

Introduction

The collapse of a tunnel in 2005, during construction works in the underground of Barcelona, affects several buildings and two schools, in a densely populated neighborhood. In the same week and in the same zone, the failure of other tunnel was prevented with difficulty by injecting concrete. However, all works were interrupted because of the insecurity and danger that still represented the damage. The weakest sectors were still unknown, either the detailed geology. The ground evaluation, to define the most damaged areas and the ground conditions was really complex because of the high density housing. Due to the risk, an intensive geophysical exploration by means of borehole ground-penetrating radar was considered. This exploration was carried out during two weeks, in two different phases. The first one consists on the exploration of the tunnel front. The second one involves a more detailed evaluation, obtaining data from the soil station and from the tunnel vault and walls. This paper presents some of the results obtained in the exploration of the tunnel front. The aim of the survey was to detect possible anomalies associated to cracks or non-homogeneous materials that could cause the tunnel collapse in the front area. It was crucial to define their position and to determine their volume. The first phase planned in the survey consisted of the study of the front tunnel.

Ground penetrating radar is a near surface geophysical survey technique based on the emission and reception of electromagnetic waves. A transmitter antenna emits a wave that propagates through the medium. Abrupt discontinuities in the medium electromagnetic parameters (conductivity or dielectric permittivity mainly) create surfaces where energy reflections and refractions are produced (figure 1a). Receiver antenna incorporates an electronic circuit, connected to an amplifier and receiver circuit. Electromagnetic arrivals generate an audio frequency band pulse that is sent through a highly screened cable to the central unit, where the signal is reconstructed, processed and stored. Each received pulse is show up as a trace. So, moving the antenna on the medium surface, an image record is obtained revealing the existence of anomalies due to electromagnetic changes in the inner materials. In the radar data, horizontal axis represents the antenna position, while vertical axis corresponds to the two-way travel time (TWT). The conversion TWT into depths depends on the wave velocity knowledge. Different grounds and materials could be characterized with velocity intervals, depending on the minerals and physical conditions. However, the methodology presents an uncertainty: two related parameters are unknown: the distance to the target and the wave velocity. In the case of unshielded borehole antennas, a third parameter is also unknown: the location of the targets around the antenna. This rotational ambiguity is an additional difficult in the application of this methodology in boreholes.

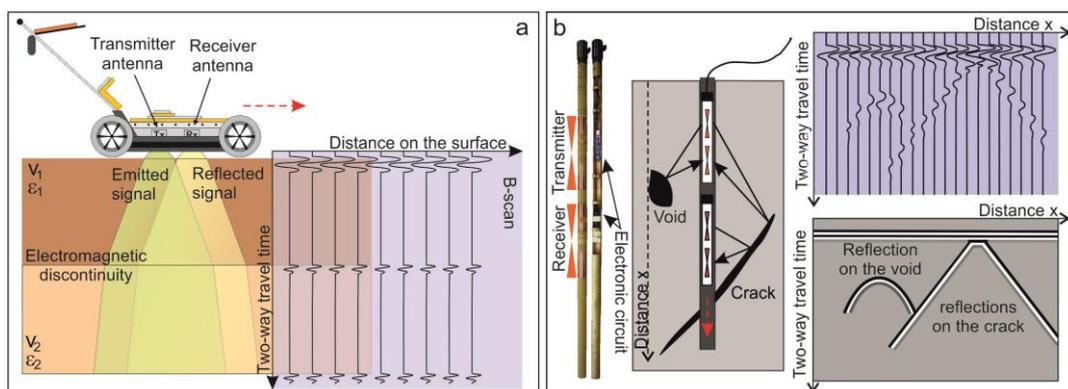


Figure 1. a) GPR surface radar scheme showing the different parts and radar data. b) Borehole radar in reflection configuration, and images of the reflections caused in one void and in one crack.

Even though these problems, this geophysical survey is widely applied in many civil engineering problems. Some of the most usual applications are in pipes location (e.g., Sheng-Huoo et al, 2010), roads and bridges evaluations (Al-Qadi et al., 2001; Lahouar and Al-Qadi, 2008), archaeology (e.g.,

Barone et al., 2007) and concrete inspection (e.g., Hugenschmidt and Kalogeropoulos, 2008; Hugenschmidt et al., 2010). Recently, the development of borehole radar systems facilitates the application of this methodology in a wide number of cases where conventional GPR systems are inaccessible. Sounding data allows cross-hole and tomographic images based on the wave attenuation (e.g., Chang et al., 2006) or on the wave velocity (Galagedara et al., 2003), as additional data in soil water content evaluations (Binley et al., 2002). Notwithstanding, non-directional antennas are usually applied in GPR borehole studies. Then, it is not always easy to correlate the different zones between the holes to the GPR images (Wänstedt et al., 2000). Other applications, as the detection of tunnels, are established even supplementary data are needed to define proper synthetic models (Di Donato et al., 2012). GPR sounding information was also recently used to evaluate geological fractures, comparing results from single hole reflection data to cross hole data (Dorn et al., 2012).

Radar equipment: borehole radar antenna

Borehole radar is a particular GPR system designed to be used in holes. It operates in a similar way than a surface GPR system, but the results could be more detailed because the antennas could be emplaced closer the subsurface targets. Then, the recorded anomalies are more precise and detailed. On the other hand, it is possible to use borehole radars in areas inaccessible to other common surface equipment. Borehole antenna contains two dipoles and their electronics in a curved container (Figure 1b). 100 MHz borehole center frequency antenna was used in this survey, in a reflection mode configuration (Figure 1b). In this configuration, both antennas –transmitter and receiver– are in the same borehole at a fixed separation and enclosed in a cylindrical container. The container is moved down the hole while the energy arriving from different targets is detected, being the radar image the result of the different reflections around the antenna. Usually these antennas are unshielded devices and, therefore, they present an omnidirectional radiation pattern. Therefore, these antennas radiate the energy uniformly in all directions in the space. This means that the transmitter dipole radiates energy in a 360° lobe, and receiver dipole could detect energy from all directions. In this way, anomalies could be caused by targets all around the borehole, and it could be difficult to define their direction and as a consequence, the exact position of the targets because signals due to reflections in targets around the borehole could be overlapped each other. On the other hand, this rotational ambiguity could also produce that different points with equal slant range could be observed as a single point (Mukhopadhyay, 2005). As a result, radar data obtained under these conditions could provide information about the distance to the anomaly, but not about its exact position because the azimuth to the reflector cannot be determined using a GPR data from a single borehole. At least GPR data from three non collinear boreholes are necessary in order to define the precise position of the targets, including azimuth (Mukhopadhyay, 2005). Slob et al. (2010) propose an algorithm based on the synthesized radiation pattern of the antenna to estimate azimuth orientation by using omnidirectional borehole antennas. However, these authors indicate that the effect of the cylindrical container and the wires causes a complex radiation patterns that are difficult to model numerically. In the case study presented in this paper, targets position was defining by using correlated data from seven non parallel boreholes in the front tunnel, and additional boreholes lateral to the front tunnel and over the station.

First phase: studying the front tunnel. Survey and results

The main problem relate to the study was that the access to the surface over the front tunnel was highly limited due to the high density housing and the intricate city neighborhood. Therefore, the application of conventional GPR survey with ground coupling antennas was not possible. Borehole radar was the most feasible option, even the number, the position and the direction of the holes needed to be adapted to the conditions of the structure. Therefore, the geophysical evaluation of the tunnel front state was difficult because of the small space that forced the position and the direction of the holes. No enough space was available to obtain cross-hole data, because of the accessibility (figure 3). The front tunnel was studied, in a first phase, using seven boreholes, defining a cone. Figure 4 present the holes positions on the front tunnel, and the distribution of the studied areas around of each one of

the holes. Boreholes started in the middle of the tunnel and crossed the damaged area. The objective was to determine if other weak zones exist, and to define the volume of the affected area.

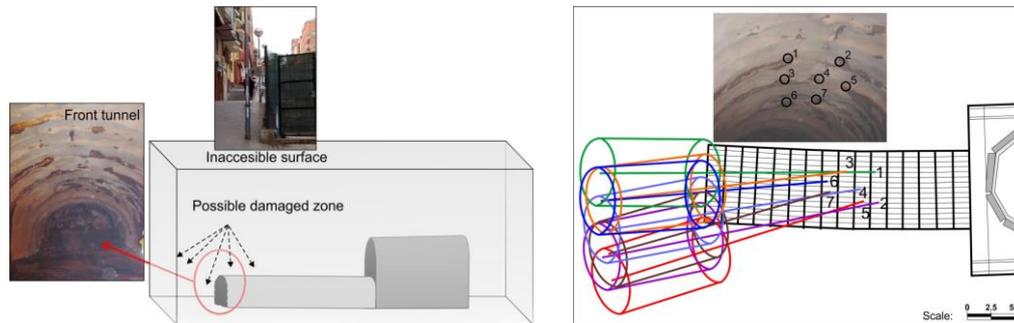


Figure 3. a) Front tunnel and the possible damaged area. b) Position of the seven boreholes. The cylinders indicate approximately the rock volume evaluated around each hole.

Around each hole GPR allows to evaluate the ground in, approximately, a cylindrical volume, even the shape of the volume depends on the wave velocity in the ground materials. Defining the volume of the damaged areas and to detect other weak zones needs to determine the position of the anomalies in the ground, but unidirectional radiation pattern causes azimuth ambiguity. More than one borehole, having superposed investigation ground volumes allows to define the azimuth of the detected anomalies. Raw data was processed in order to improve radar images. Then, manual gain was applied to compensate geometrical spreading. Also, a band pass frequency filter was also applied between 10 MHz and 300 MHz. Ringing noise was noticeable in raw data. To reduce its effect on the images, an average trace estimated with 500 traces, was subtracted. However, noise due to electric noise was not possible to remove or minimize. Deconvolution helps to reduce noise due to multiple reflections. Wave velocity was estimated using the reflections caused in the borehole edges. Radar data images in the profiles demonstrate the existence of an area where numerous reflections appears, most likely due to cracks and contacts between materials, voids and irregular materials in the collapsed area and in other close sectors. Also, several reflections in planes were detected. These anomalies could most likely indicate the existence of faults. Figure 4 shows the images and the possible interpretation. Figure 4a shows one of the radargrams and the interpretation the images. The final result defining the medium was obtained by comparing and interpreting all the radar images, correlating the anomalies. This result consists of the location of the most damaged zones, indicating the possible existence of a fault (Figure 4b). In this result, the location of fractures are marked in grey and the existence of a zone where the radar images present a large number of anomalies, associated to the existence of numerous voids and heterogeneities is marked in brown.

Conclusions

The study of the front tunnel allowed to determine the location of several anomalies that could affect the stability of the structure. The main difficult in this study was associated to the rotational ambiguity that force the analysis by means of several non-parallel boreholes. Even though, some cracks were detected, observed in the radar images as long anomalies. Also, voids were located and correlated to the anomalies observed in all the B-scans. This methodology allowed to define a problematic zone that could be associated to a less compacted materials, most likely heterogeneous, characterize by voids. Therefore, the near-surface survey, although the uncertainties associated to the method and the unshielded borehole antennas, provides in this case a valuable result, defining the zones that might be strengthening or more widely studied in order to avoid problems. This first assessment was useful to plan further studies and a final solution for the construction.

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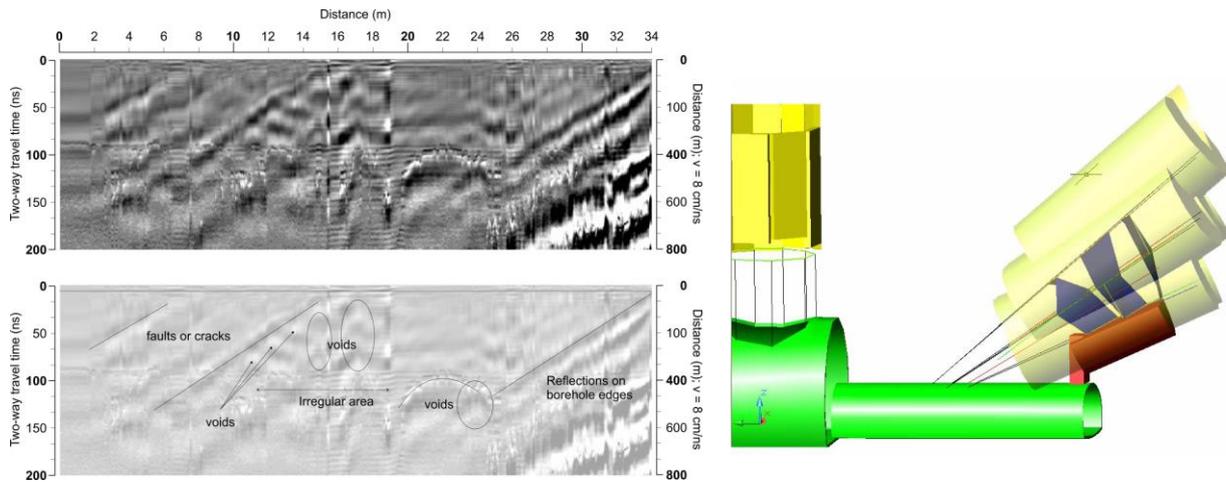


Figure 4. a) Radar images obtained from one of the boreholes. b) Final result obtained after correlating all the B-scans at each borehole. In green, the tunnel. In light yellow, the zone studied with the borehole radar. In grey, surfaces of fracture. In brown, zones where anomalies suggest the existence of a large number of voids.

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