Imaging structural elements of a cathedral using ground penetrating radar

D.B. Woodham
Atkinson-Noland & Associates, United States

Abstract

The Basilica of the Assumption of the Blessed Virgin Mary in Baltimore, Maryland is the first Catholic cathedral to be established in the United States. The cathedral was designed by architect Benjamin Henry Latrobe and is an important religious building as well as a significant example of the Greek Revival style in the United States.

As part of a condition assessment and historical research program, the configuration and condition of several critical structural elements of the cathedral were evaluated in the autumn of 2000. Ground penetrating radar (GPR) was used to nondestructively determine the thickness of the cathedral dome at numerous locations. The radar was also used to determine the configuration of a main supporting column for the dome and a column supporting one of the two bell towers at the cathedral. A comprehensive image of the columns could be reconstructed based on their accessibility from all sides. The results from the GPR investigations at the tower column agreed well with borescope observations and the results from a previously conducted investigation using acoustic tomography.

Ground penetrating radar has been shown to provide valuable information about building components (structural and nonstructural) nondestructively. The radar data reveals voids, construction layers, the presence of other materials (e.g. metal inclusions), as well as the thickness of the element. In some instances, it is the only practical nondestructive technique capable of providing the required information.
Introduction

During the autumn of 2000, several investigations were conducted at the Basilica using ground penetrating radar (GPR). The GPR method involves sending radar energy into the material of interest via an antenna and recording reflections generated within the material received by the same antenna. Reflections are created when the electromagnetic properties of the material vary over a short distance.

Ground penetrating radar was used to:
- Image one pier supporting a bell tower at the undercroft level
- Image one pier at the sanctuary level
- Determine the thickness of the main dome
- Investigate a voided structure at the perimeter of the main dome
- Investigate the floor structure of the main floor of the Basilica

The radar equipment worked well in the cathedral interior due to the absence of moisture within most materials. Determination of a radar energy velocity for the clay masonry construction of the Basilica was accomplished by comparing calculated and measured thickness of several piers in the undercroft. A large aluminum plate placed on the opposite side of the pier from the antenna created a large amplitude reflection that allowed calculation of the travel time of the radar energy.

Radar Investigations

Undercroft Pier

Ground penetrating radar was used to image one of the stone and brick masonry piers in the undercroft. The southwest pier of the north bell tower had been previously investigated using acoustic tomography. The radar investigation was deemed valuable to corroborate the information gathered during the previous investigation.

The pier is roughly 1.8 m by 3.0 m in plan with the larger dimension running east to west. A grid was established around the pier at an elevation of approximately 60 cm above the undercroft floor. The grid points were established at 30 cm intervals resulting in 5 points on the east and west faces and 9 points on the north and south faces. A Geophysical Survey Systems SIR-2000 was used with a 900 MHz antenna to image the pier. The data acquisition consisted of placing the antenna on one of the grid points and recording radar data sets – one with a large aluminum plate on the opposite side of the pier and one without the reflector. The aluminum plate reflected nearly all the radar energy arriving at the opposite side of the wall (Figure 1) and provided an accurate location of both sides of the wall within the radar trace.
Based on the time elapsed between radar energy reflections on each pier face and the measured dimensions of the pier, the average velocity of the radar signal could be calculated. Once the average velocity is known, the approximate location (assuming uniform velocity) of each portion of the signal can be correlated to a known location within the pier.

To analyze the data, plots of the radar reflection amplitudes were developed using the scans acquired on each face of the pier. The data from each pier face was multiplied by a linear weighting function to accentuate the data obtained from the near face and to de-emphasize the data obtained farther from the antenna. The data obtained farther away from the antenna is less reliable due to the number of reflection-producing anomalies that tend to scatter the signal and the increased width of the radar signal. In addition, the radar energy passes through the pier twice (transmitted and reflected), weakening the energy reflected from the farther regions. Figure 2 shows the final results of the radar tomography.

Sanctuary Pier

A pier in the sanctuary was also investigated using ground penetrating radar. The southwest pier supporting the dome was investigated using the technique described above. However, in this instance the pier was not rectangular in plan. As shown in Figure 3, the pier appears solid, with only small areas producing higher-amplitude reflections. It was postulated that this pier might contain a voided section for a chimney, however this does not appear likely based on the radar tomography.

Main Dome

The thickness of the main dome was investigated at nine isolated locations and three continuous scans (each approximately 2.3 meters in length) at accessible areas of the upper dome surface near an entry stairwell. Both 900 MHz and 1GHz antennae were used to evaluate the thickness of the dome. From the data taken using the 900 MHz antenna, it appears that the dome is approximately 70 cm thick. The 1 GHz antenna indicates a dome thickness of 57 to 63 cm. It is most likely that the dome thickness is 64 to 66 cm thick (6 wythes of brick plus plaster interior and an exterior parge coat). It is interesting to note that one of the radar scans intercepted a coffer on the dome’s interior. The radar trace is reproduced as Figure 4 below. The minimum thickness of the dome at the base of the coffer appears to be about 25 cm.
Structural Studies, Repairs and Maintenance of Historical Buildings

Arched Structure near the Exterior Perimeter of the Dome

A voided structure was encountered near the exterior perimeter of the dome during the GPR survey. A nearly horizontal surface is present near the perimeter of the main dome with alternating arched and flat panels. The GPR indicated that the arched sections were voided under a 15 to 20 cm masonry arch (Figure 5). Subsequent borescope investigations confirmed the thickness of the arch at 20 cm and the presence of a voided structure below the arch and above the spring line of the dome.

Sanctuary Floor

The sanctuary floor system was investigated using GPR. The objective was to determine the thickness of the floor and obtain any information about the composition of the floor. The 900 MHz antenna was used to image the floor system (Figure 6) with good results. The results show a cellular construction of the floor system and the presence of the barrel vaults supporting the floor system. The presence of the cellular construction has not yet been verified by other methods.

Conclusions

The use of impulse radar to nondestructively reveal details in historic constructions has been demonstrated on several elements of a cathedral. Impulse radar can be used to image cross sections of structural elements given that access is available from at least two sides. The thickness of an element can be determined once the velocity of electromagnetic waves has been established within the material. The application of ground penetrating radar is not applicable in all situations and many materials (e.g. clays and salt-laden masonry) will not conduct electromagnetic energy over large distances.
Figure 1: This figure shows the amplitude of the reflected radar signal versus time. The right side of the figure shows a large reflection due to an aluminum plate placed on the north side of the pier. It is known that the entire record length is 40 nanoseconds, thus allowing approximate correlation of each portion of the signal to a location within the pier cross section.
Figure 2: Plot of the combined radar reflection data acquired on the four faces of the pier. Areas with high amplitude reflections are areas where voids or dissimilar inclusions are located. The high amplitude areas around the perimeter of the pier are due to the high amplitude reflection generated at the air interface between the antenna and the masonry. The center section of the pier is constructed of rubble stone masonry while the ends of the pier are constructed of clay masonry.
Figure 3: Radar amplitude plot from all faces of the pier. The high amplitude areas around the perimeter of the pier are due to the high amplitude reflection generated at the air interface between the antenna and the masonry. The interior appears relatively uniform in composition with only small areas of higher-amplitude reflections. The graphing program tends to extrapolate the data to points outside the boundary of the pier.
Figure 4: Vertical scan of the Basilica dome using GPR. The top of the figure represents the top surface of the dome. The first reflection is the surface reflection at the upper dome surface (the location of the GPR antenna). The distance between the top of the figure and subsequent reflections lower in the figure indicates the depth to a reflection producing material interface. The first strong reflection (indicated by the darker) is the interior surface of the dome. This particular scan intersected one of the circular coffers located on the underside of the dome and indicates how the dome thickness varies at the coffers.

Figure 5: Radar reflection profile taken along the exterior perimeter of the dome. The top of the figure is the upper surface of the cellular construction. The figure shows the thickness of the arch (center of figure) and how the thickness increases at each edge (left and right of figure). The strong reflection at approximately 15 cm indicated that the brickwork was voided below the upper surface.
Figure 6: Transect down the center aisle of the cathedral showing reflections from the barrel vaults supporting the main floor. The reflections within the floor slab are not continuous along the length of the transect. This indicates that the floor construction could be cellular or contain metal elements on a regular spacing. The floor is approximately 50 cm thick.

References

