to correct the down-shifting of the radar section due to the air-ground interface and to amplify the received signal, as well as to remove both low- and high-frequency noise in the vertical and horizontal directions.

The air-coupled system data was processed in Road Doctor Pro 2.5 [22] with basic processing steps: bouncing removal operation

to correct antenna elevation due to antenna bouncing and zero-level correction to adjust zero-time with zero-depth. These operations were necessary to correct the effects caused from the air-coupled antennas being suspended, about 0.45 m, above the pavement. Since the thicknesses of the layers had small variations, no background removal was applied [20]. Note that no filters were applied at this stage because the data from the air-coupled system was already collected with band-pass Finite Impulse Response (FIR) and Infinite Impulse Response (IIR) filters from RADAN software [23] to try to minimize the interference frequencies outside the frequency range of the transmitting antennas. A linear gain amplification function was also applied during data acquisition.

Table 3 shows the processing sequence applied and the parameters used for the filters for both GPR systems.

2.2.2. Deflectometers

Deflections were measured, using both Falling Weight Deflectometer (FWD) and Light Weight Deflectometer (LWD) (Fig. 6), to evaluate the bearing capacity of the pavement.

The FWD used was the PRI 2100 from Carl Bro Pavement Consultants (Fig. 6a) and a 30 kN impulse impact load was applied over a load plate of 0.30 m of diameter. The deflections were measured

Table 3

GPR data processing parameters.

Ground-coupled				Air-coupled			
Step	Processing	1.0 GHz	2.3 GHz	Step	Details	1.0 GHz	1.8 GHz
1	Time-zero correction			1	IIR filters		
2	Dewow filtering	1 ns	0.5 ns		Low pass:	1000 MHz	2000 MHz
3	Gain function				High pass:	100 MHz	100 MHz
	Linear:	1.00	1.44	2	FIR filters		
	Exponential:	1.00	1.44		Low pass:	3000 MHz	5000 MHz
4	Subtracting average				High pass:	500 MHz	500 MHz
	Average traces:	250	200	3	Gain function		
5	Band-pass Butterworth				Linear:	1.00	1.00
	Low pass:	600 MHz	1100 MHz	4	Bouncing removal		
	High pass:	1200 MHz	3400 MHz	5	Time-zero correction

Fig. 6. (a) Falling Weight Deflectometer and (b) Light Weight Deflectometer.

Fig. 7. Line C – GPR data obtained with the 1.0 GHz (a) and the 2.3 GHz (b) ground-coupled antennas.

on 9 geophones located at 0, 0.30, 0.45, 0.60, 0.90, 1.20, 1.50, 1.80 and 2.10 m (which correspond to the designated deflections D_0 , D_1 , D_2 , D_3 , D_4 , D_5 , D_6 , D_7 , and D_8) from the centre of the load plate.

The spacing between FWD test points was 1.5 m and they were only performed along the survey line C, due to the lateral size of the equipment (Fig. 6a).

During the FWD load tests, small variations of the peak value of the applied force can occur. These variations may be related to deformability characteristics of the pavement, to the existence of friction in the guiding system of the falling mass and to the stiffness variation of dampers with temperature. To compensate these variations, a normalization of the deflection measurements was performed.

The LWD used was a Prima 100 system designed by Carl Bro Pavement Consultants (Fig. 6b). The drop mass weighed around 0.15 kN and the diameter of plate used in this study was 0.3 m.

The LWD tests were done along all survey alignments where GPR tests were performed (Fig. 4), and the spacing between test points was 0.5 m. The tests procedure described on ASTM E2835–11 [24] refers the need to perform six falling mass drops of the LWD and then use the first three drops for seating and the last three for analysis. However, for research studies, LNEC generally performs 10 drops, to be on the safety side, and to ensure the correct positioning of the load plate on the layer surface and the repeatability of the measurements. Consequently, at each point, 10 drops were collected: the first five drops were used for plate seating and the next five drops were used for analysis and the results were calculated as the average of these last five drops.

The vertical deformation on the centre of the plate was measured with a geophone and used to determine the Dynamic Elastic Modulus (ELWD), based on the Boussinesq theory [25]. As concerns to the stress distribution, the assumptions on this theory are based on elastic analysis: homogenous, isotropic and linear elastic half-space. Accordingly, the elastic modulus was determined by Eq. (1):

$$E_{LWD} = \frac{A(1 - \nu^2) \times R \times P}{D} \quad (1)$$

where A is a stress distribution factor ($A = \pi/2$ for uniform stress distribution, $A = 2$ for inverse parabolic stress distribution or $A = 3\pi/2$ for parabolic stress distribution); R is the radius of the load plate (mm); P is the peak applied pressure (kPa); D is the peak vertical deflection (mm) and ν is the Poisson's ratio.

3. Results and discussion

The radargrams obtained in the GPR surveys were analysed in order to detect possible damaged areas. The results from the survey line C with the ground-coupled system can be seen in Fig. 7, while the results from the air-coupled system are shown in Fig. 8. For each system, the first GPR image (a) corresponds to the 1.0 GHz antennas and the latter (b) to the higher frequency antennas (2.3 GHz ground-coupled and 1.8 GHz air-coupled systems).

From the analysis of all, ground- and air-coupled, data it was possible to identify the first layer through the reflection of the

Fig. 8. Line C – GPR data obtained with the 1.0 GHz (a) and the 1.8 GHz (b) air-coupled antennas.

bottom of the improved subgrade at $t = 4$ ns, which corresponds to a dielectric value of about 16 for the subgrade soil. As expected, stronger reflections were observed in the locations where there are metal sheets at the interfaces between layers (Fig. 4), highlighted in the figures by the (red) squares. However, it was not possible to detect the boundaries between the foundation layers below 4 ns (approximately 0.15 m), not even with the metallic sheets present. This signal attenuation or loss of information is most probably because the GPR reflection amplitudes decrease systematically with the increase of clay content and water content [5,12]. Research developed for EU project iSOIL quantified this decrease with experimental tests [26] using a plastic cylinder filled with 34.5 cm of soil and with a metal plate on the bottom. These laboratory tests were performed with a 1.6 GHz ground-coupled antenna on probes with variable clay and water content. The results showed that the amplitude reflection of the bottom plate turned to zero with an increase of clay content from 5.5% to 62.5%. Moreover, the attenuation resulted higher with an increase of water content from 6% to 19%. Similar results were obtained in this work, with soils having 45% clay content (particles less than 0.002 mm) and moisture content up to 21%, being the most probable cause of attenuation and loss of GPR signal to reach the boundary of the second layer at 0.30 m deep.

The zones marked by (yellow) circles in the radargrams in Figs. 7 and 8 correspond to the possible anomalous areas identified with discontinuities in the reflections and changes in the amplitudes of the reflected GPR signals. These anomalies can be attributed to cracking or debonding, due to changes in the dielectric constants caused by the presence of air in cracking or debonded layers.

Observing Fig. 7, ten different faults or discontinuities in layering were detected with both 1.0 GHz and 2.3 GHz ground-coupled antennas. Nevertheless, the 2.3 GHz antenna allowed determining the extension of the damage in subsoil, providing the best results in detecting both layer interface and its discontinuities due to cracking.

The comparison of the 1.0 GHz and 1.8 GHz air-coupled antennas (Fig. 8) allows determining some differences regarding the identification of the layer interface between the improved and the compacted interface. The 1.0 GHz antenna provided better continuity in reflection than the 1.8 GHz antenna (Fig. 8), which can be partially justified by the higher sample rate (200 and 50 scans/m,

respectively). Moreover, the continuity of the layer was better defined with the air-coupled antennas than the ground-coupled antennas. However, the 1.8 GHz air-coupled antenna allowed for a better definition of discontinuities in layering, although only six anomalies were identified if compared with the ten damage areas identified with the 2.3 GHz ground-coupled antenna. This is because the ground-coupled systems have better signal to noise ratio and better resolution when compared with air-coupled systems [20,27]. Moreover, the resolution is a function of the wavelength and it increases while the frequency antenna increases [28,20]. Thus, the 2.3 GHz ground-coupled antenna would present the highest resolution of the different antennas configurations tested.

After the identification of the areas that can present anomalies from the GPR data, the next step was to analyse the results from the deflection tests and verify if there is a correlation between the GPR results on these locations and the deflections measured.

Fig. 9a shows the deflections D_0 to D_3 measured along the survey line C with the FWD. To enhance the interpretation the deflection results are overlain with the radargram from the 2.3 GHz ground-coupled antenna measured along the same survey line and with the location of the cores extracted. Fig. 9b and c present the deflection bowls of the most and the less affected areas, respectively. Finally, Fig. 10 indicates the elastic modulus calculated from the LWD tests, on survey line C, applying the Boussinesq theory, Eq. (1), using the vertical deformation on the centre of the plate, and also the equivalent FWD elastic modulus using the same approach.

Analysing the FWD deflection bowls at 1.5 m and 7.5 m (Fig. 9b), we notice that there is a discontinuity between the deflections D_2 and D_3 which can be caused by cracking or debonding of the subgrade layers. Furthermore, at 1.5 m and 9 m, the difference between deflections D_0 and D_1 is higher than in the other locations which can be attributed to the cracking on the top layer.

On the other hand, looking at Fig. 9c we may see the only two points that present better continuity of the deflection bowls: 0 m and 12 m. At this points the load transmission was better which can be related to a better continuity of the layer (no significant cracking).

Comparing the FWD data with the 2.3 GHz data (Fig. 9a), it corroborates the good agreement between the methods when identifying both anomalous FWD deflections and GPR reflections.

Fig. 9. (a) Major FWD deflections from Line C overlay with the reflections from the 2.3 GHz ground-coupled antenna; FWD Deflection bowls of (b) most affected areas and (c) less affected areas.

Fig. 10. Dynamic elastic modulus from LWD and equivalent FWD modulus, from line C.

A similar conclusion can be drawn from LWD results (Fig. 10) where higher modulus corresponds to areas without anomalies on GPR registers.

However, it is important to note that the information provided by the LWD data did not reach as deep (only around 0.60 m) as the FWD and it is more sensitive to the structural condition variation of the top layer. In this particular study, where clays soils were used, it means that the dispersion of the modulus calculated by the LWD for each point and along the survey line is higher from the superficial cracks that appeared due to clay shrinkage (Fig. 11a). Comparing the results obtained with the equivalent modulus from the FWD, the values are higher than the ones from the LWD which corroborates the last statement as the LWD is more

influenced by the cracks on the top of the pavement. Nevertheless, as it was already mentioned, the LWD results were in agreement with the GPR results in detecting anomalous areas, mainly in the surface layer, making it a useful tool to use for subgrade assessment whenever FWD is not available.

Cores were extracted to validate the presence of anomalies detected with GPR, FWD, and LWD and were performed not only in areas that presented anomalies (C1, C2, and C3) but also in areas without any anomaly (C4). Fig. 11a illustrates the overall appearance of the surface of the subbase and the position of the cores in the test section. Fig. 11b displays the core drill holes showing the visual aspect of the subgrade at each location. We can see the defects between layers (delamination) at C1 that are

Fig. 11. Cores extracted in positions 7.5 m (C1), 9.0 m (C2), 10.5 m (C3) and 12.0 m (C4).

compatible with the inversion in the deflections D_2 and D_3 measured from the FWD at 7.5 m. Severe cracking can also be seen in the subgrade at C2 and C3 where cracks are developed in depth or shallower and concentrated, respectively. This fact is in agreement with the anomaly observed in the GPR data showing larger pattern reflections at these positions, and also with the higher FWD deflections measured at 9.0 m. Finally, no deficiencies were detected in depth at position C4, as supported by the GPR data, even though it has shrinkage superficial crack on the top of the subgrade layer.

4. Conclusions

The subgrade provides support to the pavement system and assures an effective distribution of traffic loads in depth. Failure of the subgrade will result in deficient pavement behaviour. A combination of different NDT techniques, applied to assess the pavement subgrade, is presented in this study. The joint use of GPR antennas of different frequencies, ground- and air-coupled, and two deflectometers for assessment of subgrade condition is presented herein and the main achievements are referred.

The air-coupled GPR system lead to a better identification of the pavement layers interfaces as for the ground-coupled system it showed a better resolution in the identification of the anomalous areas, such as cracking and debonding, located at the surface of the pavement. The radargrams from the air-coupled system presented higher noise levels when compared to the ones from the ground-coupled, which make the interpretation of the signals more difficult.

The LWD modulus showed higher sensitivity on the structural condition of the pavement surface, resulting in a greater dispersion of the values due to the superficial cracks due to clay shrinkage. On the other hand, the FWD deflection bowls tests provide more information regarding the behaviour of deeper layers and therefore of the entire subgrade.

Combining the deflection methods with the GPR, there was a good correlation between the variations of the deflections and the changes of the GPR reflections. Delamination and severe cracking were identified as the main anomalies leading to inversion of the deflection values D_2 and D_3 and also to higher deflections mea-

sured at D_0 . These results were corroborated with the cores extracted in areas with and without identified deficiencies.

The use of combined NDT techniques proved to be a useful approach to identify anomalous areas in the subgrade. This methodology is recommended for construction quality control of subgrade layers, with special relevance for pavement structures where the subgrade can be a critical layer due to the magnitude of the traffic stresses at this level.

The main findings can be summarised as bellow:

- Air-coupled antennas are more suitable for measuring the continuity of the layers. Therefore, they should be selected when the evaluation of the layer thickness is needed.
- Ground-coupled antennas provided better signal to noise ratio and better resolution. Thus, they are preferable to detect the superficial cracks and debonding.
- For soils with a high percentage of clay or high moisture content, the penetration depth of the GPR electromagnetic waves is limited. Thus, it may be useful to use different types of antennas to improve the interpretation of the measured data.
- The use of LWD is more appropriate for the evaluation of the surface layer and to detect local heterogeneities.
- The FWD is more appropriate for the structural evaluation of the overall pavement. Thus, it provides information regarding the behaviour of all subgrade.
- To achieve better results, it is recommended to use a combination of high-frequency antennas GPR systems with the falling weight deflectometers, when available.

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