Quality Survey of Shotcrete for Underground Construction Using NDT Methods

Bernardo Lopes Poncetti
Doutorando, Universidade de São Paulo, São Paulo, Brasil, Bernardoponcetti@usp.br

Dianelys Vega Ruiz
Pesquisadora, Universidade de São Paulo, São Paulo, Brasil, dvegaruiz@usp.br

Leandro Silva de Assis
Doutorando, Universidade de São Paulo, São Paulo, Brasil, leandroassis@usp.br

Lucas Bellini Machado
Doutorando, Universidade de São Paulo, São Paulo, Brasil, lucasbmachado@usp.br

Marcos Massao Futai
Professor Dr., Universidade de São Paulo, São Paulo, Brasil, futai@usp.br

RESUMO: O uso de concreto projetado é uma solução comum para escavações de tuneis, essa técnica é usada tanto para estabilizar o maciço na etapa de escavação quanto como revestimento final de tuneis construídos. Esse sistema estrutural tem a importante função tanto na estabilização da escavação quanto no suporte blocos de rocha soltos. Sua capacidade de suporte depende de variáveis com elevadas incertezas incorporadas. Para verificar a qualidade e a confiabilidade das estruturas em concreto projetado diversos ensaios destrutivos são executados durante a construção do túnel para verificar sua espessura, aderência e propriedades mecânicas. Esse artigo apresenta a aplicação de Ensaios Não Destrutivos (ENDs) como possibilidade de otimizar a verificação de qualidade do concreto projetado, mostrando um estudo de caso real com aplicação de Ground Penetration Radar e Impacto Eco para estimar a espessura de concreto, a cobertura de proteção das armaduras e a aderência do concreto à rocha, além de discutir a aplicabilidade dos métodos.

PALAVRAS-CHAVE: Impacto Eco, Ground penetration radar, Inspeção, GPR, Concreto projetado.

ABSTRACT: A shotcrete layer is a common solution for underground excavation, used even to stabilize the excavation as a final layer of the constructed structures. The shotcrete has an important role in stabilizing the excavation and supporting loose blocks. The load-bearing capacity of this structural system depends on variables with large uncertainties incorporated. To verify the quality and reliability of this structural system several destructive tests are carried out during the tunnel construction to verify its layer thickness, adherence, and mechanical properties. This paper suggests the use of Non-destructive testing to improve the shotcrete quality survey, showing a real case study with real application of ground penetration radar and impact eco to estimate the concrete thickness, rebar covering, and shotcrete adherence, and discussing the applicability of the methods.

KEYWORDS: Impact-echo, Ground Penetration Radar, Inspection, GPR, Sprayed concrete.

1 INTRODUCTION

Guaranteeing the stability of an underground construction during tunnel excavation is a challenge. A common solution is the use of shotcrete (sprayed concrete) to support loose blocks (as an example the model of Barret and McCreath, 1995) and to help in the stabilization of the massive deformation (Einstein and Schwartz, 1979) working as a strengthening method for the surrounding massive (ITA, 2010). The sprayed concrete may be a temporary stabilization solution or a permanent lining, being used as the final layer of tunnels.

However, there are large uncertainties incorporated in the variables involving the support capacity (Bjureland et al., 2019). The properties of a shotcrete structure have larger variability in its geometric and mechanical characteristics if compared to other concrete structures. This variation is inherent in its executive procedures. Thus, it is essential to perform testing in the shotcrete before the construction, during the tunnel construction, and after its adequate hardening and cure to guarantee its quality and reliability.

After hardening is common the extraction of concrete samples to verify the rebar covering, the layers thickness, and the adherence, and samples to perform some laboratory analysis to verify the concrete mechanical properties. For example, Bjureland et al. (2019) report a total of 354 adhesion tests, 6068 samples for thickness estimation, and 690 compressive strength tests during the railway tunnel construction in Stockholm, Sweden, all of them destructive testing.

The quality survey of shotcrete for tunnel support is usually made only by destructive testing, however, several Non-Destructive (NDT) methods can collect information about the subsurface without opening holes in the structures. Some examples are Ground Penetration Radar (GPR), Impact Echo (IE), Ultrasound, Ultrasonic Tomograph, and Infrared Thermography. Their ability to detect variation in the material can complement the quality evaluation of the shotcrete layer during the tunnel execution by providing fast and easy information about the concrete thickness, adherence, voids, water presence, and rebar spacing.

Therefore, this work presents a real case of the use of GPR and IE to verify the shotcrete quality. Both methods are explained, and different data analyses are explored to obtain better results. The objective is to use NDT methods to estimate the shotcrete thickness, verify the rebar covering, and have information about the adherence of the material to complement the quality survey.

2 Non-destructive methods

2.1 Impact-echo

The impact-echo (IE) method is an NDT method that consists of generating an elastic wave into the material by an impact force on the surface of the material. The generated wave propagates into de media being reflected by internal flaws, voids, and material layers depending on the acoustic impedance of the material interfaces. The reflected signal is recorded by a transducer placed close to the impact location (Gibson and Popovics, 2005; Sansalone and Carino, 1986). The signal analysis of the IE allows the estimation of the thickness of layers and the location of voids. For tunnel applications the method has been applied to verify the grouting quality (Aggelis et al., 2008), tunnel shotcrete bonding state (Song and Cho, 2009), layer thickness, void detection, and adherence analysis (Cao et al., 2019).

The equipment registers a signal in the time domain. Its data analysis can be done in the registered time domain, in the frequency domain using the Fourier Transform, or in the Time-Frequency domain using the Short-time Fourier Transform or the Wavelet Transform.

There are at least four main cases in the IE signal. The case with one layer of sound concrete (Figure 1(a)) generates a signal with one clear peak in the frequency domain which is the resonant frequency of the concrete layer. The case of a void in the concrete layer (Figure 1(b)) also creates a clear peak in the frequency domain, but in this case, the peak frequency is higher than the layer thickness frequency since the distance for wave propagation is lower. The third case is a void between the concrete and the massive (Figure 1(c)), it causes a peak in the frequency domain equal to the peak of the sound concrete, in this case, the presence of a void can be seen in the time domain or in the time-frequency domain because the difference in the impedance between the concrete/air and the concrete/massive interface. If there is a void, the impedance of the interface concrete/air is higher and reflects mostly of the energy, so the registered reflections will have a higher amplitude and lower attenuation during the time. Therefore, a void can be located by analysis in the time domain or with a time-frequency analysis by observing the reflection intensity over time, this analysis can also be used to indicate the concrete bond state (Cao et al., 2019). The last case is the multi-layered structure, which may cause multi-peaks in the frequency domain (Figure 1(d)).

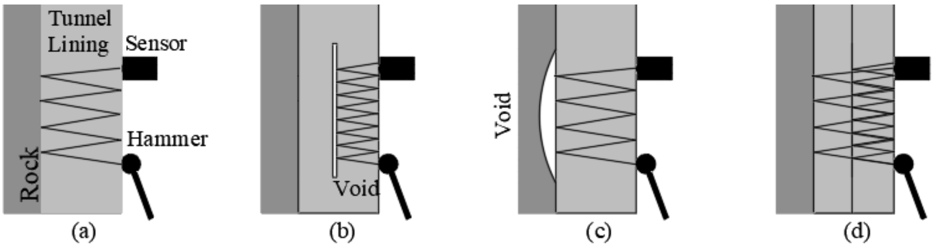


Figure 1 – Impact-Echo cases in tunnel evaluation.

With the resonant frequency of the material interface or a void, the depth of the reflector may be calculated by Equation 1. Where d_r is de deep of the reflector, C_P is the speed of the elastic compression wave in the media (m/s), f_r is the resonant frequency, β is a shape factor equal a 0.96 for solid place (ASTM C1383-04).

$$d_r = \beta \frac{C_P}{2f_r} \tag{1}$$

2.2 Ground Penetration Radar

Ground Penetration Radar is an NDT method able to generate images of the inside of structures. The method uses electromagnetic principles to detect objects, layer interfaces, material properties variation, voids, and water. The GPR antenna works by sending electromagnetic waves through the material and reading reflections that occur when there are variations in the electromagnetic properties of the medium.

As the radar is moved on the surface it sends electromagnetic pulses into the concrete. The energy is reflected to the radar when the wave finds a material with different electromagnetic properties than the medium of propagation. Because of the behavior of the pulse propagation, an object is detected before the radar is placed over the object, and it keeps being detected after the radar passes through the object (Figure 2(a)). As the travel time is higher when the radar is far from the object, and lower when it is closer, the received signal of an object registers a parabolic pattern in the radargram (Figure 2(b)), making the equipment a good option for rebar location.

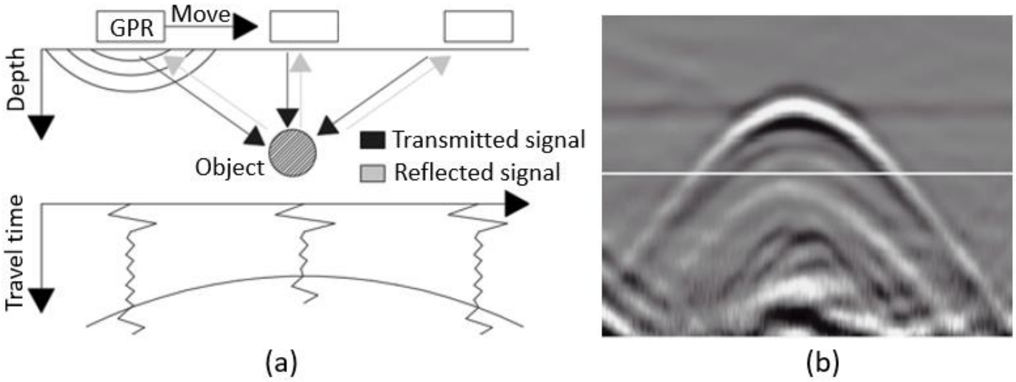


Figure 2 – (a) GPR principle. (b) Radargram patter of metallic object.

For tunnel inspection, the GPR can be used to locate and quantify rebars (Xiang et al., 2013; Zan et al., 2016), estimate the concrete layer thickness if there is a variation of the dielectric constant (Li et al., 2011; Punto et al., 2021; Ling et al., 2022), verify the grouting quality behind tunnel lining (Peng et al., 2021), and detect voids, water and some pathologies (Dawood et al., 2020; Nuñes-Nieto et al., 2015; Zan et al., 2016).

The position of the reflector (object or layer interface) can be calculated with the propagation velocity of the wave in the medium (V_M) and the travel time (t), using Equation 2. The velocity of the electromagnetic wave may be estimated with Equation 3, where c is the speed of light (approximately 300000 km/s) and ε_r is the relative dielectric constant of the medium.

$$d_r = 0.5V_M \times t \tag{2}$$

$$V_M = \frac{c}{\sqrt{\varepsilon_r}} \tag{3}$$

3 CASE STUDY

The GPR and IE were tested in a still under construction tunnel with shotcrete as the final layer. The Ground Penetration Radar used was the GSSI StructureScan Mini LXT, with 2700MHz center frequency, and the Impact Echo was the Pundit PI8000 from Proceq. The test was done in a passenger passage between two highway tunnels (Figure 3). A grid, with two horizontal lines (0.90m and 1.80m high) and six vertical lines spaced 1.0 meters each was used for the orientation of the testing. The GPR was passed in each line, and the IE was used at the intersection of each line.

Figure 3. Test’s location.

The tunnel blueprints specify for this pedestrian passage a structure with two reinforced shotcrete layers and rock bolts with 3.0 m length (Figure 4). For the first shotcrete layer, a regularization layer with a variable thickness (approximately 5cm) is specified, followed by a steel mesh and a shotcrete with 10 cm thickness. The second layer has a shotcrete layer of 15 cm with 7 cm of rebar covering. The complete concrete layer has approximately 30 cm thickness.

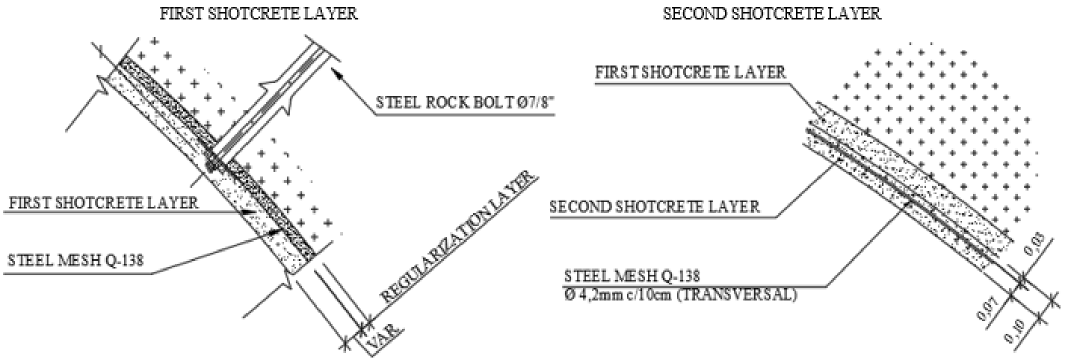


Figure 4. Shotcrete layer specifications.

4 RESULTS AND DISCUSSION

Figure 5 shows the GPR radargram of the 1.80 m high line on the top and 0.90 m on the bottom image. It is possible to easily identify the parabola shape of rebars to qualify and estimate their concrete covering. Some places have a signal attenuation and a variation in the parabola shape, one possible cause is a higher water content in these regions (Note N1 in the radargram). Note N2 (Figure 5) shows a pattern variation caused by a region with a steel mesh overlay.

The horizontal red line marks the 7cm covering specified by the executive project. There are 26 rebars with shotcrete covering lower than the project value. Although there is more than 2,5m of the scanned area with the shotcrete covering lower than the specified, according to the NBR 6118, the rebars should have a concrete covering of at least 3 cm for concrete in contact with soil and for concrete in urban areas. Mostly the rebars covering satisfy the normative value except the area on Note N3. In this region, the steel mesh covering is varying from 2.4 cm to 3.0 cm.

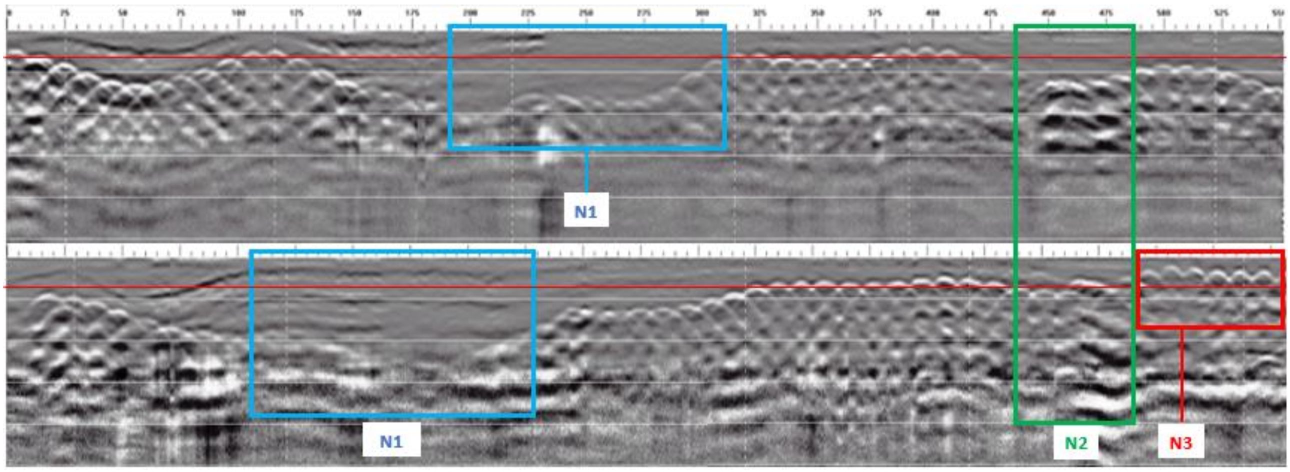
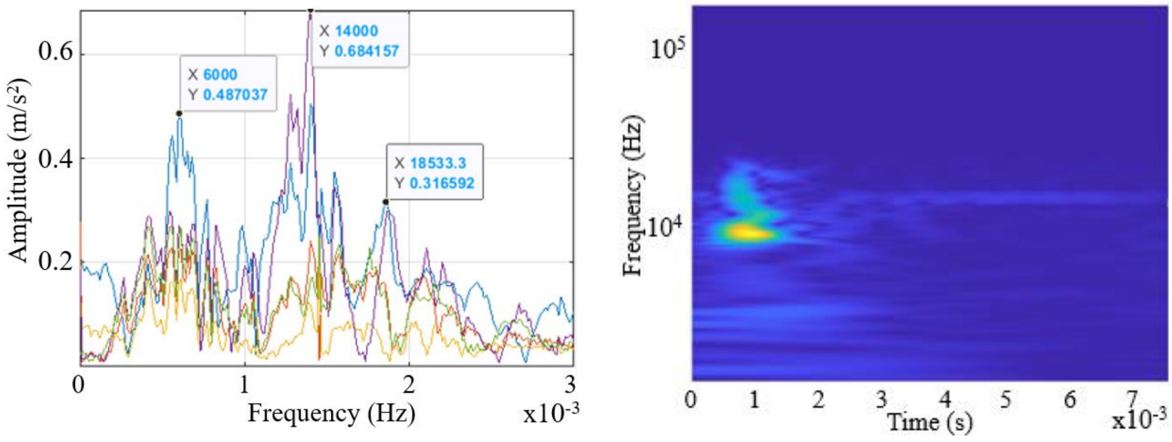


Figure 5. Radargram of the shotcrete in the passenger tunnel.

The Impact Echo data can be analyzed in the time-domain, frequency-domain, and time-frequency domain. The frequency obtained by the Fourier Transform (Figure 6(a)) or Wavelet Transform (Figure 6(b)) may be used to estimate the layer thickness. The multi-peaks that appear in the frequency spectra are caused by rough surfaces. Knowing the speed propagation of the wave in the concrete, is possible to estimate how deep is the interface that is generating the resonant peaks using the Equation (1). For this concrete, the measured velocity in laboratory is 4371m/s which means that the frequency of 6000 Hz refers to 0.34cm and 14000Hz to 0.14cm deep.



(a) (b)

Figure 6. (a) Fourie Transform. (b) Wavelet transforms.

The thickness analysis done in the Impact Echo and GPR data showed a variation in the shotcrete layer thickness of 22.5 cm to 34.9 cm. According to the project specification, it was expected values higher than 25 cm and close to 30 cm of shotcrete. Despite the regions with thicknesses lower than the specified, mostly the estimated values are in accordance with the project. As example, only two IE data registered values lower than 25 cm.

According to Song et al. (2019) the Time-domain and the Time-Frequency domain analysis can reveal the bonding condition of the shotcrete. The author uses the IE to classify the shotcrete bond condition into fully bonded condition, partially debonded, debonded, partially void, and void condition. The Figure 7 shows the Time-frequency analysis of a recorded signal classified in debonded condition. In comparison, the Figure 6(b) shows an example of bond condition.

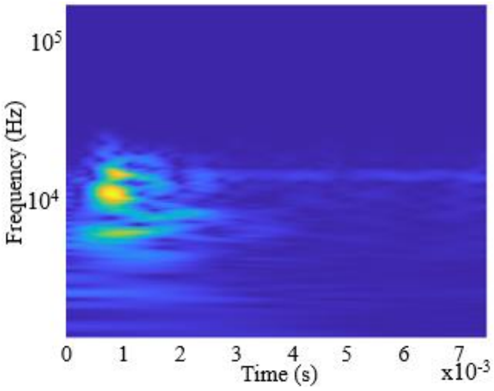


Figure 7. Time-energy analysis of IE signal of a debonded spot.

5 CONCLUSIONS

Comparing the use of both equipment, the GPR was easier to use since it can be applied on rough surfaces. The Impact Echo on the other hand showed high dependence on a smoother surface to get good results. To improve the IE data the shotcrete surface needed to be regularized with a grinder. However, even with the regularization some places still had a very noisy signal. For example, for the 12 spots measured in the testing wall, only 8 spots had useful readings.

With the data analysis of both equipment is possible to estimate the concrete layer thickness, quantify the number of rebars, verify the rebar covering, detect voids, and obtain information about the shotcrete bond condition. Table 1 lists the application of each method and the difficulties observed during the testing.

Table 1. Comparison of both methods.

Method	Application and advantages	Difficulties and disadvantages
Impact Echo	Layer thickness, void detection, and shotcrete bonding state. Easy to operate, fast application.	Hough surfaces produce multi-peaks making analysis difficult. Needs a regular surface to improve its results.
GPR	Easy to locate and quantify rebars. Useful to verify the rebar covering. Able to estimate the concrete layer thickness. Detect some voids, and water infiltration. Easy to operate, fast application.	The trade-off between frequency, deep detection, and resolution (see Alani and Tosti, 2018). Limited propagation in structures with high steel density. Needs variation in the dielectric constant of the material

The data analysis concluded that mostly the inspected area followed the project and the normative, with fill exceptions where the concrete layer thickness was lower than the specified and the rebar covering was lower than the normative recommendation. The data analysis also was able to find places with possible bonding issues.

The results showed the high variability of the geometric properties of a shotcrete structure. This variation justifies the necessity of testing the shotcrete after its hardening to verify the accordance with the project. The destructive testing can not be replaced, it is necessary to guarantee the quality of the process. However, the results show that the NDT methods may be useful to complement the quality survey of tunnels under construction improving the evaluation with fast measurements.

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