NEW NON-DESTRUCTIVE INSPECTION METHOD WITH GROUND PENETRATING RADAR TO EVALUATE THE SUITABILITY OF THE BACKFILLING GROUTING INJECTION IN TUNNEL BORING MACHINES

Catalina Mondragón-Enguidanos[1], Amparo Verdú-Vázquez[2*], José L. Hernández-Álvarez[3], Jorge Gómez-Hoyos[3], Luis A. Méndez-Lanza[3]

[1] PhD, Escuela Técnica Superior de Edificación, Universidad Politécnica de Madrid

[2] Departamento de Tecnología de la Edificación. Escuela Técnica Superior de Edificación. Universidad Politécnica de Madrid

[3] ACCIONA Construcción, Spain.

*Corresponding Author. Tel +34-91.336.76.05 - E-mail address: amparo.verdu@upm.es. Avenida de Juan de Herrera, 6. 28040 – Madrid (Spain). Universidad Politécnica de Madrid.

ABSTRACT.

This research focuses on the development of a new non-destructive inspection method, based on the interpretation of electromagnetic waves by means of a ground penetrating radar (GPR), in order to evaluate the condition of the backfilling two-component mortar grouting behind the segmental lining in tunnels made by tunnel boring machines (TBM). The data processing by digital models and the analysis of the propagation speed of the along the backfilling grouting layer have enabled the technical and operational feasibility of this novel inspection method.

Once the conceptual framework of the research was defined, it was possible to validate the developed method in a full-scale operational environment in the Metro of Quito Line 1 (Ecuador). This validation involved a battery of tests collating the results obtained through the core-drilling extractions in comparison with the ones obtained with GPR. As a result of these calibration tests, it was possible to identify a range of propagation speeds linked to grouting in optimal execution conditions, as well as other ranges associated with potential anomalies. Finally, it was possible to implement this new inspection methodology on a regular basis in the Metro of Quito, where the conventional quality control by core-drillings was replaced almost entirely for the new method with GPR.

Keywords: TBM; gap; mortar; Ground Penetrating Radar; Electromagnetic.

1. INTRODUCTION.

Mechanized tunnel boring with TBM has becoming a regular method in construction. As any other constructive process it presents some geometrical factors that should been considered during the design phase and controlled during the construction phase. A cutter head, combining torque and thrust force, performs the excavation process in full section. This section includes a gap between the ground and the segmental lining that encompasses the whole over-excavation space from the shield, as well as the conicity and width of the sealing system by means of ploughs, as shown in figure 1. This gap habitually ranges from 13 to 18 cm [1] [2].

Figure 1. *TBM standard section and gap representation.*

This gap behind the segments must been filled with a fluid material, ensuring an optimal contact area between the excavation perimeter and the concrete lining. The most common materials for this application are hydraulic mortars and gravels. However, in recent projects a new kind of two-component mortar is being applied [3]. Said mortar is composed of a cementitious grouting and a second additive, sodium silicate, whose properties and low gel-time, from 5 to 45 seconds, facilitate the grouting process and improve the sealing of this area, especially in the presence of water.

The grouting process execution control is performed in an indirect way, by analyzing the pressure and injected grout volume during the excavation and the ring assembly phases. However, this estimation is not reliable enough, so it is common to complement it with direct measurements through core-drillings to determine the grouting thickness. The progress on electronics and data processing has led to the application of non-destructive techniques in tunnels, habitually based on seismic methods [4] [5]. In recent years, the use of GPR [6] [7] [8] [9] in underground construction has multiplied in a remarkable way, due to its advantages such as safety, rapidity, low cost and minimal environmental impact.

This paper develops the GPR operational principles that allow incorporating this procedure as a new inspection method to evaluate the suitability of the backfilling grouting injection in tunnel boring machines. Section 2 reviews the theoretical basis regarding electromagnetism and radar data processing for the intended application. Section 3 describes the experimental development carried out for its full-scale implementation in the Metro of Quito Line 1 (Ecuador). For this purpose in section 3.1 a theoretical analysis, supported by a finite difference model, was conducted in order to determine the radar wave behavior along the tunnel lining. Then, section 3.2 describes the calibration tests and field tuning, section 3.3 defines the validity criterion to determine the suitability of the backfilling grouting and section 3.4 describes the methodology to apply this new inspection technique in operating conditions. Finally, section 4, analyses the obtained results along the whole inspection campaign.

2. GPR. THEORETICAL CONSIDERATIONS AND WORKING PROCEDURES.

GPR is an interesting geophysical method to detect structures and changes in the properties of the traversed materials, based on the principles of propagation of electromagnetic waves (EM) according to Maxwell's equations, depicted in expression 1-4 [10] [11]:

$$\nabla \cdot \varepsilon E = \rho ; \tag{1}$$

$$\nabla \cdot B = 0 ; \tag{2}$$

$$\nabla \times \frac{B}{\mu} - \varepsilon \frac{\partial E}{\partial t} = \sigma \cdot E + J\,; \qquad (3)$$

$$\nabla \times E + \frac{\partial B}{\partial t} = 0\,; \qquad (4)$$

Where, E and B are the electric field [V/m] and magnetic field [T] respectively; ε is the permittivity [F/m], μ is the magnetic permeability [H/m], σ is the medium conductivity [S/m], J is the current density [A/m2]; and t is time [s]

The EM pulse propagates as a non-dispersive wave: the emitted radar wave travels along a medium with a given dielectrical behavior, defined by the conductivity σ and the permittivity ε [10], whose relationship determines an easy identification parameter to characterize the medium traversed by the wave: the propagation speed, defined in expression 5.

$$vel_{EM} = \frac{1}{\sqrt{\sigma\varepsilon}} \qquad \text{[m/ns]} \qquad (5)$$

Figure 2. *Esquema de funcionamiento de un equipo de Geo-Radar.*

Figure 2 shows the basic scheme for the operation with GPR: the wave travels along the medium until the contact between two different materials produces a reflection, traversing a distance equal to twice its thickness. The GPR records this travelling time, so given the wave propagation speed it is possible to estimate the thickness of the structure, according to expression 6.

$$thickness, d = vel_{EM} \frac{t_{travel}}{2} \qquad (6)$$

In case of analyzing several layers, the total thickness of the whole comes defined by expression 7 [12]:

$$d_1 = v_1 \frac{t_1}{2}; \qquad d_2 = v_2 \frac{(t_2 - t_1)}{2}; [\ldots] \qquad d_n = v_n \frac{(t_n - t_{n-1})}{2}$$

$$d_{total}=v_1\frac{t_1}{2}+\sum_{i=2}^{n}v_i\frac{(t_i-t_{i-n})}{2} \quad (7)$$

Regarding the devices, the current electronic science allows data acquisition at high speeds in a continuous and automatized way, without recording errors. Moving the GPR along the inspected surface, it is possible to emit and receive a huge number of EM pulses, which combined conform a linear profile called radargram. Thus, for each radargram it is feasible to determine the position of the reflecting surfaces associated to the lining segment and the contact with the ground. The identification of each of these reflection planes represents the most remarkable challenge, since raw data may not be properly visualized on site due to the need for post-processing using a sequence of digital filters and processing tools [13] [14] [15] listed below:

- **Dewow and Back Ground Removal:** Set of band-pass filters to remove the low frequency waves, such as the multiple reflections from surface.
- **Determination of the instant frequency: Hilbert Transform.** The Hilbert Transform consists of a mathematical procedure that determines the relationship between phase, amplitude and the instant frequency (R(t)) of a temporal continuous signal (x(t)) according to expressions from 8 to 11 [16]. The analysis of each of these components, especially the instant frequency, allows the identification of very subtle variations in wave behavior and sub-parallel distributions for similar elements, as seen in the case study proposed in this paper. Figure 3 depicts an average trace, reflecting amplitude values on the time domain, and instant frequency values. In the figure, the first broken line from the top indicates the outer face of the segment while the second line indicates the excavation perimeter.

$$R(t)=x(t)\cdot\frac{1}{\pi t} \quad (8)$$

$$A(t)=\sqrt{x^2(t)+R^2(t)} \quad (9)$$

$$\theta(t)=arctg\left[x(t)\right] \quad (10)$$

$$\omega(t)=\frac{d\theta(t)}{d(t)}=\frac{d\left\{arctg\left[R(t)\right]/x(t)\right\}}{dt} \quad (11)$$

***Figure 3**. Representation of the amplitude (left) and the instant frequency (right) in an average trace.*

- **Attenuation calculation:** EM waves tend to attenuate with propagation, attenuation being related with medium characteristics and operational frequency, according to expression 12 [17]:

$$A(d) = A_0 \cdot \frac{e^{-2d\cdot\alpha}}{2d} \qquad \text{where,} \qquad \alpha = \sqrt{\frac{2\pi \cdot f \cdot \mu \cdot \sigma}{2}} \qquad (12)$$

Where A is the amplitude, d is depth/distance covered by the wave, α is the attenuation coefficient [dB/m], f is the frequency [Hz], μ is the permittivity, and σ is the conductivity, respectively [10].

- **Determination of the nominal frequency. Fourier Transform (FFT):** Additionally to speed and thickness analysis, the frequency spectrum of EM waves was also analyzed through a Fast Fourier Transform, according to expression 13

$$X(k) = \sum_{n=0}^{N-1} x(n) e^{-j2\pi k\frac{n}{N}} \qquad (13)$$

Wave intensity loss (attenuation) and nominal response frequency modification have a direct relation with the humidity of the medium traversed by the wave [18].

3. EXPERIMENTAL DEVELOPMENT FOR A REAL SCALE IMPLEMENTATION IN THE METRO OF QUITO.

Three tunnel boring machines with an excavation diameter of 9.405 mm excavated the tunnel for the Metro of Quito. The lining section was a universal ring with 6+1 segments, an internal diameter of 8.430 mm, a thickness of 32 cm, a concrete resistance of 45 MPa and a steel quantity of 165 kg/m3 plus 20 kg/m3 of short steel fibers. The tunnel geometry leaves a gap between the excavation perimeter and the outer face of the ring of 17 cm, filled with a two-component mortar, designed with a gel-time between 5 and 15 seconds after the grouting.

The initial quality procedure to control the thickness of the backfilling grouting in Metro of Quito was based on the extraction, through the segmental lining, of several core-drillings distributed along the layout, at a rate of one drill every 50 rings. During the first drillings, performed from the TBM back-up, water ingress toward the tunnel was caused several times, therefore it was necessary to seal the entry points. Additionally, these water ingress events may result in fine soil loss and mortar washing.

3.1. Theoretical considerations. Synthetic model.

Based on the Maxwell equations and using the REFLEX W v.8.5.6 software, a synthetic model to simulate the radar wave propagation into the different structures was developed. This model takes into account the spatial distribution of each element inside the tunnel [17]: segment, grouting and ground, whose basic electromagnetic properties are collected in table 1 [11] according to similar reference literature for this kind of applications [10] [17] [19].

Table 1. *Material properties*

The input parameters in the model respond to the propagation of a sinusoidal wave with an operational frequency similar to others used for this kind of applications, variable from 500 to 1000 MHz. The design parameters also include the spatial and temporal calculation shown in table 2.

Table 2*. Design parameters in the synthetic model.*

Figure 4 shows the result of the synthetic model, representing in light grey the materials with a cementitious base (segment and mortar) and in dark grey the ground. On the right, the synthetic radargram for the analyzed profile is depicted. It is possible to observe the different behavior of the wave in the first layer by means of short sub-horizontal reflectors (concrete segment); the contact between the mortar and the ground; and in the middle a blurred area corresponding to the grouting layer.

Figure 4*. Synthetic model applying a finite difference model..*

The model revealed that the propagation of this EM wave along these materials is feasible and it is possible to identify the different layers that make up the tunnel structure. This way, the outer face of the segment was identified at 5,7 ns from the start of the pulse, resulting in a wave propagation speed of 0,125 m/s. After this contact, according the model, the irregular excavation perimeter was recognized in a time range between 9,0 and 13,6 ns, implying a propagation speed of 0,100 m/ns.

The results of this model validated the working hypothesis to apply GPR as a potential tool for the inspection of the backfilling grouting injection [20].

3.2. **Data acquisition. Field tuning.**

In order to tune the developed technique in real conditions, a set of measurements were taken using a screened aerial bow-tie antenna at an operational frequency of 800 MHz.

The resolution of this equipment is between 15 and 30 mm, with a penetration depth into the ground slightly above 1 m. The measurements were configured with a trace interval of 25 mm, a time window of 25 ns, and a sampling frequency of 0,028 ns. In addition, several core-drillings were extracted in the same sections inspected with GPR to compare both results.

Analyzing the radargrams, contact between the segment and the mortar (first broken line from the top) and natural soil (second broken line from the top) were identified. Applying the procedure developed for the finite difference model in the time domain, which in turn comes from the expressions mentioned before, it was possible to estimate the propagation speed (time travel) along the grouting layer, as shown in table 3, considering that the theoretical grouting thickness is about 17 cm.

Figure 5. *Contacts between segment-mortar and mortar-ground (left). Average trace in the time domain (right)*

Table 3. *Travel time for each contact*

In order to determine the mortar thickness with a higher accuracy, the spacing between the transmitter (Tx) and the receiver (Rx) was also included in the formula, according to the expression 14 [4] [5]. In this case, the spacing for the 800 MHz antenna was 14 cm. Table 4 shows the results comparing the measurements between GPR and core-drillings.

$$d_{real}=\sqrt{\left(\frac{\left(t_{GAP}-t_{ring}\right)\cdot vel_{EM(GAP)}}{2}\right)^2-\left(\frac{Rx-Tx}{2}\right)^2} \quad (14)$$

These results revealed than the thickness variation between both methods did not exceed 10%, being the average, in the most of the cases, lower than 5%, as indicated in table 4.

Table 4. *Comparison between the core-drillings and the GPR measures.*

3.3. Determination of the validation criterion.

After the first field tuning, a criterion to evaluate the backfilling grouting condition was defined on the basis of the estimated propagation speed into the structure. This criterion is described below:

- Average speed of the EM wave along the concrete segment should vary from 0,105 to 0,125 m/ns.
- Average speed of the EM wave along a mortar in optimal conditions should varies from 0,070 to 0,090 m/ns.

Outside this range, there were other variable registers associated with anomalous conditions:

- There were areas where the grouting presented a higher porosity, and therefore a consistency slightly lower than optimal. In these areas, the propagation speed was higher than 0,120 m/ns.
- The water presence entails a notable increase in grouting humidity. The radar wave experimented a remarkable slowdown, recording in this positions propagation speeds lower than 0,070 m/ns.

Simultaneously, an analysis in the frequency domain complemented the interpretation, comparing the results with the core-drillings visual inspection. This analysis revealed that lower nominal frequencies mean a higher attenuation, associated with a higher water presence. For this application, as mentioned above, an antenna with a fixed frequency of 800 MHz was used, so taking into account the properties of the materials and relatively dry conditions, an attenuation of around 10% should be considered [18]. Table 5 shows how this statement coincides almost in all the cases.

Table 5. *Estimation of the humidity behind the segments*

3.4. Implementation in real conditions.

The application of this new inspection technique in Metro of Quito lasted from the end of 2017 to the beginning of 2019. Firstly, the quality assurance staff identified all those rings with any deviations during the construction phase in the excavated weight or in theoretical volume of grouting in order to inspect them with GPR.

In all these rings, the most potentially adverse positions in the tube regarding grouting injection were the shoulders and the key of the vault, being this last position very complicated to access due to the presence of the ventilation conduct, as shown in figure 6. Therefore, the measurements were conducted at two and ten o´clock (applying to the cross section a clock position analogy) and in the longitudinal direction (parallel to the tunnel axis), linearly analyzing not only the rings of interest but also the anterior and posterior ones.

Thus, it was possible to analyze all the sections between stations, achieving an inspection density of around 20% in each of the positions. A total of 2350 rings over the 12900 rings constructed in Metro of Quito were inspected with GPR in each of the two mentioned positions. Due to the quickness of this new inspection method, it is possible to analyze more than 1000 linear meters per working day.

Figure 6. *Measuring inside the tunnel*

The estimation of the EM wave speed, with a sampling frequency of 2,5 cm, allowed a detailed analysis of each radargram, as shown in Figure 7, including the thickness and the estimated speed of the grouting layer as well as an assessment of its state according to the criteria defined during the calibration tests.

Figure 7. *Chart extracted from one the results report for the Metro of Quito.*

4. RESULTS AND DISCUSSION.

The results along the layout showed a propagation speed between 0,071 and 0,104 m/ns (percentile P20 and P80 respectively) and an average value of around 0,081 m/ns, confirming an optimal grouting injection along the layout, as shown in figure 8. In this figure, the area between the broken lines indicates an optimal performance of the grouting injection, and the spaces outside this area indicate areas with a low consistency in the grouting. Nonetheless, and excepting only a few cases, the inspection with GPR confirmed a proper grouting injection in the entire inspected tunnel.

Figure 8. *Speeds distribution along the layout.*

In more detail, some areas present anomalous propagation speeds, such as the are in the middle of the layout, where there are higher propagation speeds than in the rest, due to particular geological conditions: rock excavation and relatively dry conditions. In other areas, such as the one at the end of the layout, corresponding with the south of Quito, the high water presence in the ground conditioned the response of the EM wave, showing registers characteristic of a fully saturated grouting.

The thickness of the grouting layer varies mostly between 11 and 19 cm, with an average value of around 15-16 cm, as shown in figure 9. In general, the results are coherent with the injection volume values registered during the excavation phase, reflecting also the local characteristics of the layout, as seen with the propagation speed.

Figure 9. *Maximum and minimum thickness along the layout.*

Finally, Table 6 includes the characteristic values for each section between stations, showing the propagation speed in the grouting layer, the registered frequency, the estimated humidity and the thickness of each layer.

Table 6. *Average results for each action between stations.*

The results were coherent with those provided by the core-drillings, reflecting the geotechnical and hydrological variations along the layout with a high level of reliability.

5. CONCLUSIONS.

The usual inspection method for the backfilling grouting injection is via a direct observation, through core-drillings in random checkpoints along the layout. However, this kind of work involves a high risk of water ingress and soil washing. Therefore, the need to identify a technology capable of performing this inspection without compromising the tunnel integrity has been one of the main motivations to develop this new non-destructive technique with GPR.

The first experiences performed at full-scale in a tunnel under construction allowed the validation of this inspection method and established an evaluation criterion to determine the suitability of the grouting injection. Thus, it was concluded that an optimal grouting involves a radar propagation speed between 0,070 and 0,090 m/ns, while values over 0,11 m/ns are indicative of a low compacted grouting or a high void presence in the structure. In the opposite case, estimated values under 0,70 m/ns together with a significant reduction of the response frequency are associated to areas where the grouting space presents a high amount of water.

This new non-destructive inspection method was implemented on a regular basis in the tunnel, replacing almost entirely the conventional method through core-drillings, achieving a 20% of the total tunnel length.

The achieved results confirmed the inspection with GPR as a versatile and reliable method to evaluate the suitability of the backfilling grouting injection in tunnels with TBM. The advantages associated with this new inspection method in relation to the conventional methods are detailed below:

- Given the non-destructive character of this technology, the inspection with GPR does not affect the tunnel structure, avoiding water infiltrations inside the tube.
- The measurements, linear and continuous, provide more information that the local extractions through core-drillings.
- Quickness in data acquisition and processing. While it is true that this method requires more complex hardware and software, it is possible to visualize the results quasi instantaneously and cover a larger working area, notably improving the performance of the inspection campaign.

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7. DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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Table 7. *Material properties*

Material	Dielectric constant, ε [-]	Thickness [mm]
Concrete	7,5	320
Mortar	20	150 – 180
Ground	10	Inf.

Table 8*. Design parameters in the synthetic model.*

Type of pulse	Ricker

Nominal frequency [MHz]	800
Time differential, dt [ns]	0,05
Space differential, dx [m]	0,01
Tmax [ns]	50
Boundary conditions [-]	Edges with linear absorption.

Table 9. *Travel time for each contact*

No Radargram	Ring	Time travel in the segment [ns]	Time travel in the grouting [ns]	EM Speed [m/ns]	Dielectric constant, ε [-]
GPR_001	860	6,37	10,91	0,075	16
GPR_002		6,38	9,99	0,094	10
GPR_003	1055	6,26	10,24	0,085	13
GPR_004		6,28	10,47	0,081	14
GPR_005	14	6,32	11,01	0,072	17
GPR_006		6,28	12,12	0,058	27
GPR_007		6,27	11,22	0,069	19

Table 10. *Comparison between the core-drillings and the GPR measures.*

No Radargram	Reference	Ring	Core-drilling thickness [mm]	GPR estimated thickness [mm]	Variation
GPR_001	C-0960	860	160	149	7%
GPR_002				162	1%
GPR_003	C-1093	1055	160	156	2%
GPR_004				153	4%
GPR_005	C-1522	14	150	148	1%
GPR_006				156	5%
GPR_007				154	3%

Table 11. *Estimation of the humidity behind the segments*

CORE-DRILLINGS			GPR		
Reference	Ring	Water presence	Nº de Perfil	Frequency [MHz]	Humidity estimation
C-0960	860	SI	GPR_001	646	Wet
			GPR_002	677	Wet
C-1093	1055	SI	GPR_003	642	Very wet
			GPR_004	646	Very wet
C-1522	14	SI	GPR_005	834	Dry
			GPR_006	718	Dry
			GPR_007	781	Dry

Table 12. *Average results for each action between stations.*

Section	Speed [m/ns]	Frequency [MHz]	Humidity	Thickness cm]
Labrador - Jipijapa	0,073	713	DRY	12,6-19,1
Jipijapa - Iñaquito	0,089	661	WET	10,8-18,7
Iñaquito - Carolina	0,074	694	WET	12,7-17,5
Carolina - La Pradera	0,082	697	WET	12,8-17,7
La Pradera - Universidad Central	0,082	688	WET	13,8-17,8
Universidad Central - El Ejido	0,072	695	WET	13,5-17,9
El Ejido - Alameda	0,086	704	DRY	14,0-17,7
La Alameda - San Francisco	0,096	711	DRY	11,9-18,7
San Francisco - Magdalena	0,105	716	DRY	10,9-18,8
Magdalena - El Recreo	0,077	670	WET	13,8-18,5
El Recreo - Cardenal de la Torre	0,077	658	WET	13,5-17,9
Cardenal de la Torre - Solanda	0,077	692	WET	13,7-18,3
Solanda - Morán Valverde	0,075	682	WET	12,9-18,3
Morán Valverde - Quitumbe	0,084	706	DRY	12,8-18,2