Geophysical investigations of historic buildings—A case study of the great church of St. Sophia

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As part of a structural restoration project in 2010, a 3D ground-penetrating radar (GPR) survey was conducted at the great church of St. Sophia to investigate the foundations of the present structure. The geometry of the foundation remnants from the previous structure that existed at the same site, mixed with the landfill which we know exists based on the construction history of the current structure, was inferred from time slices. Furthermore, the geometry of the cistern which we discovered beneath the inner narthex during a previous 2D reconnaissance GPR survey was delineated. The cistern is approximately 60 m long and 5 m wide at a depth of 1 m below the ground level. A water pipe that approaches the cistern in the perpendicular direction from the outer court of the church grounds was also discovered. The cistern may be connected with this pipe to the Great Cistern of the Byzantine period about 500 m away from the church grounds.

In addition, a shallow seismic survey was conducted to estimate the P- and S-wave velocity-depth models beneath the foundations of the church. The P-wave velocities vary from 1500 m/s close to the ground level to 3000 m/s at a depth of 10 m. Whereas, the S-wave velocities reach nearly 700 m/s at a depth of 6 m, 900 m/s at a depth of 12 m, and more than 1000 m/s at a depth of 18 m. Based on the seismic velocities, it is evident that the church was built upon a strong bedrock.

The GPR survey at St. Sophia

Built between 532–537 by the Byzantine Emperor Justinianus, the great church of St. Sophia in Istanbul has an imposing structure with the main dome that has not been surpassed in size and height by any other church or mosque in the world. During the earthquake in 550, the dome partially collapsed, but was quickly repaired back to its original grandeur. The current building is the third structure built at the site; the two previous structures were destroyed by fire and riots.

The GPR survey used a 250-MHz system at the ground level in the grand hall beneath the dome, the side halls, and the inner and outer narthexes of the church along line traverses at 25-cm intervals and with a 5-cm spatial sampling (trace interval). The cumulative length of the recorded GPR profiles is more than 7000 m. Accessibility was restricted and, therefore, the survey was conducted in rectangular patches of various sizes (Figure 1). A 3D image of the church foundations has been derived down to a depth of 5 m.

GPR data from each line traverse were migrated following dc removal and band-pass filtering. Two distinct zones
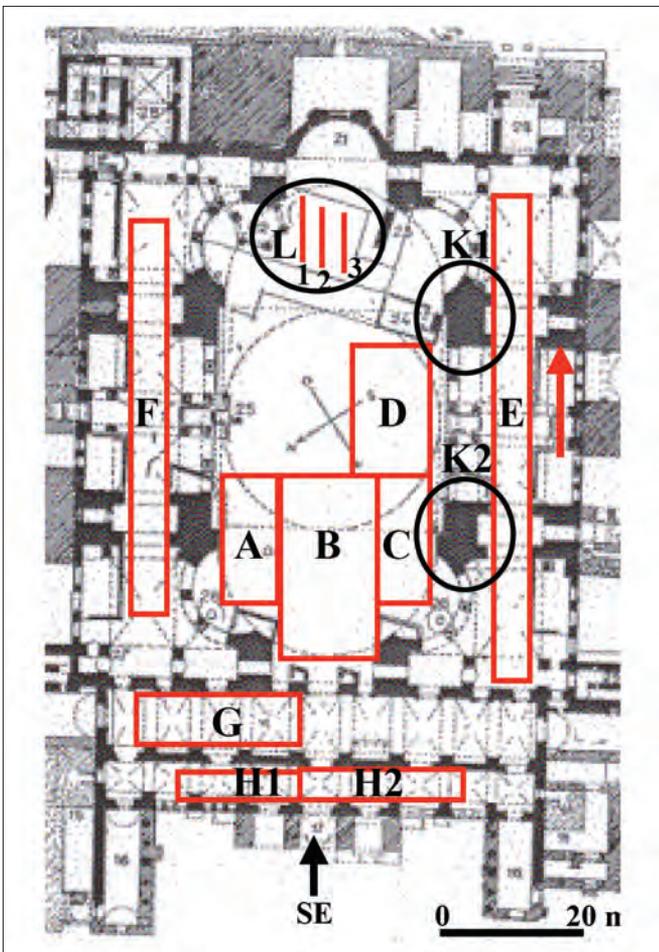

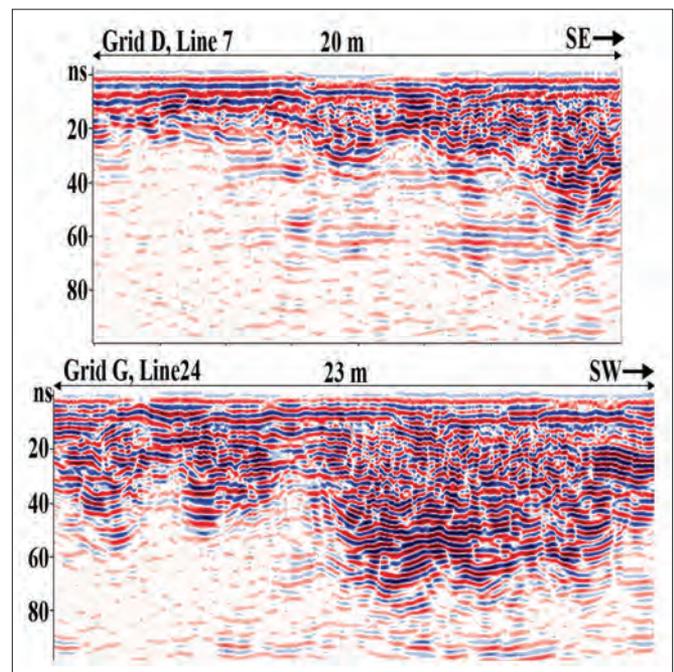**Figure 1.** *The GPR survey grids over the ground level of the church.*

Figure 2. *Selected time-migrated GPR sections from survey grids D and G shown in Figure 1. Depth interval is approximately 0–5 m.*

Figure 3. (a) A time-migrated GPR section from survey grid A shown in Figure 1; (b) a foundation wall from a structure in the courtyard; and (c) time-migrated GPR section along the AB profile on the wall. Note the resemblance of the two sections as evidence to the presence of the remnants of the foundations associated with the previous structure at the site.
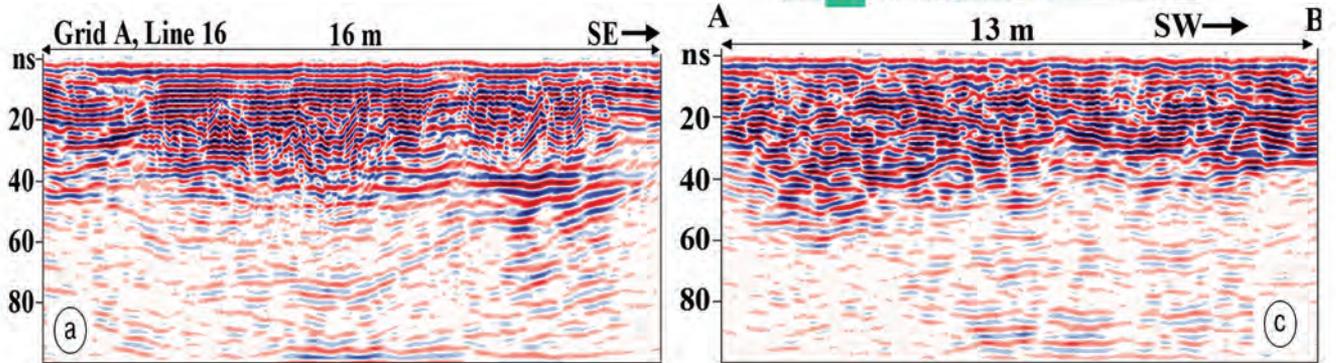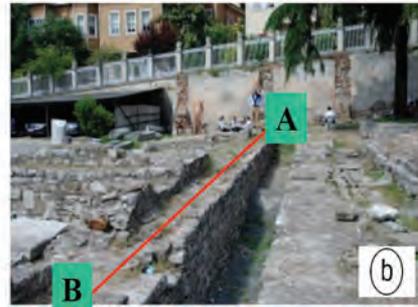

Figure 4. A nearly flat reflection R1 is observed in many GPR sections, which may be associated with the stone ground-floor surface of the previous structure.
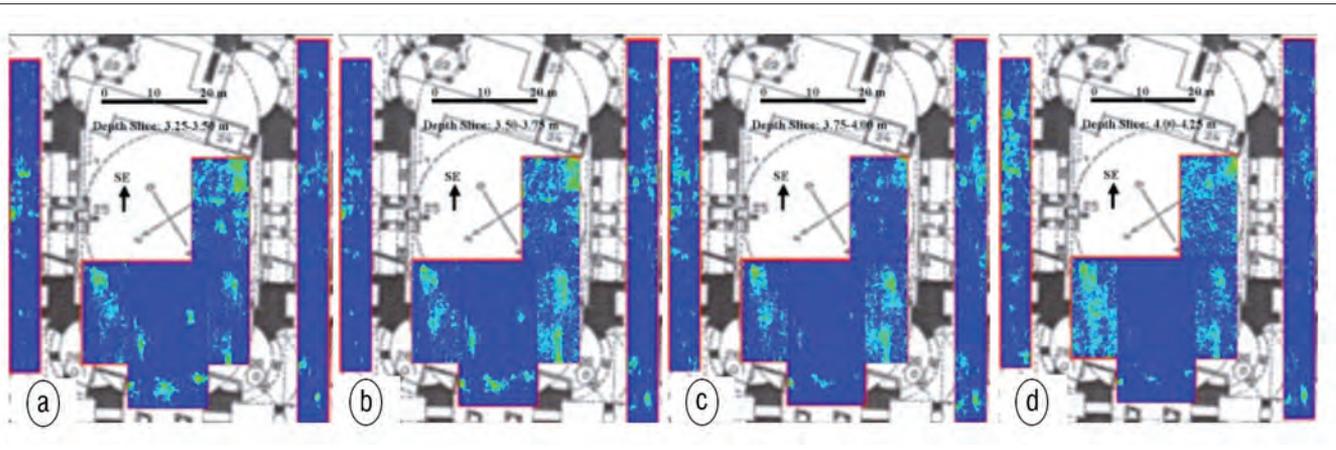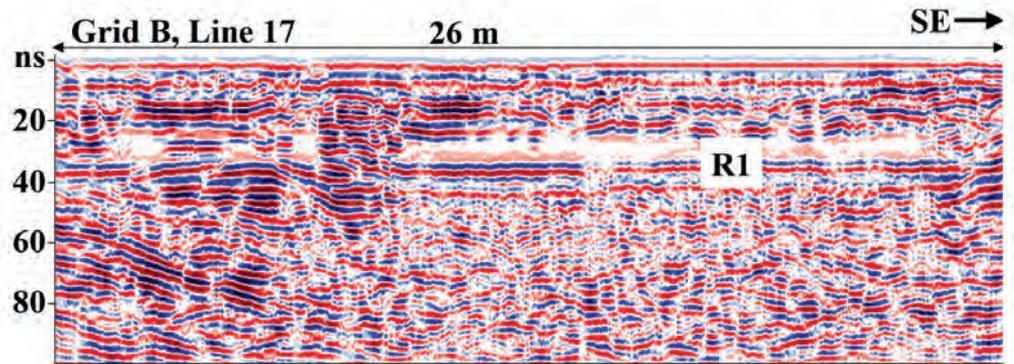

Figure 5. GPR depth slices at intervals of (a) 3.25–3.50 m, (b) 3.50–3.75 m, (c) 3.75–4.00 m, and (d) 4.00–4.25 m. A velocity of 0.1m/ns was used to convert the time-migrated GPR data to depth. Light green corresponds to the zone composed of landfill and foundation walls, and blue corresponds to the natural soil column.
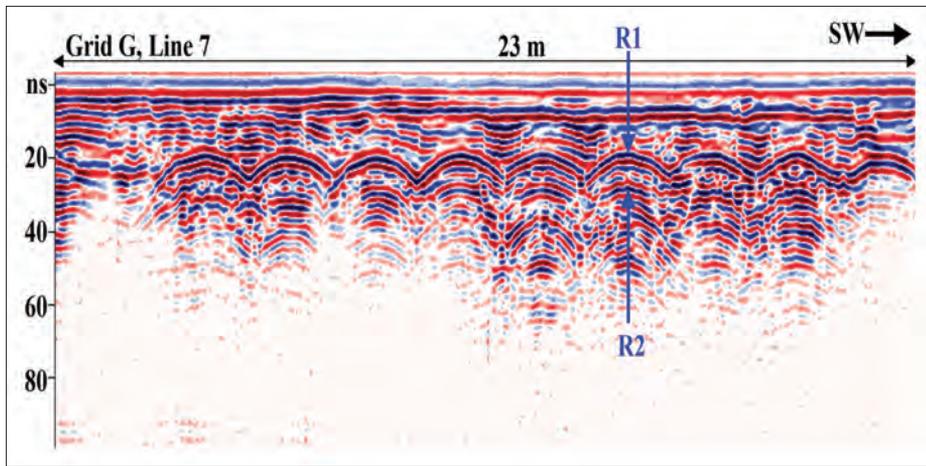
Figure 6. An unmigrated GPR section from survey grid G shown in Figure 1. Note reflections R1 and R2 from the top and base of the cistern beneath the inner narthex, respectively, and their multiples.
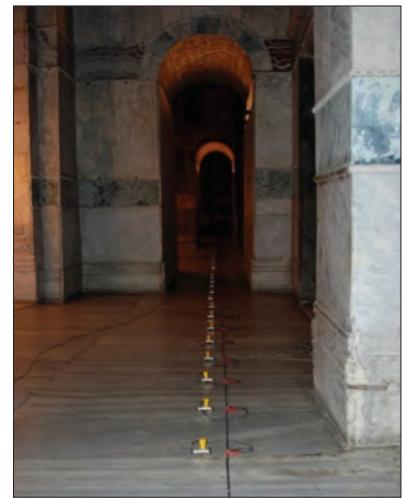

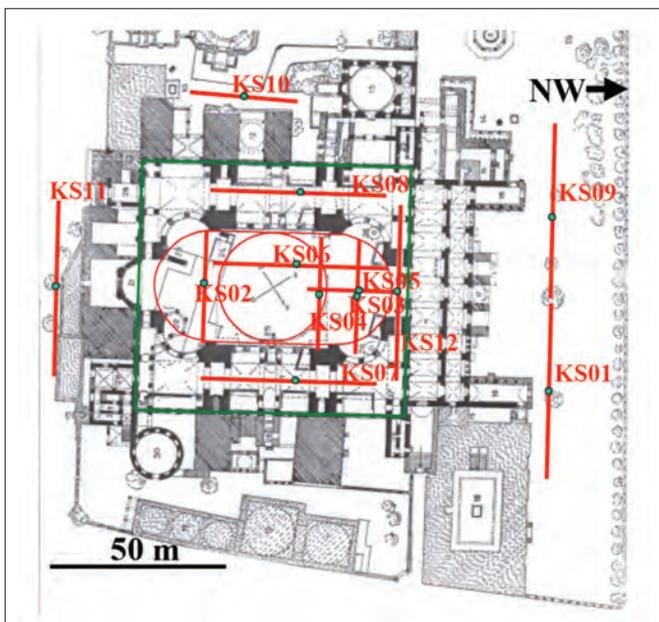*Figure 8. A receiver spread at one of the KS locations inside the church.*

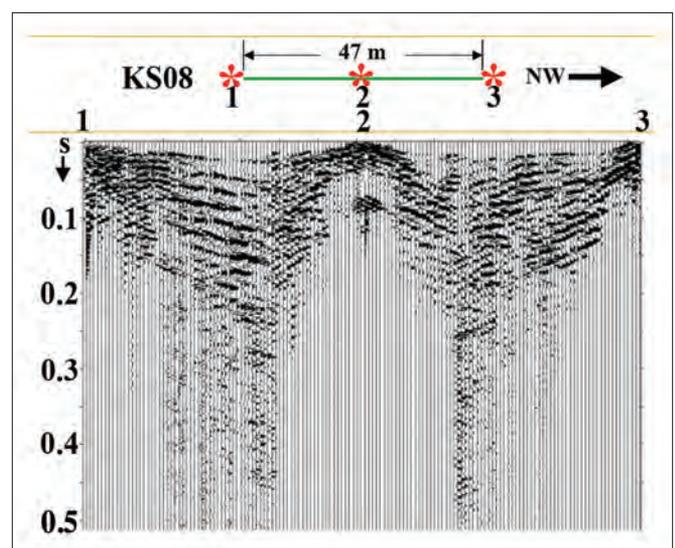*Figure 7. Receiver spread locations for the seismic survey at St. Sophia.*

Figure 9. Three seismic records acquired at one of the KS locations inside the church.

are apparent in many GPR sections—the upper zone with strong, chaotic reflectors, and the lower zone with relatively weaker amplitudes (Figure 2). The upper zone extends down to a depth of 5 m and most likely corresponds to the remnants of the foundations of the previous structure mixed with landfill material. The lower zone corresponds to the natural soil column.

A GPR section from Grid A (Figure 3) exhibits strong evidence supporting the interpreted presence of the foundation remnants from the previous structure. The ruins from a building unrelated to the church lie exposed in the courtyard. The GPR section along the top of the wall shown in Figure 3 contains in the upper zone strong, chaotic reflectors associated with the mortar composition of the wall, and in the lower zone relatively weaker reflectors associated with the natural soil column below—an observation similar to the GPR response in the sections from the grid lines inside the church.

A strong, nearly flat reflection is observed in many of the grid lines (Figure 4). This may be associated with the stone ground-floor surface of the previous structure.

Figure 5 shows selected depth slices from the 3D GPR image volume in which the lineations associated with the foundation walls can be detected.

The geometry of a cistern beneath the inner narthex of the church, which we discovered previously during a 2D reconnaissance GPR survey (Yilmaz and Eser, 2005), was also delineated. A vaulted structure 60 m long and 5 m wide is evident (Figure 6); it is associated with an underground cistern that supplied water for the church. The average depth of the ceiling of this underground structure is 1 m below the ground level. The structure, however, has been displaced and distorted in the lateral and vertical directions over the centuries. The reflection from the base of the structure exhibits a velocity pull-up in time; this suggests that the interior of the structure is filled with air. This was later verified by an archaeologist who went down into the cistern and took a picture of the interior.

The seismic survey at St. Sophia

At each of the 11 locations (KS01–KS11) within the project site (Figure 7), a receiver spread with 48 4.5-Hz vertical geophones (mounted on alloy shoes) was deployed at 1-m and 0.5-m intervals, depending on the spatial limitations (Figure 8). A handheld hammer and an aluminum plate with a soft rubber cushion to prevent damage to the floor marbles was the energy source. Three shot records were acquired with source locations at each end of the spread and at the center of the spread (Figure 9).

By applying a nonlinear traveltime tomography (Zhang and Toksoz, 1998) to the first-arrival times picked from the three shot records, a near-surface P-wave velocity-depth model was estimated along the receiver spread at each of the 11 locations. By applying smoothing during the inversion and lateral averaging after the inversion, a P-wave velocity-depth profile down to a depth of 20 m representative of each location was subsequently obtained.

Next, the off-end shot record with the most pronounced dispersive surface-wave pattern was used in a plane-wave decomposition to transform the data from the offset-time to phase-velocity versus frequency domain to compute the dispersion spectrum (Figure 10). A dispersion curve associated with the fundamental mode of Rayleigh-type surface waves was picked in the transform domain based on the maximum-energy criterion and inverted to estimate the S-wave velocity as a function of depth (Figure 10) (Park et al., 1999; Xia et al., 1999). Following the analysis of refracted waves to estimate the P-wave velocities and the analysis of surface waves to estimate the S-wave velocities at each of the 11 locations, they were assigned to the receiver spread centers and velocity contour maps generated for depth levels 0–20 m at 4-m intervals (Figure 11).

Conclusions

From the 3D GPR survey at the Great Church of St. Sophia, the geometry of the foundation remnants of the previous structure that existed at the same site, mixed with the landfill which we know exists at the site from the construction history of the current structure, was inferred. In addition,
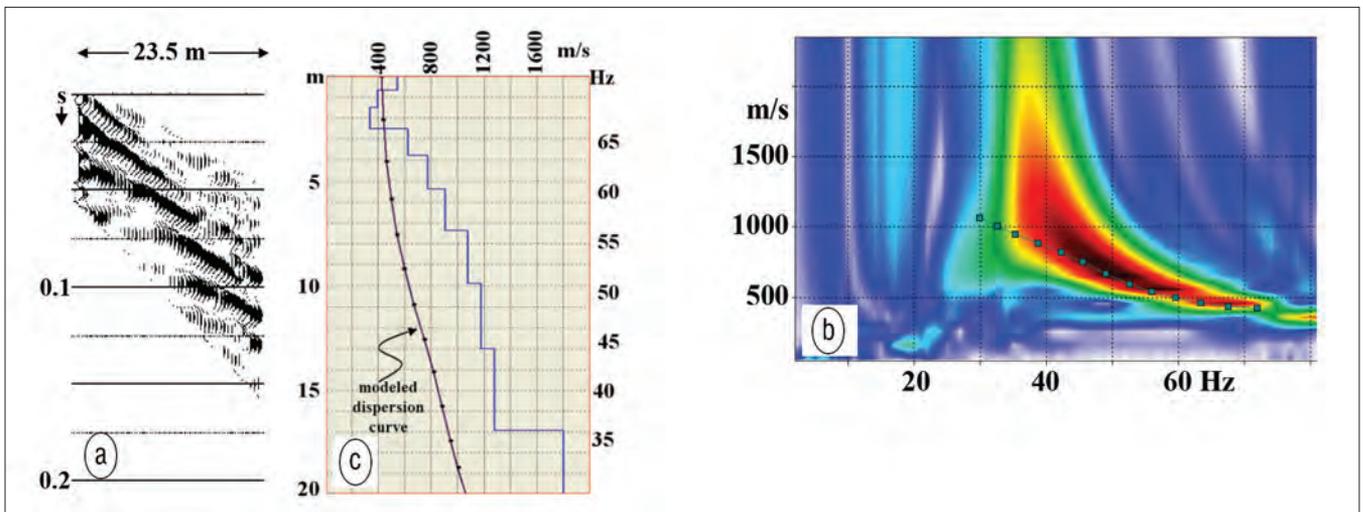

Figure 10. (a) An end-on shot record from one of the KS locations; (b) the dispersion spectrum with the picked fundamental mode of the Rayleigh waves; and (c) the S-wave velocity-depth profile.
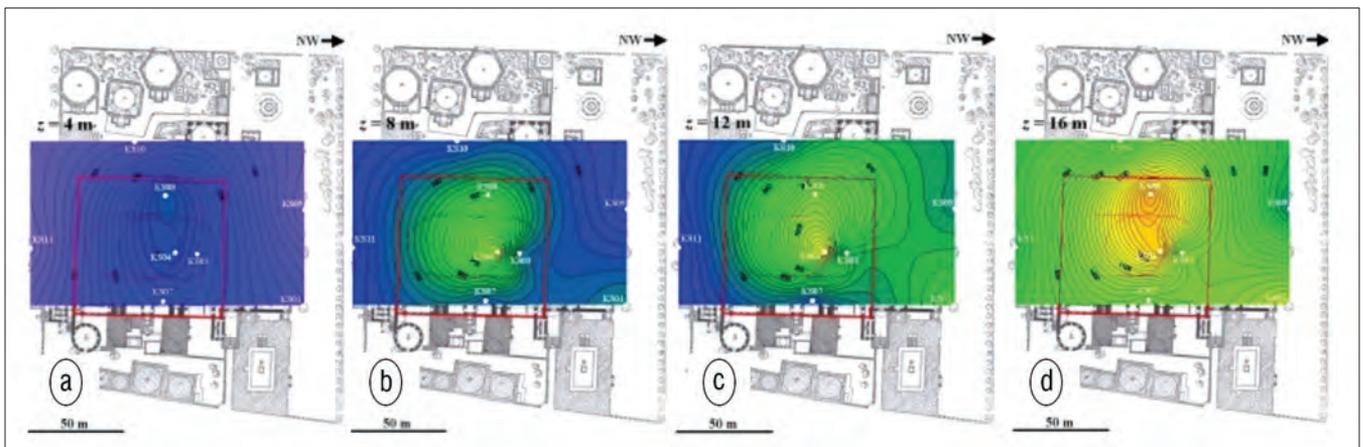

Figure 11. Depth slices from the S-wave velocity depth model at depths of (a) 4 m, (b) 8 m, (c) 12 m, and (d) 16 m. The lowest velocity is 200 m/s (dark blue) and the highest velocity is 1200 m/s (yellow).

the geometry of the cistern, discovered beneath the inner narthex during a previous 2D reconnaissance GPR survey, was delineated.

The shallow seismic survey allowed estimation of the P- and S-wave velocity models beneath the foundations of the church. Except for the shallow depth range (0–6 m), the S-wave velocities are greater than 700 m/s which indicates that the church was built upon a strong bedrock. *TLE*

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