2025 IMEKO TC26 International Conference on
Metrology for Archaeology and Cultural Heritage
Bergamo, Italy, October 15-17, 2025

Post-earthquake structural assessment using Ground Penetrating Radar (GPR): preliminary insight for guidelines from literature review

Antonio Minervino Amodio[1], Giovanni Leucci[2], Fabrizio Terenzio Gizzi[1]

[1] *National Research Council (CNR), Institute of Heritage Science (ISPC), Tito (Potenza), Italy,*
[2] *National Research Council (CNR), Institute of Heritage Science (ISPC), Lecce, Italy*
antonio.minervinoamodio@cnr.it, giovanni.leucci@cnr.it, fabrizioterenzio.gizzi@cnr.it

Abstract **– Ground Penetrating Radar (GPR) is a Non-Destructive Testing (NDT) technique for quick and reliable post-earthquake structural assessment of buildings. GPR allows for identification of internal, hidden damage like cracks, voids, delaminations, and measurements of reinforcement integrity, which are often missed by visual inspections. Effective use of GPR depends upon careful planning, such as proper selection of antenna frequency depending upon the target and material being analysed. Though prompt and flexible, GPR has limitations such as shallow penetration in conductive targets and complex data interpretation. Therefore, integration with other NDT techniques can be required for a comprehensive and reliable building diagnosis. Standardized guidelines can support the reliability and effectiveness of GPR use in post-earthquake assessment. In this perspective, the article aims to provide some initial results through the analysis of literature in the field.**

I. INTRODUCTION

The destructive impact of seismic events on civil infrastructure and, in particular, buildings [1], imposes the need for damage assessment procedures that are both rapid and reliable. In the immediate post-earthquake phases, the ability to discern the state of safety and fitness of buildings is crucial for the management of rescue operations, the securing of affected areas, and the initiation of medium- and long-term recovery and reconstruction processes [2]. Timely and accurate assessment not only prevents further human losses due to secondary collapse or the use of unstable structures, but also has profound socioeconomic implications, directly affecting the recovery time of communities and the resilience of the urban fabric [3]. Purely visual inspections, although the first expeditious approach, have intrinsic limitations, as they often fail to detect internal, hidden but potentially critical damage to structural stability. Non-surface-emergent cracking elements, internal detachments, voids or damage to reinforcement may escape an exterior examination, compromising the validity of the assessment [4, 5]. In this scenario, Non-Destructive Testing (NDT) emerges as irreplaceable diagnostic tools, capable of "looking" inside materials and structures without altering their physical integrity [6,7]. Among the various NDTs, Ground Penetrating Radar (GPR) has emerged as one of the most versatile and effective techniques for inspecting concrete and masonry elements. GPR uses pulses of high-frequency electromagnetic waves to probe the subsurface or interior of materials, generating images (radargrams) that represent changes in the electromagnetic properties encountered [8]. In the specific context of post-seismic assessment, GPR offers significant advantages: it is a non-invasive technique, a crucial aspect for historic buildings or when the aim is to avoid inducing further damage to already vulnerable structures; it allows relatively rapid data acquisition over large areas; and it can detect a wide range of internal defects such as cracks, voids and cover delaminations. Despite its recognized potential, the application of GPR in post-earthquake scenarios needs a rigorous and standardized methodological approach to maximize its effectiveness and ensure the reliability of results [2]. This paper aims to providing a framework and operational guidelines for the use of GPR in post-earthquake structural analysis. The goal is to provide a tool that can assist structural engineers, diagnosticians, and technical specialists in planning, executing, processing, and interpreting GPR surveys in order to improve the quality and consistency of damage assessments.

II. PRINCIPLES OF GPR AND DETECTION OF STRUCTURAL DAMAGE

Understanding the physical principles governing GPR is prerequisite to its proper application and reliable interpretation of acquired data, especially in the complex scenario of seismic damage assessment. The basic principle of GPR is to send short pulses of high-frequency electromagnetic (EM) waves into the material (e.g., concrete, masonry). When a wave encounters an interface between materials with different electromagnetic properties, some of the energy is reflected and recorded by an antenna [4]. The time taken by the wave to return (bidirectional propagation time) is related to the depth of the reflection. The amplitude and polarity of the reflected signal give information about the contrast between materials at the interface [9]. The data are displayed in radargrams (B-scan profiles). The properties of materials that affect GPR wave propagation are mainly dielectric permittivity (ϵ), which affects propagation velocity, and electrical conductivity (σ), which causes attenuation and limits depth. Variations in ϵ between adjacent materials (such as concrete and air/water in a crack) cause reflections [4]. Materials with high conductivity (e.g., wet or contaminated concrete) strongly attenuate the signal [10]. Metal elements are strong reflectors because of their high conductivity and magnetic permeability. Seismic damage makes damage detectable because it locally modifies these electromagnetic properties. The GPR can detect different types of seismic damage: internal cracks and detachments between facings that are detectable as interruptions of reflections or anomalies; internal voids and disorganization of texture, identified by disordered signals, strong reflections from voids, or high attenuation; presence of metal elements are detected with strong reflectors; detachment of plaster detectable as surface reflection.

III. METHODS

In order to select the proper documents to be analysed, the Scopus database was utilized. Scopus is one of the global largest and most extensive multidisciplinary databases of peer-reviewed, academic publications, with over 22,000 journals published by almost 5,000 global publishers, in addition to books, conference papers and patents. There are over 330 disciplines covered and over 40 languages in which content appears, providing a powerful set of tools for the analysis and visualization of global output (https://www.elsevier.com/products/scopus, accessed, 29 May 2025). We used the following keywords to extract documents such as "GPR" (and its variants in the spelling the word) "earthquake", "building", "heritage", "church", and "cathedral". To ensure the dataset was accurate and free of false positives, the titles and abstracts of all retrieved documents were manually reviewed and assessed. Subsequently, a detailed selection process involved creating a table to systematically extract and compare information from each paper, including authors and year, purpose of the work, materials analyzed, antenna frequencies employed, achieved investigation depths, acquisition locations, and type of building. Through this search criteria one hundred relevant documents were identified. In examining the selected documents, we specifically focusing on antenna types and frequency used for investigating buildings and monuments, particularly in contexts related to earthquake assessment. In addition, useful information was extracted to provide guidance for the acquisition of GPR data starting from planning through data processing. Here we report some initial evidence from the preliminary literature review.

IV. RESULTS AND DISCUSSION

The effectiveness of a GPR survey depends critically on rigorous planning, accurate data acquisition, and informed processing and interpretation [5, 11, 12, 13]. For the planning phase it is essential to start by gathering as much information as possible about the building, including its structural type, the time of construction, the history of interventions, and existing documentation such as drawings or previous reports [14]. In parallel, it is essential to acquire data on the seismic event that struck the site, such as recorded intensity and ground acceleration values, if available. This prior knowledge is vital for understanding the likely seismic behavior of the structure and making assumptions about the most expected damage, guiding the investigation strategy. A critical aspect of planning is the choice of antenna and frequency. There is an inverse relationship between antenna frequency, penetration depth, and resolution. In general, antennas with:

A. *High frequencies (>1 GHz): Offer high resolution for small, superficial details (e.g., thin cracks, cover-over, surface rebar) but have limited depth.*
B. *Low frequencies (< 250 MHz): They penetrate deeper (e.g., massive masonry, foundations) but have lower resolution.*

Depth is also severely limited in wet, clay or conductive materials, especially at high frequencies. The choice of frequency must therefore be weighed against the type of damage being sought and the material of the structure. Table 1 shows part of the results obtained from the selection of papers from the main database

Table 1. Column A specifies the antenna frequency range (Hz), Column B lists the application filed, Column C details the typical vertical resolution, and Column D provides the references.

A	B	C	D
1000 to 2600	To estimate shallow and sub-surface cracks, thin delaminations, concrete cover thickness, shallow rebar location, very shallow voids	mm to cm	[1, 2, 4, 5, 15, 16, 17, 18, 19]
400 to 900	To rebar mapping, moderate internal cracks, medium-sized voids, element thickness (e.g., slabs, thin walls), plaster detachment	cm	[20, 21, 22, 23, 24, 25, 26, 27]
< 200	Geometry of deep foundations, extensive voids in foundation soil, mapping of underground cavities	dm to m	[6, 9, 28, 29, 30, 31, 32, 33]

The data reveals a clear inverse correlation between the antenna frequency used and the depth of investigation, as well as a direct correlation between frequency and vertical resolution. Higher frequencies (1000-2600 MHz) offer higher resolution (mm-cm) but are limited to shallow investigations and the detection of small-sized defects. As the frequency decreases (400-900 MHz and <200 MHz), the penetration capability increases, allowing for the analysis of deeper structures and larger elements, albeit at the cost of a progressive reduction in vertical resolution (cm to dm-m, respectively). This study, therefore, provides some operational guidelines for selecting the appropriate antenna frequency range based on the specific objective of the non-destructive investigation and the dimensional characteristics of the targets to be investigated. Further details and specific methodologies are contained in the cited references. In addition to selecting the appropriate antenna planning also includes defining a scan grid (regular and dense for detailed mapping) and setting acquisition parameters (number of samples, time window, stack) [34]. The field data acquisition phase in a damaged building presents several difficulties. In general, in masonry structures, the investigation aims to assess the integrity of the faces, the internal composition, and the connection between elements. Internal lesions, detachments between faces and internal voids, or disorganization of the texture (which can generate disordered or high-attenuation signals) can be identified.

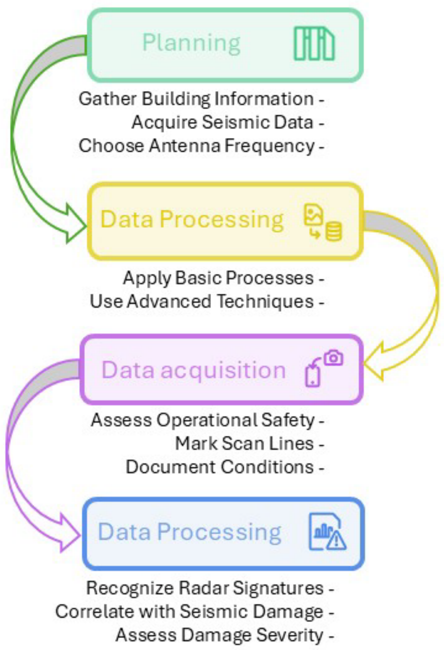

Fig. 1. Workflow description for the GPR data

Vaults and arches can be inspected and metal elements such as tie rods can be located. Scan lines should be marked and documented photographically, possibly georeferenced, also noting environmental and surface conditions that may affect the data. Next, raw data requires processing to improve its quality and facilitate interpretation. Basic processes include zero-time correction, removal of low frequencies, application of gain to compensate for attenuation with depth, and filtering (bandpass, background subtraction) to reduce noise. Advanced techniques such as migration help focus reflections and correct position reflectors. Analysis of individual reflectors can reveal changes in materials and creating time-slices or amplitude maps from dense grids allows visualization of the areal extent of anomalies. Processing is an iterative process that requires the operator to understand the effect of each step. The most critical phase is data interpretation and damage diagnosis. It requires experience in GPR, but also structural knowledge and knowledge of seismic damage mechanisms. It consists of recognizing typical radar signatures and associating them with structural defects: hyperbolas are typical of rebar or piping and breaks or distortions may indicate damage; planar reflections indicate extensive interfaces such as delaminations or cracks parallel to the surface; areas of strong attenuation suggest conductive or highly fractured material; a chaotic signal may indicate disaggregated masonry or crushed concrete. The goal is to correlate these radar signatures with seismic damage types (cracks, voids, delaminations, detachments, etc.), aided by 2D and 3D visualizations. Damage severity is assessed by the extent, continuity, and depth of the anomaly, and the magnitude of the reflection, being able to correlate the results with damage classification scales. Figure 1 shows and summarizes the different steps described above.

V. CONCLUSIONS

Ground Penetrating Radar (GPR) is a valuable diagnostic resource for post-earthquake structural assessment, providing crucial information on the internal state of building elements often inaccessible to visual inspection, and the presented operational guidelines aim to offer a structured methodological framework to maximize its effectiveness in critical seismic emergency contexts. The aim of the guidelines , for which we have set out some preliminary indications here, is emphasize accurate survey planning based on preliminary building knowledge and specific assessment objectives, the careful choice of GPR antenna frequency relative to damage types and structural materials, and specific data acquisition procedures for reinforced concrete and masonry elements, alongside critical data processing and interpretation that integrates geophysical and structural engineering expertise. This organized methodology is strategically significant as it enhances survey objectivity and reproducibility, diagnostic information consistency and reliability, stakeholder communication, and more informed building safety, usability, and repair or retrofitting decision-making. Principal recommendations for decision-makers and operators are providing GPR technicians with specialist training in seismic engineering, material response, and damage mechanisms of structures, as opposed to merely instrument operation, as well as meticulous planning prior to survey with clear objectives and suitable strategies; a multi-technology strategy by combining GPR with other NDT and minimally invasive tests; the effective and judicious use of GPR data processing techniques with the requirements for experienced staff capable of relating radar signs with seismic damage and critically assessing ambiguity; and strict record keeping throughout the survey phase for traceability and validation purposes. Extensive experimental validation in the seismically tested structural elements in the future would be required for more precise correlations between GPR signs and damage, the development of Artificial Intelligence and Machine Learning algorithms for automated damage detection in GPR radargrams, national and international GPR application protocol standardization in the seismic field, and advanced GPR data integration, such as 3D damage modeling, into Building Information Modeling (BIM) modules. Overall, the general use of sound GPR operational procedures can boost societal resilience in the occurrence of seismic events by allowing faster, more precise, and more certain building health diagnosis, thus allowing more timely, suitable, and informed public safety, reconstruction resource allocation, and building stock and city infrastructure overall resilience in the face of seismic events.

Funding. This research received external funding from the Project CHANGES Spoke 7 financed by PNRR (Missione 4 Componente 2, dalla ricerca all'impresa; Linea di Investimento 1.3—Partenariati allargati estesi a università, centri di ricerca, imprese e finanziamento progetti di ricerca di base; finanziato dall'Unione Europea—NextGenerationEU, Piano Nazionale di Ripresa e Resilienza—CUP B53C22003890006).

REFERENCES

[1] D.Ranalli, M.Scozzafava, M.Tallini, "Ground penetrating radar investigations for the restoration of historic buildings: the case study of the Collemaggio Basilica (L'Aquila, Italy)", J. Cult. Herit. 5 (1), 2004, pp. 91–99.

[2] R.Apdeni, Z.Citra, F.Rifwan, P.Y.Putri, N.Sandra, Y.Malinda, P.D.Wibowo, R.F.Ashadi, A.P.Melinda, "Application of ground penetrating radar for evaluating foundation structure condition after earthquake", Teknomekanik, 7(1), 2024, pp. 85–100.

[3] M.Guadagnuolo, G.Faella, A.Donadio, L.Ferri, "Integrated evaluation of the Church of S. Nicola di Mira: Conservation versus safety", NDT & E International, 68, 2014, pp. 53-65.

[4] B.Johnston, A.Ruffell, J.McKinley, P.Warke, "Detecting voids within a historical building façade: A comparative study of three high frequency GPR antenna", Journal of Cultural Heritage, 32, 2018, pp.117-123.

[5] C.C.Yalçıner, Y.C.Kurban, E.Altunel, "Research using GPR into the cause of cracks and depressions in the floor of the gallery of Hagia Sophia Museum", Construction and Building Materials, 139, 2017, pp. 458-466.

[6] R.Martorana, P.Capizzi, C.Giambrone, L.Simonello, M.Mapelli, A. Carollo, V. Genco, "The "Annunziata" Garden in Cammarata (Sicily): Results of integrated geophysical investigations and first archaeological survey", Journal of Applied Geophysics, 227, 2024.

[7] F.T.Gizzi, G.Leucci, "Global Research Patterns on Ground Penetrating Radar (GPR)", Surveys in Geophysics, 39, 2018, pp. 1039-1068.

[8] T.B.Kelly, M.N.Angel, D.E.O'Connor, C.C.Huff, L.E.Morris, G.D.Wach, "A novel approach to 3D modelling ground-penetrating radar (GPR) data – A case study of a cemetery and applications for criminal investigation", Forensic Science International, 325, 2021.

[9] N.Işık, F.M.Halifeoğlu, S.İpek, "Detecting the ground-dependent structural damages in a historic mosque by employing GPR", Journal of Applied Geophysics, 2022.

[10] K.Labropoulos, A.Moropoulou, "Ground penetrating radar investigation of the bell tower of the church of the Holy Sepulchre", Construction and Building Materials, 47, 2013, pp. 689-700.

[11] G.Leucci, "Nondestructive Testing for Archaeology and Cultural Heritage: A practical guide and new perspective", Springer, 2019, pp. 217, ISBN 978-3-030-01898-6.

[12] G.Leucci, "Advances in Geophysical Methods Applied to Forensic Investigations: New Developments in Acquisition and Data Analysis Methodologies", Springer, 2020, pp. 200, ISBN 978-3-030-46241-3.

[13] F.Giannino, G.Leucci, "Electromagnetic Methods in Geophysics: Applications in GeoRadar, FDEM, TDEM, and AEM", Wiley, 2021, pp. 359, ISBN: 978-1-119-77098-5.

[14] W. Zhao; E. Forte; S.T.Levi; M.Pipan; G.Tian; "Improved high-resolution GPR imaging and characterization of prehistoric archaeological features by means of attribute analysis", Journal of Archaeological Science, 54, 2015, pp. 77-85.

[15] D.C.B.Cintra, P.M:B.Manhaes, F.M.C.P.Fernandes, D.M.Roehl, J.T.Araruna Junior, E.S.Sa´nchez Filho,

Evaluation of the GPR (1.2 GHz) technique in the characterization of masonry shells of the Theatro Municipal do Rio de Janeiro, Revista IBRACON de Estruturas e Materiais, 13(2), 2020, pp. 274-297.
[16] V.Perez-Gracia, J.O.Caselles, J.Clapes, G.Martinez, R.Osorio, "Non destructive analysis in cultural heritage buildings: Evaluating the Mallorca cathedral supporting structures", NDT & E International, 2013, 59, pp. 40-47.
[17] C.C.Yalçıner, A.Büyüksaraç, Y.C.Kurban, "Non-destructive damage analysis in Kariye (Chora) Museum as a cultural heritage building", Journal of Applied Geophysics, 171, 2019.
[18] M.Solla, S.Laguela, N.Fernandez, I.Garrido, "Assessing Rebar Corrosion through the Combination of Nondestructive GPR and IRT Methodologies", Remote Sensing, 11, 2019.
[19] M.Rucka, E.Wojtczak, M.Zielinska, "Interpolation methods in GPR tomographic imaging of linear and volume anomalies for cultural heritage diagnostics", Measurement, 154, 2020.
[20] V.Perez-Gracia, S.Santos-Assuncao, O.Caselles, J.Clapes, V.Sossa, "Combining ground penetrating radar and seismic surveys in the assessment of cultural heritage buildings: The study of roofs, columns, and ground of the gothic church Santa Maria del Mar, in Barcelona (Spain), Structural Control and Health Monitoring, 26(4), 2019.
[21] R.Cataldo, A.De Donno, G.De Nunzio, G.Leucci, L.Nuzzo, S.Siviero, "Integrated methods for analysis of deterioration of cultural heritage: The Crypt of \Cattedrale di Otranto\, Journal of Cultural Heritage, 6(1), 2005, pp. 29-38.
[22] G.Leucci, L.De Giorgi, I.Ditaranto, I Miccoli, G.Scardozzi, "Ground penetring radar prospections in Lecce Cathedral: New data about the crypt and the structures under the church, Remote Sensing, 13(9), 2021.
[23] M.Matias, F.Almeida, R.Moura, N.Barraca, High resolution NDT in the characterization of the inner structure and materials of heritage buildings walls and columns", Construction and Building Materials, 267, 2021.
[24] V.Perez Gracia, J.A.Canas, L.G.Pujades, J. Clapes, O.Caselles, F.Garcıa, R.Osorio, "GPR survey to confirm the location of ancient structures under the Valencian Cathedral (Spain), Journal of Applied Geophysics, 43, 2000, pp. 167-174.
[25] D.F.Barbolla, I.Ferrari, F.Giuri, I.Miccoli, G.Scardozzi, V.Ferrari, G.Leucci, "Multichannel GPR and multi-depth electromagnetic surveys for the study of *Villa Eucheria* and *Aquinum* at Castrocielo (Frosinone, Central Italy), Journal of Applied Geophysics, 228, 2024.
[26] C.Balkaya, Y.L.Ekinci, O.Çakmak, M.Blömer, "A challenging archaeo-geophysical exploration through GPR and ERT surveys on the Keber Tepe, City Hill of Doliche, Commagene (Gaziantep, SE Turkey)", Journal of Applied Geophysics, 186, 2021.
[27] S.Yilmaz, C.Balkaya, O.Çakmak, E. Oksum, "GPR and ERT explorations at the archaeological site of Kılıç village (Isparta, SWTurkey)", Journal of Applied Geophysics, 170, 2019.
[28] J.Ortega-Ramírez, M.Bano, M.T.Cordero-Arce, L.A.Villa-Alvarado, C.Chavez Fraga, "Application of non-invasive geophysical methods (GPR and ERT) to locate the ancient foundations of the first cathedral of Puebla, Mexico. A case study", Journal of Applied Geophysics, 174, 2020.
[29] G.Silva Cezar, P.L.Ferrucio da Rocha, A.Buarque, A.Costa, "Two Brazilian archaeological sites investigated by GPR: Serrano and Morro Grande", Journal of Applied Geophysics, 47, 2001, pp. 227-240.
[30] M.G.Drahor, M.A.Berge, C.Öztürk, "Integrated geophysical surveys for the subsurface mapping of buried structures under and surrounding of the Agios Voukolos Church in _Izmir, Turkey", Journal of Archaeological Science, 38, 2011, pp. 2231-2242.
[31] M.Bini, A.Fornaciari, A.Ribolini, A.Bianchi, S.Sartini, F.Coschino, "Medieval phases of settlement at Benabbio castle, Apennine mountains, Italy: evidence from Ground Penetrating Radar survey", Journal of Archaeological Science, 37, 2010, pp. 3059-3067.
[32] U.Boniger, J.Tronicke, "Improving the interpretability of 3D GPR data using target–specific attributes: application to tomb detection", Journal of Archaeological Science, 37, 2010, pp.672-679.
[33] K.Grzyb, L.drobiec, J.Zajac, K.Drobiec, "Preliminary assessment of structural masonry damage in Malbork Caste", Case Studies in Construction Materials, 22, 2025.
[34] A.Calia, M.Lettieri, G.Leucci, L.Matera, R.Persico, M.Sileo, The mosaic of the crypt of St. Nicholas in Bari (Italy): integrated GPR and laboratory diagnostic study", Journal of Archaeological Science, 40(12), 2013, pp. 4162-4169.