

Automated Rebar Recognition and Evaluation Through Hyperbolic Fitting and Signal Analysis of Ground Penetrating Radar GPR Data

Wael Zatar and Hien Nghiem

ABSTRACT

Precise rebar spacing and depth determination are essential for evaluating the integrity and load-bearing capacity of reinforced and prestressed concrete structures. Traditional manual interpretation of ground penetrating radar (GPR) data can be time-consuming and inconsistent, particularly when dealing with complex radargram signals. This study presents an automated rebar-picking method that employs hyperbolic fitting and positive peak signal analysis to enhance the accuracy of rebar detection. The developed algorithm processes GPR data by identifying hyperbolic reflections and extracting amplitude values from the peaks of these hyperbolas. It then compares these values to theoretical hyperbolas. A user-defined threshold is incorporated to enhance reliability, enabling users to adjust acceptable deviations. The algorithm constrains the difference between the detected hyperbolic amplitude patterns and the theoretical hyperbolas to 80 percent, accommodating a certain level of noise or signal variations. Once a rebar is identified, the algorithm automatically determines its location. Controlled experiments were conducted on a prestressed concrete beam to validate the method, during which GPR data was collected and analyzed. The results show that the algorithm achieves over 90 percent accuracy, successfully detecting and localizing most rebars. Additionally, field scans of prestressed concrete box beams confirm the efficacy of this method in determining rebar spacing and depth, even in challenging conditions involving signal noise or overlapping reflections. The findings demonstrate that this proposed method significantly enhances GPR non-destructive evaluation techniques by improving efficiency, precision, and repeatability while reducing the need for manual interpretation. Furthermore, the study highlights the potential of automated hyperbola based GPR analysis in structural health monitoring, offering a reliable and scalable solution for rebar detection in reinforced and prestressed concrete bridge infrastructure.

Wael Zatar, Marshall University, Huntington, WV 25755, USA

Hien Nghiem, Marshall University Research Corporation, Huntington, WV 25755, USA

INTRODUCTION

Bridge inspection is crucial for ensuring public safety and economic stability in the United States. The field inspection process typically involves quick, cost-effective visual evaluations and simple on-site tests to assess the structural integrity of bridges. However, these traditional methods often fail to detect internal defects, particularly in reinforced and prestressed concrete members, and can be subjective. This subjectivity can lead to inconsistent assessments due to varying judgments among inspectors [1-2]. Non-destructive testing and evaluation (NDT&NDE) techniques have been popular in complementing traditional visual inspections. These methods provide rapid and reliable assessments of bridge conditions without causing damage or disrupting traffic, making them valuable tools for inspection and maintenance [3-4].

Ground-penetrating radar (GPR), initially developed for geophysical soil exploration, began to be used in the 1990s for inspecting reinforced concrete structures. GPR employs a high-frequency antenna to emit electromagnetic pulses that reflect off embedded objects. A computer then interprets these signals. GPR has been utilized to assess bridge decks [5], identify rebar layout and size [6-8], evaluate concrete cover and slab thickness [9], among other applications [10-12].

The analysis and interpretation of GPR data can be complex and time-consuming, requiring significant expertise and computational effort to extract meaningful insights. A fully automated GPR data interpretation system to identify embedded rebars could effectively address this challenge. Zatar et al. [13] presented an innovative methodology using curve fitting principles to simultaneously determine the horizontal location, depth, concrete cover, and size of rebars.

AUTO REBAR PICKING

The hyperbolic shape observed in a radargram of GPR data represents the reflection signal from rebar embedded in concrete structures. The theoretical equations for the hyperbola are based on two key assumptions [11]:

- The reflected wave's positive peaks correspond to the transmitted wave's negative peaks, indicating a phase reversal.
- Reflections occur at the surface of the rebar along the shortest two-way travel path. The length of the travel path for the signal reflected from the rebar can be determined using the equations illustrated in Figure 1:

$$L_1 = \sqrt{(z)^2 + \left(X - \frac{S}{2}\right)^2} \quad (1a)$$

$$L_2 = \sqrt{(z)^2 + \left(X + \frac{S}{2}\right)^2} \quad (1b)$$

where: $X = x_p - x$ is the distance in the horizontal direction between the rebar and the center line of the transmitter and receiver (T-R); z is the depth of the rebar center; S is the spacing of the transmitter and receiver (T-R offset); x_p is the horizontal coordinate of the rebar; x is horizontal coordinate of the antenna.

In considering the peak point of the hyperbola, the two-wave travel time is expressed in Equation (2) as follows:

$$t_p - t_0 = \frac{\sqrt{4z^2 + S^2}}{v_s} \quad (2)$$

where t_0 is time zero and t_p is the time corresponding to the peak of the hyperbola. Consider a point on the hyperbola (t_i), the two-wave travel time can be obtained by employing Equation (3):

$$t_i - t_0 = \frac{L_1 + L_2}{v_s} \quad (3)$$

Substituting Equation (1) and Equation (2) into Equation (3) results in produces Equation (4):

$$t_i = (t_p - t_0) \frac{\sqrt{(z)^2 + (x - \frac{S}{2})^2} + \sqrt{(z)^2 + (x + \frac{S}{2})^2}}{\sqrt{4z^2 + S^2}} + t_0 \quad (4)$$

Equation (4) defines the theoretical hyperbolic curve produced by rebars in reinforced concrete, demonstrating minimal variation across different rebar sizes. The developed algorithm analyzes GPR radargrams by detecting hyperbolic shapes and extracting their peak amplitudes. These amplitudes are then compared to the theoretical curve using a sum of squared differences (R^2). To enhance detection accuracy, users can set a threshold (Q); in this study, the difference was limited to 80%. Once the rebars are identified, the algorithm automatically calculates their depth and location.

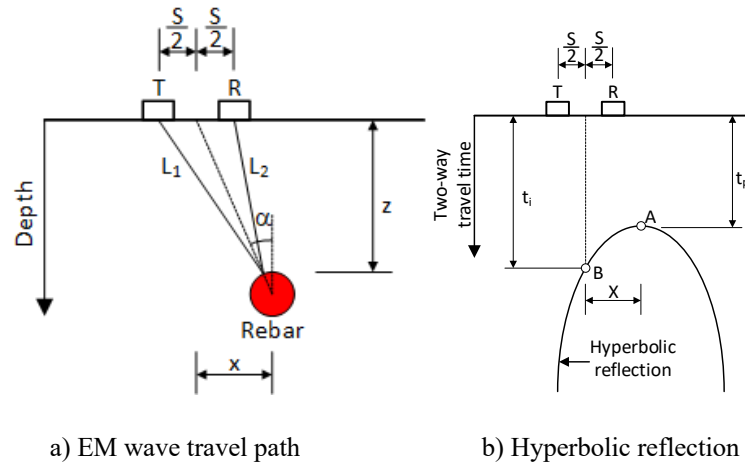


Figure 1. Reflected electromagnetic wave from a rebar [13].

EXPERIMENTAL PROGRAM

This study focused on determining rebar depth and spacing in bridge beams by analyzing electromagnetic wave travel times from GPR scans. A Delphi-based graphical tool was created to automatically detect hyperbolic reflections and compute rebar locations using best-fit equations. The method demonstrated efficiency and reliability in estimating rebar positions, showcasing GPR's capabilities and advancements in non-destructive testing for bridge inspection and maintenance.

A precast, prestressed concrete box beam from a decommissioned bridge, the Toms Creek Bridge, in Cabell County, West Virginia, was provided by the West Virginia Division of Highways. The beam has the following dimensions: 32.5 feet in length, 3.0 feet in width, and 17 inches in height, as illustrated in Figure 2. The beam's reinforcement includes four #4 longitudinal rebars at the top, with stirrups spaced 12

inches apart. Additionally, there are two groups of five prestressed tendons at the bottom and one prestressed tendon along the centerline. The beam features two voids, each with a diameter of 10 inches. Figures 2 and 3 display the beam's typical cross-section and plan view.

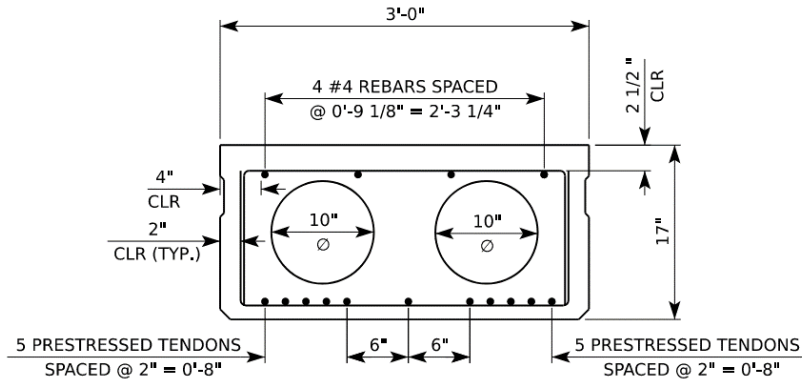


Figure 2. Cross-section of the experimentally tested prestressed concrete box beam.

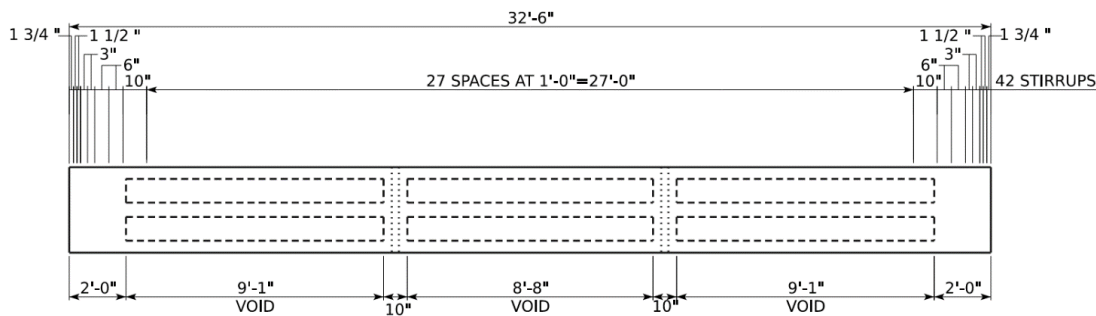


Figure 3. Plan view of the experimentally tested prestressed concrete box beam.

The prestressed concrete box beam underwent comprehensive NDT and non-destructive evaluation (NDE) from all four sides. Various scan lines and directions were used to gather the structural profile information of the beam. The scanning directions varied depending on the specific face being analyzed and the type of data required from beneath the surface. Three longitudinal lines, spaced 11.0 inches apart, were employed to evaluate the proposed algorithm.

FIELD TESTING

Field NDT and NDE were performed on another in-service bridge located in Cabell County, West Virginia, utilizing the technology developed to test the decommissioned Toms Creek Bridge box beam shown in Figure 2 and Figure 3. The in-service bridge consists of six prestressed concrete box beams. Figure 4 shows the cross-section of these beams, while Figure 5 illustrates their dimensions. The beam's cross-section measures 36 inches by 27 inches and features a large void that measures 26 inches by 16 inches. Each box beam is 40 feet (480 inches) long and includes four

full-length rebars and a 9-foot rebar at each end. A concrete cover of 2.5 inches is maintained throughout.

GPR scans were performed in the transverse and longitudinal directions to assess the in-service bridge's structural integrity and condition. This comprehensive evaluation included 39 transverse and 18 longitudinal scans, explicitly focusing on the bridge's six prestressed concrete box beams. The data collected from these assessments provides valuable insights into the prestressed concrete bridge's structural performance and will aid in developing future maintenance strategies.

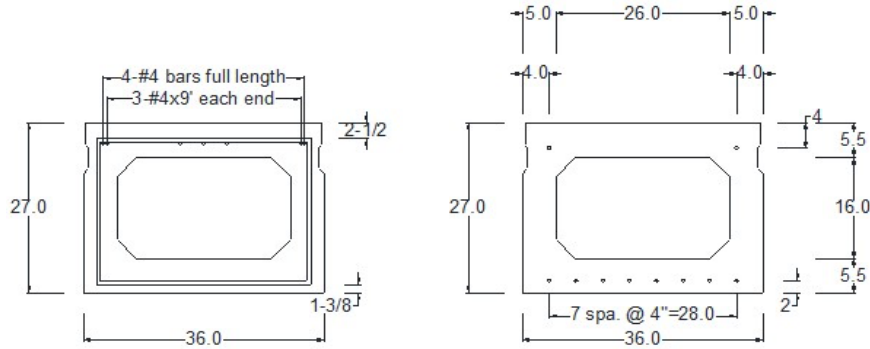


Figure 4. Cross-section of the in-service bridge's prestressed concrete beam.

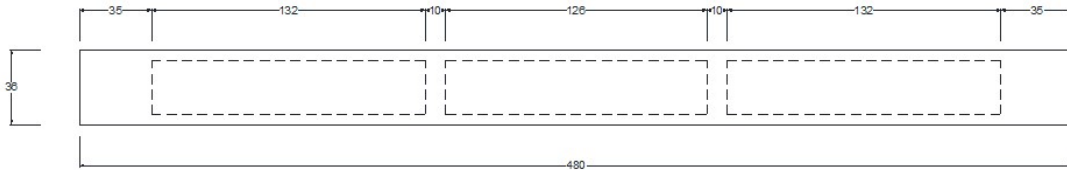


Figure 5. Dimensions of the in-service bridge's prestressed concrete box beam.

RESULTS AND DISCUSSIONS

This study's developed algorithm automatically determines the rebar's depth and spacing, improving both speed and accuracy. The electromagnetic wave velocities crucial for these depth calculations were measured at 5.31 inches per nanosecond (in/ns) for the experimentally tested decommissioned prestressed concrete box bridge beam and 4.92 in/ns for the field-tested in-service bridge box beam. These measurements were obtained by correlating Equations 2 and 3 with the known depth of the steel duct within the concrete box beam. Accurate wave velocity is essential for calculating rebar depth, spacing, and concrete cover from the GPR data.

The radargrams shown in Figures 6 and 7 illustrate the field scans of the top face of the in-service prestressed concrete box beam, capturing the number and locations of the stirrups. Figure 6 displays well-defined hyperbolas along the centerline scan, with minimal noise interference. In contrast, Figure 7 shows increased noise along the scan line above the main rebars due to strong reflections from those rebars. The auto rebar picking (ARP) algorithm successfully detects all stirrups, except those at both ends of the beam, where closely spaced stirrups fail to produce distinct hyperbolas. The ARP missed only three stirrups within the scan line above the main rebars and incorrectly identified one non-stirrup reflection out of 34 detected stirrups.

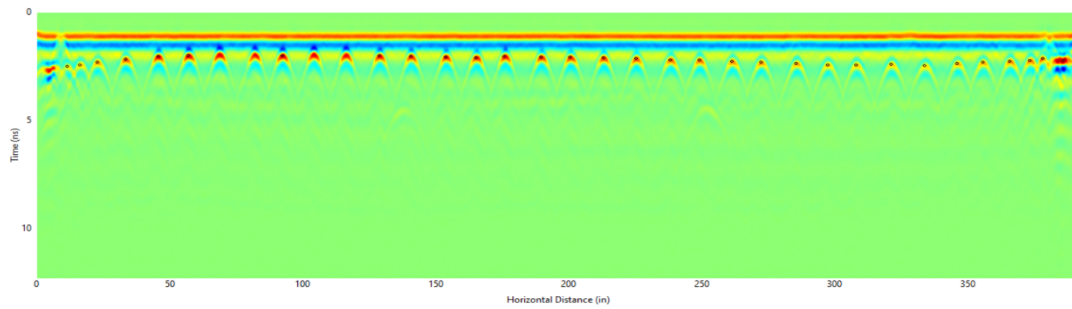


Figure 6. Automatic rebar selection for stirrups during the centerline scan.

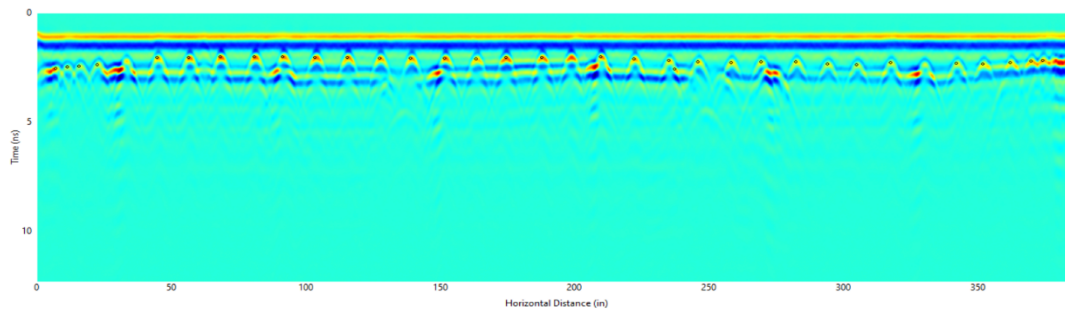


Figure 7. Automatic rebar picking of stirrups for a scan line positioned above the main rebars.

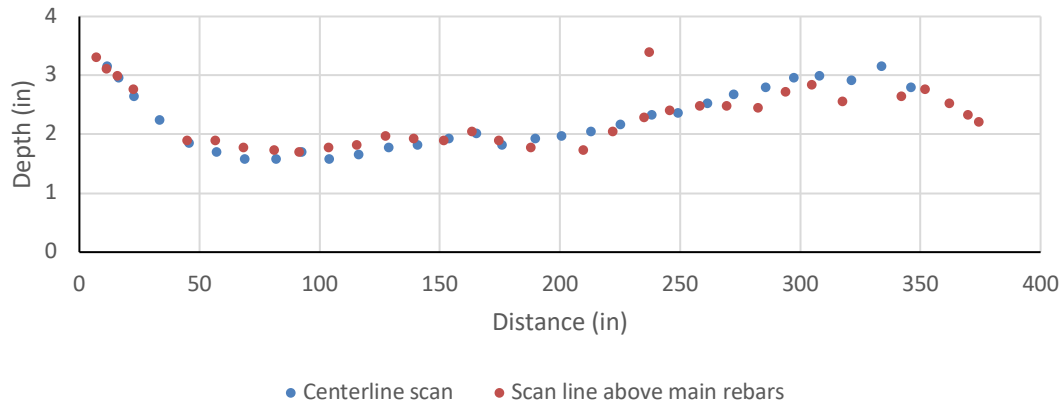


Figure 8. Locations of rebar along the longitudinal direction of the beam.

Figure 9 provides a detailed illustration of the GPR radargram for the in-service prestressed concrete bridge box beams, exhibiting the intricate patterns and signals captured during the scanning process. One notable observation from this diagram is that the stirrups are not consistently positioned at the same depth throughout the bridge. This inconsistency led to a considerable variation in the reflected signals received during the GPR analysis, making interpretation more complex. Despite these challenges, the ARP identified 76 out of 78 hyperbolic patterns associated with the rebar structures. This outcome resulted in only two missed detections and an occurrence of two false positives, as illustrated in Figure 10, underscoring the efficiency and effectiveness of the algorithm in real-world applications.

While the ARP algorithm exhibits certain limitations, particularly in accurately calculating rebar depth and spacing in specific scenarios, it nonetheless embodies a significant advancement over previous methodologies. One of the most notable improvements is its ability to eliminate the need for template selection, which has traditionally been a cumbersome and often subjective process. Historically, reliance on large hyperbola datasets for template comparison posed another challenge; as not all hyperbolic shapes observed in concrete necessarily indicate the presence of rebars, this can lead to a higher incidence of false positives.

In stark contrast, the proposed algorithm leverages typical amplitude patterns derived from rebar reflections, allowing for a more reliable identification process. This shift enhances the detection accuracy and significantly reduces instances of misidentification, providing greater confidence in the analysis results. The improvements reflect a pivotal step forward in non-destructive testing techniques for assessing the condition and integrity of in-service prestressed concrete box beam bridges with large voids.

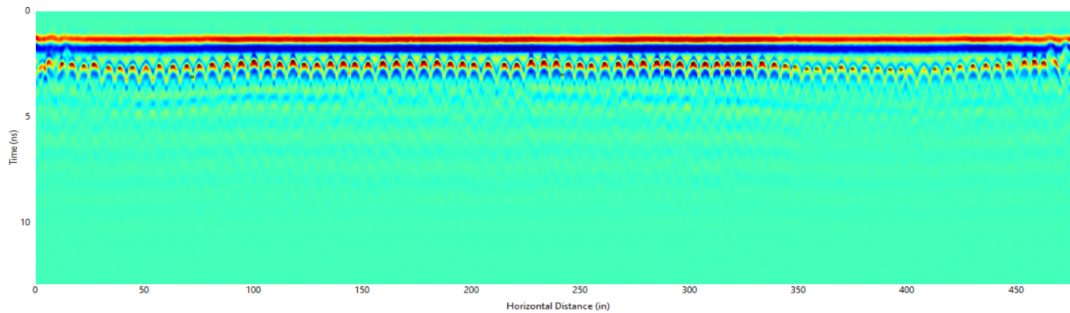


Figure 9. Auto rebar picking for stirrups for the centerline scan.

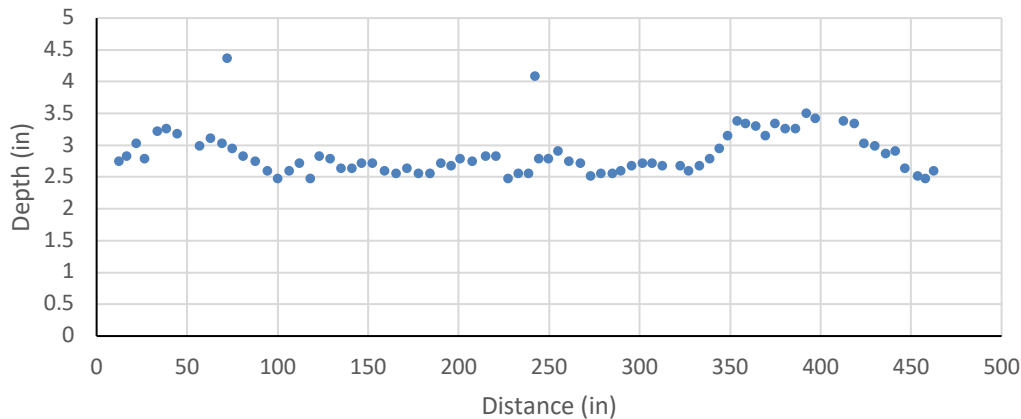


Figure 10. Rebar locations of the in-service bridge.

CONCLUSIONS

The proposed automated method for rebar detection, utilizing this study's hyperbolic fitting and peak signal analysis, significantly enhances the accuracy, reliability, and efficiency of GPR data interpretation. Validation tests on scans of decommissioned and in-service bridge prestressed concrete box beams showed over 90% accuracy in identifying rebar depth and spacing, even in challenging conditions with noise and overlapping reflections. The developed algorithm takes advantage of characteristic

amplitude patterns of rebar reflections, effectively minimizing false positives caused by non-rebar hyperbolas. While minor detection errors occurred in areas with unclear hyperbolic signatures, the method substantially reduces the need for manual interpretation, improves precision, and enhances repeatability. Overall, this approach marks a significant advancement in non-destructive GPR testing and evaluation and offers a scalable and practical solution for the structural health monitoring and maintenance of prestressed concrete bridge infrastructure.

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REFERENCES

1. Nguyen, H. Zatar W., and H. Mutsuyoshi. 2014. "Hybrid fiber-reinforced polymer girders topped with segmental precast concrete slabs for accelerated bridge construction," *Journal of the Transportation Research Record*, Volume 2407, issue 1, pp83-93.
2. Kaiser, H., Karbhari, V.M. and Sikorsky, C., 2004. "Non-destructive testing techniques for FRP rehabilitated concrete. II: an assessment," *International Journal of Materials and Product Technology*, 21(5), pp. 385–401.
3. Zatar, W., Nguyen, H., and H. Nghiem. 2020. "Ultrasonic pitch and catch technique for non-destructive testing of reinforced concrete slabs," *Journal of Infrastructure Preservation and Resilience*, Volume 1, Issue 1, pp1-13.
4. Büyüköztürk, O., 1998. "Imaging of concrete structures," *NDT & E International*, 31(4), pp.233-243.
5. Alani, A.M., Aboutalebi, M. and Kilic, G., 2013. "Applications of ground penetrating radar (GPR) in bridge deck monitoring and assessment," *Journal of Applied Geophysics*, 97, pp.45-54.
6. He, X.Q., Zhu, Z.Q., Liu, Q.Y. and Lu, G.Y., 2009. "Review of GPR rebar detection," *In PIERS proceedings*, pp. 804-813.
7. Hasan, M.I. and Yazdani, N., 2016. "An experimental study for quantitative estimation of rebar corrosion in concrete using ground penetrating radar," *Journal of Engineering*, 2016.
8. Hugenschmidt, J., 2002. "Concrete bridge inspection with a mobile GPR system," *Construction and building materials*, 16(3), pp.147-154.
9. Hasan, M.I. and Yazdani, N., 2014. "Ground penetrating radar utilization in exploring inadequate concrete covers in a new bridge deck," *Case Studies in Construction Materials*, 1, pp.104-114.
10. Zatar, W.A., Nghiem, H.M., and Nguyen, H.D., 2022. "Effects of antenna frequencies on detectability and reconstructed image of embedded objects in concrete structures using ground-penetrating radar," *9th Forensic Engineering Congress*, ASCE.
11. Zatar, W. and Nghiem, H., 2023. "Detectability of embedded defects in FRP strengthened concrete deck slabs," *Risk-Based Strategies for Bridge Maintenance*. CRC Press, pp.221-234.
12. Zatar, W., Nguyen, T., and Nguyen, H., 2022. "Environmental effects on condition assessments of concrete structures with ground penetrating radar," *J. of Applied Geophysics, Elsevier*, Vol. 203.
13. Zatar, W., Nghiem, H. and Nguyen, H., 2024. "Detecting Reinforced Concrete Rebars Using Ground Penetrating Radars," *Applied Sciences*, 14(13), p.5808.