

Article

Detecting Reinforced Concrete Rebars Using Ground Penetrating Radars

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Abstract: A new algorithm is developed to automatically detect rebar locations and diameters of reinforced concrete structures using the ground penetrating radar technique. The study uses two-way travel time and biquadratic equations to formulate electromagnetic wave speed in reinforced concrete structures where hyperbolic signatures are approximated. Leveraging an established algorithm, a computer code has been developed to offer automated analysis of ground-penetrating radar data obtained from survey grids. Four reinforced concrete slabs were designed, fabricated, and tested to validate the developed evaluation approach. The proposed methodology demonstrates outstanding signal processing proficiency and reliably and effectively identifies rebar information.

Keywords: nondestructive evaluation; ground-penetrating radar; rebar depth; rebar diameter; reinforced-concrete structures



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1. Introduction

Concrete bridge structures must undergo proper inspection, maintenance, and rehabilitation to ensure the nation's economy and the traveling public's safety [1–9]. Visual inspection offers a quick, convenient, cost-effective, versatile, and straightforward testing method for the on-site assessment of concrete structures. However, this method usually restricts the inspector's capacity to detect and inspect anomalies, defects, and discontinuities solely on the structural members' surface. It heavily relies on subjective assessments, which can vary significantly from inspector to inspector [10,11]. Therefore, there is a need for more dependable, efficient, and cost-effective testing methods to enhance the rehabilitation and maintenance of concrete structures.

Advanced non-destructive testing and evaluation (NDT & E) techniques are invaluable for assessing deteriorated concrete bridges. They offer fast, cost-effective, and efficient data collection, allowing for reliable condition assessment of existing structures. These techniques are particularly significant because they can be carried out without causing damage to bridge structures or interrupting traffic flow [12,13]. NDT & E of reinforced concrete (RC) structures can involve various techniques, such as acoustic-based methods like impact echo and ultrasonic-pulse velocity, and electromagnetic-based techniques like ground-penetrating radar, infrared thermography, and radiography. Furthermore, the use of electromechanical impedance for real-time monitoring [14–16], fiber optic sensors for corrosion detection [17], distributed optical fiber sensors for crack monitoring [18], and scanning laser Doppler vibrometer [19] have all proven to be effective for evaluating RC structural members. It is crucial to recognize that each NDT & E technique has unique advantages and limitations [20].

For several decades, ground-penetrating radar (GPR) has been used in geophysics for soil explorations. Due to the development of high-frequency antennas and advanced software and hardware computer systems, GPR has become a rapid and robust method for assessing

concrete structures since the early 1990s. This technique was applied to monitor and evaluate bridge decks [21], to detect rebar size and location in the concrete structures [22–24], and to estimate the concrete cover and thickness of the bridge deck [25–27].

The GPR method has also been widely used for concrete moisture evaluation [28], deterioration mapping of old bridge decks [29], tracking cracks [30], assessment of rebar corrosion in concrete slabs [31,32], detection of embedded defects [33], detection voids in grouted post-tensioned concrete ducts [34], investigation of concrete mix variations and environmental conditions on defect detection [35], identification of corrosion-induced anomalies of bridge decks [36], rebar detection [37], visualization defects of fiber-reinforced polymer-wrapped reinforced concrete slabs [38–40], and mapping rebar layers [41]. The environmental factors affecting the GPR signal were also investigated [42], and new techniques were applied in GPR signal processing [43].

Zatar et al. [44] proposed a method based on a synthetic aperture focusing technique to determine the rebar depth and spacing. Chang et al. [45] introduced a physical model that accounts for the electromagnetic signature of a buried reinforcing steel bar, considering the rebar's radius. The GPR radargrams underwent several digital image processing stages, with subsequent analysis of power reflectivity variations within the energy zone as the GPR antenna traversed the reinforced concrete surface. Power reflectivity data was generated for vertically oriented migration traces. Calculating the radius of the reinforcing steel bar, considering the distances and the long-dimension radius of an energy footprint. Utsi and Utsi [46] correlated the rebar depth and size with the signal amplitude, but the results indicated that the method's accuracy was low. Zhan and Xie [47] compared discrete and stationary wavelet transforms by creating a contour map of stationary wavelet transform detail coefficients. A conclusion was made that the stationary wavelet transform proves to be an effective method for measuring the diameter of a steel bar.

Wiwatrojanagul et al. [48] proposed a new method mainly focusing on automatically searching the locations of rebars in RC structures based on the modified existing hyperbolic signatures model. This method can efficiently detect embedded objects with the assumption of zero diameter of the rebars. Xiang et al. [49,50] presented an integrated approach based on pattern recognition and curve fitting principles to determine the rebar's horizontal location, depth, and size simultaneously. This approach has a few limitations. Firstly, extracting precise points of interest from hyperbolas remains challenging, especially in environments with high noise levels. Secondly, estimating electromagnetic wave velocity based on imaginary curves is prone to errors.

This study utilizes GPR data to determine the depth and size of rebar in reinforced concrete structure components such as RC slabs. A novel computer algorithm was devised to accurately extract the hyperbola representing the rebar in the radargram without requiring signal processing steps like background and noise removal. New methods were also employed to determine the time zero and electromagnetic wave velocity, offering significant advantages over existing techniques. Additionally, biquadratic, and theoretical equations for hyperbolas were developed to assess rebar spacing and depth. As a result, matching testing and theoretical curves provided rebar information regarding rebar size.

2. GPR System and Data Processing

Ground-penetrating radar (GPR) refers to electromagnetic (EM) techniques that use radar pulses to image the subsurface. The GPR is based on the propagation of high-frequency electromagnetic waves that radiate into the media from a transmitting antenna. The wave frequency usually varies from 200 MHz to 2.6 GHz for most civil engineering applications. The dielectric constant and electrical conductivity are two physical properties of the GPR that control electromagnetic wave propagation. The GPR, an EM energy, is subjected to attenuation (i.e., loss of radar energy) as it propagates into a material. If the material is resistive (i.e., low conductivity), such as dry sand, ice, or dry concrete, the signal stays immaculate longer and is thus able to penetrate a considerable depth

into the material. In contrast, the GPR energy will be absorbed before going very far in the conductive materials (e.g., saltwater, and wet concrete). As a result, the GPR techniques are suitable for inspecting construction materials such as concrete, sand, wood, and asphalt.

The material's dielectric constant indicates the speed of the radar energy traveling through the material. The GPR transmits EM waves into concrete, and it can measure travel time to receive the reflected waves from the embedded objects. As the energy speed is known, multiplying the two-way travel time and wave speed provides the objects' depths. The GPR energy propagates in the air at almost the speed of light while it propagates in the water at about one-ninth speed, corresponding to the dielectric values ranging from 1 (air) to 81 (water). For construction materials, the dielectric values typically vary from 3 to 12, corresponding to radar wave velocities from 0.178 to 0.089 m per nanosecond [51]. The GPR signal amplitude is stored in a two-dimensional matrix where column and row represent horizontal location and depth, respectively. It is directly exhibited in a two-dimensional unreconstructed image by a data interpretation proprietary software that comes with the GPR equipment.

When the radar energy encounters a subsurface/embedded object or a boundary between materials having different electrical conductivity and dielectric values, such as rebars, voids, the boundary between two different materials, or other inhomogeneous materials, it is reflected to the surface and picked up by the receiving antenna. The more significant the difference in these values, the stronger the reflections will be. For example, embedded rebars in concrete slabs show powerful reflection because they are conductive materials.

A GPR antenna consists of a pair of a transmitter (T) and a receiver (R); one transmits the signal, and the other receives the reflected signal. In this study, 1.6 GHz antenna with 58 mm T-R offset (distance between transmitter and receiver) were selected for the GPR system. It should be noted that a common GPR signal processing technique called "background removal" has been used to remove noises of the surface reflection (i.e., direct coupling) pulses.

3. Experimental program

3.1. Specimen Design and Fabrication

Four reinforced concrete (RC) slabs were created and tested to verify the efficiency of the in-house developed software. Three specimens, S1-1, S1-2, and S1-3, have the same dimensions of $914 \times 610 \times 89$ mm (length $\times$ width $\times$ thickness), as depicted in Figure 1a. These slabs contain three different rebar diameters (#3, #5, and #7) situated at the same depth with an identical spacing of 203 mm. The fourth RC slab (specimen S2) measuring $1143 \times 356 \times 178$ mm (width $\times$ length $\times$ thickness) (Figure 1b) was constructed to investigate the impact of overlap reflected signals from rebars with small spacings. Specimen S2 includes six rebars with varying sizes, ranging from #3 to #8, embedded at the same depth and with an identical spacing of 127 mm. Ready-mix concrete from in-transit mixers was used to cast the RC slab specimens. The specimens were then cured and tested in laboratory conditions.

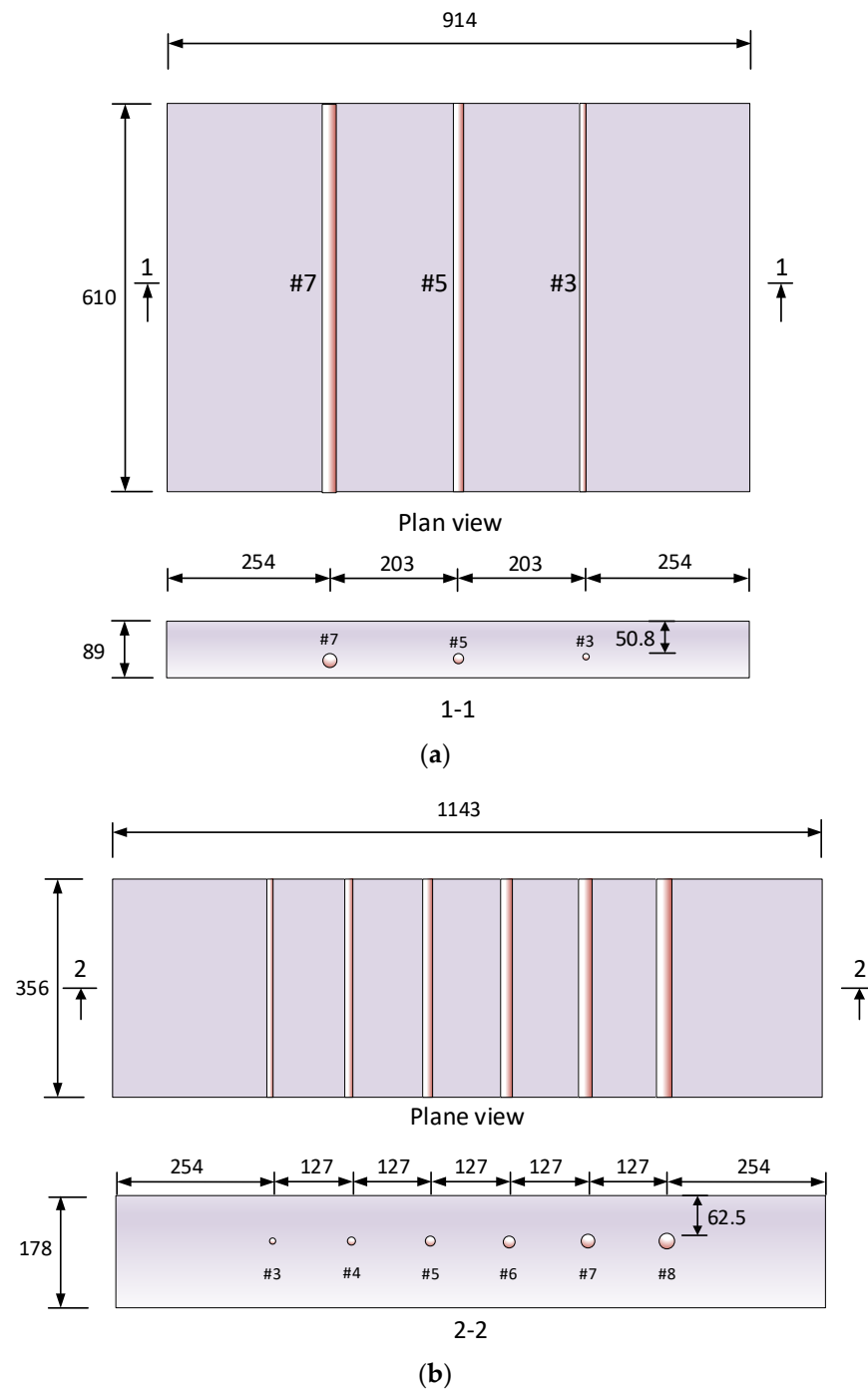


Figure 1. Details of the RC slab specimens S1-1, S1-2, S1-3, and S2 (units in millimeters). (a) Specimens S1-1, S1-2, and S1-3. (b) Specimen S2.

3.2. Data Collection and Acquisition

The data collection was conducted with meticulous attention to detail, with the direction chosen to be perpendicular to the steel rebars (i.e., parallel to the longer slab edge). The ground-coupled antenna, operating at a frequency of 1.6 GHz, was consistently used for all RC slab specimens. The sample per scan and scan per meter parameters were rigorously adjusted to account for their effects on the hyperbolic shape. For a comprehensive understanding, please refer to Table 1, which displays the other parameters of the GPR device.

Table 1. Parameters of the GPR device.

Parameters	Unit	Value	Description
SPN	-	512–16,384	Samples per scan
SPD	-	Varies	Scan per second
SPM (N _s)	-	196.85–1000	Scan per meter
Top position	m	0.08	Level of the antenna
Range	m	0.8	Scan depth
Scan spacing	mm	Varies	Scan spacing in a scan line
Antenna frequency	GHz	1.6	
T-R offset	mm	58	Distance between transmitter and receiver

4. Signal Processing

4.1. Time Zero

The time zero is defined based on the purpose of the signal processing. The time zero can be the position of the first positive peak of the direct wave [51]. Wiwatrojanagul et al. [48] proposed a method that best fits the relationship between two-wave travel time and two-way travel length of the electromagnetic wave in the air. The positive peak times of the reflection waves from the copper plate located at different depths below the antenna were used in the best fitting to find the time zero. The following equation can determine the first positive peak:

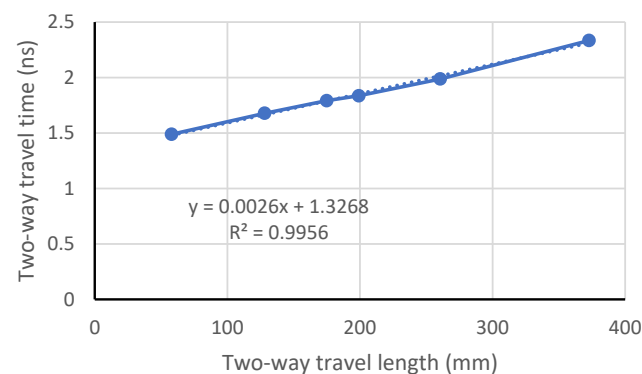
$$t_p = \frac{L}{V_0} + t_0 \quad (1)$$

where: t_0 is time zero; t_p is positive peak time; V_0 is wave velocity in the air; L is two-way travel length calculated as:

$$L = 2\sqrt{z^2 + \left(\frac{S}{2}\right)^2} \quad (2)$$

where: z is depth of the copper plate; S is distance between the transmitter and the receiver.

Figure 2 displays the best data-fitting curve utilizing Equation (2), with a time zero of 1.3268 ns. However, the calculated wave velocity of $1/0.0026 = 385$ mm/ns is significantly higher than the electromagnetic wave velocity propagated in the air, which is 299 mm/ns.

**Figure 2.** Best data fitting curve for time zero.

This study proposes a straightforward method that does not require a metal plate to calibrate the time zero. The positive peak of the reflected signal from the rebar corresponds to the negative peak of the transmitted signal due to the reversal of its phase upon reflection from an infinite dielectric object. Therefore, the time zero can be determined by utilizing the signal's negative peak of the direct wave. As the signal travels through the air from the transmitter to the receiver, this method can accurately establish the time zero.

$$t_0 = t_{nda} - \frac{S}{V_0} \quad (3)$$

In this context, t_{nda} represents the negative peak time of the direct wave in the air, as depicted in Figure 3. For instance, a t_{nda} of approximately 1.48 ns was observed at various distances (converted from traces) during a scan, as illustrated in Figure 4. Consequently, the time zero of approximately 1.3 ns can be computed using Equation (3).

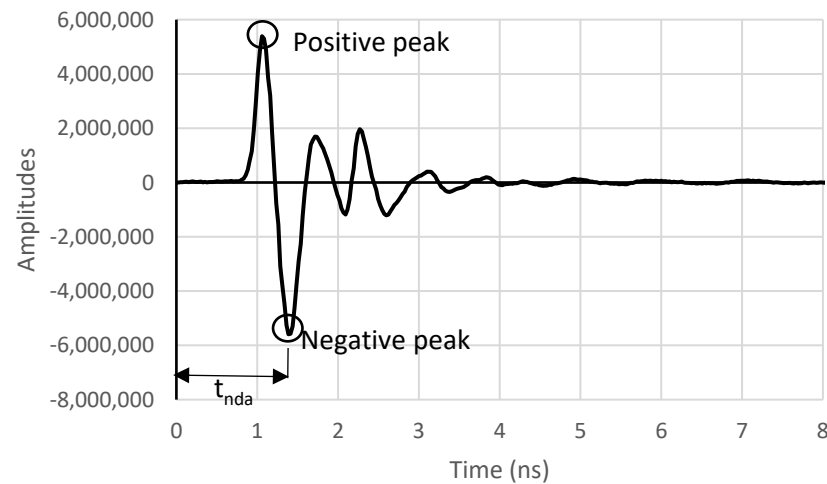


Figure 3. Definition of the negative peak time of the direct wave.

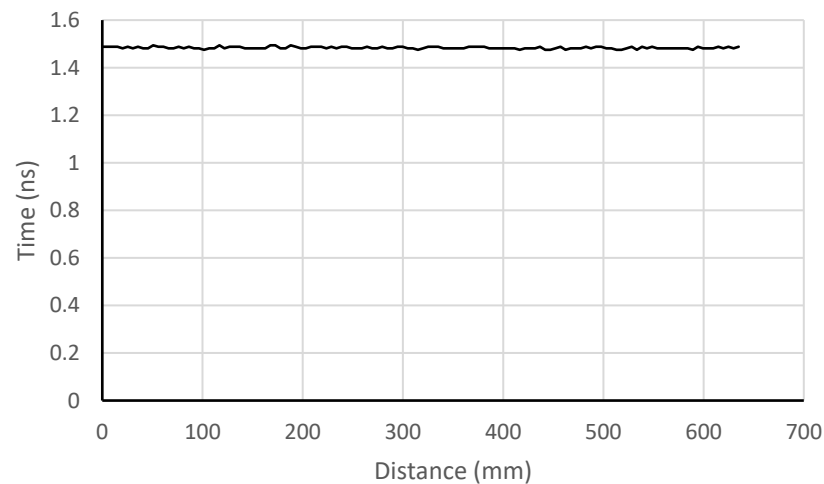


Figure 4. The negative peaks times of the direct signals.

4.2. Rebar Depth and Diameter

The shape of a hyperbola depends on two parameters [51]: (1) scan spacing, where a smaller scan's spacing (more scans per meter) produces wide hyperbolas, and (2) wave velocity, where higher velocity (lower dielectric) produces wider hyperbolas and vice versa. Targets of larger diameter produce bright reflections. The shape of a hyperbola does not change significantly with target size for any diameter under 50 mm; all such targets are point-like for the radar as their size is a fraction of the wavelength.

The following assumptions are made to establish the theoretical equation of the hyperbola:

- Positive peaks of the reflected waves from rebar correspond to the negative peaks of the transmitting wave (phase reverse).
- The transmitting wave reflects at the surface of the rebar in the shortest two-wave travel path.

Figure 5a shows the schematic of reflected wave from a rebar. The shortest two-wave travel path is represented by L_1 and L_2 as in the following equations:

$$L_1 = \sqrt{(z + r - r \cos \alpha)^2 + \left(X - \frac{S}{2} - r \sin \alpha\right)^2} \quad (4a)$$

$$L_2 = \sqrt{(z + r - r \cos \alpha)^2 + \left(X + \frac{S}{2} - r \sin \alpha\right)^2} \quad (4b)$$

where: $\tan \alpha = X/z$; $X = x_p - x$ is the distance between the rebar and the center line of the transmitter and receiver (TR) in the horizontal direction; z is the depth of the rebar center; r is the rebar radius; S is the spacing of the transmitter and receiver; x_0 is the horizontal coordinate of the rebar; x is horizontal coordinate of the antenna.

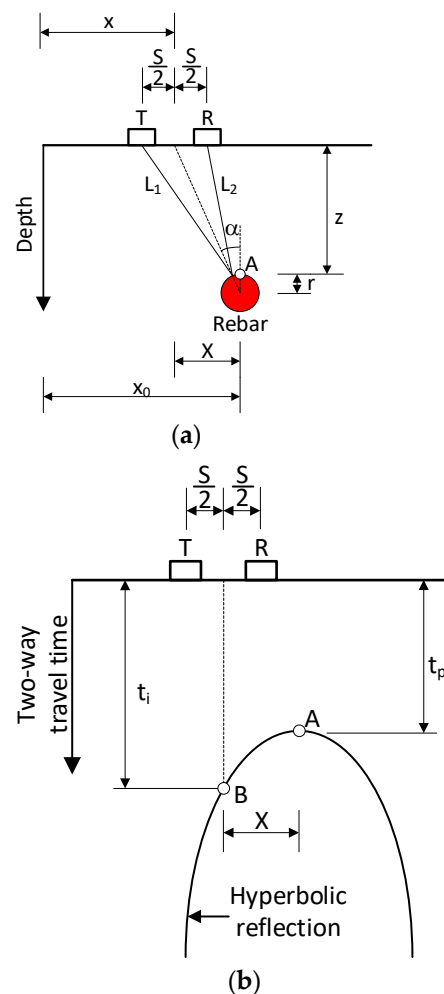


Figure 5. Reflected wave from a rebar. (a) Wave travel path. (b) Hyperbolic reflection.

Consider the peak point of the hyperbola (point A in Figure 5b); the two-wave travel time is expressed by Equation (5) where t_0 is time zero; t_p is the time of the peak of the hyperbola. Consider a point on the hyperbola; the two-wave travel time can be obtained, as can be depicted in Equation (6). Substituting Equations (4) and (5) into Equation (6) results in producing Equation (7).

$$t_p - t_0 = \frac{\sqrt{4z^2 + S^2}}{V_s} \quad (5)$$

$$t_i - t_0 = \frac{L_1 + L_2}{V_s} \quad (6)$$

$$t_i = (t_p - t_0) \frac{\sqrt{(z + r - r \cos \alpha)^2 + \left(X - \frac{s}{2} - r \sin \alpha\right)^2} + \sqrt{(z + r - r \cos \alpha)^2 + \left(X + \frac{s}{2} - r \sin \alpha\right)^2}}{\sqrt{4z^2 + s^2}} + t_0 \quad (7)$$

Equation (7) depicts the hyperbolic curve resulting from a rebar embedded in RC structures and is depicted for various rebar sizes in Figure 6. It is evident that the disparities between these curves are negligible. The suggested steps for solving for the rebar depth (z) and radius (r) in Equation (7) are as follows:

- Estimate the electromagnetic wave velocity.
- Calculate the rebar depth using Equation (5).
- Identify the coordinates at the peak of the hyperbola.
- Calculate the rebar radius using Equation (7).

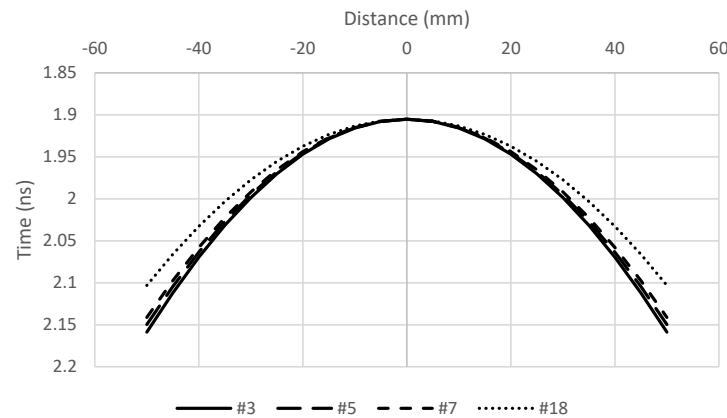


Figure 6. Theoretical hyperbolas for rebars.

4.3. Wave Velocity

The analytical method presented by Wiwatrojanagul et al. [48] and Xiang et al. [49,50] only applies when the rebar size is known, which is different in many practical situations. Consequently, this method could not be used. The wave velocity can be calculated from Equation (5) based on the reflected wave from the bottom of the concrete slabs, wherein the slab thickness d replaces the depth z . If the reflected signal is weak, a metal plate should be affixed to the bottom of the concrete slab.

4.4. Determination of the Coordinates at the Peak of the Hyperbola

The locus of the positive peak reflections from the rebars extracted from a radargram are not smooth curves, and their peak coordinates (t_p and x_p) are not provided. The curves can be approximated by a biquadratic equation to determine the coordinates as follows:

$$t_i \approx Ax^4 + Bx^3 + Cx^2 + Dx + E \quad (8)$$

The reason for choosing biquadratic Equation (8) is its close fit to the theoretical hyperbola (Equation (7)) with extremely high precision, as demonstrated in Figure 7. The x_p coordinate represents the horizontal position of the rebar, whereas t_p corresponds to its depth. The peak coordinates (t_p and x_p) can then be identified by solving the first derivative of Equation (8).

$$\frac{dt_i}{dx} = 0 \quad (9)$$

Developing a computer code with a fully graphical interface using Delphi, the authors addressed the limitations of the current commercial GPR device's post-processing software.

Employing the abovementioned principles and equations, the program can automatically detect and determine the depth and size of rebars, as well as the electromagnetic wave velocity in concrete slabs. It attracts all hyperbolic reflections represented by positive peaks from radargrams and fits them best with biquadratic equations. An iterative method was employed to solve Equation (7) and determined the unknown values to fit the biquadratic equation accurately.

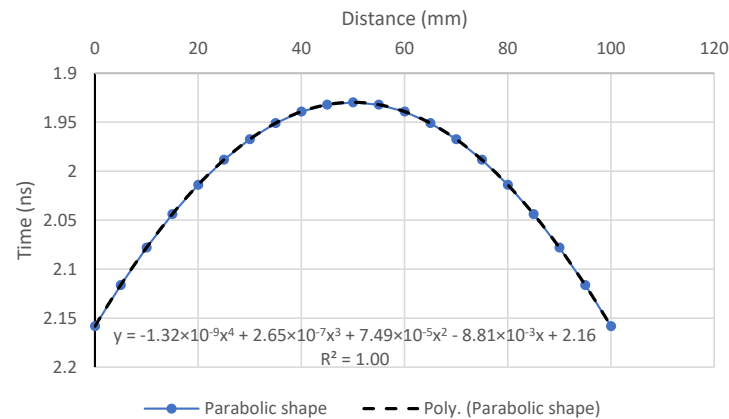


Figure 7. Biquadratic approximation.

5. Results and Discussion

The radargram shown in Figure 8 visually represents the GPR scan conducted on slabs S1-1, S1-2, and S1-3. It reveals the presence of three rebars (#3, #5, and #7) through hyperbolic reflections. Figure 9 depicts the positive peaks of rebar reflections and theoretical hyperbolic curves for all rebars. Figure 10 showcases the R-squared values of the best-fitting curves corresponding to rebar diameter, ranging from zero with increments of 0.1 mm.

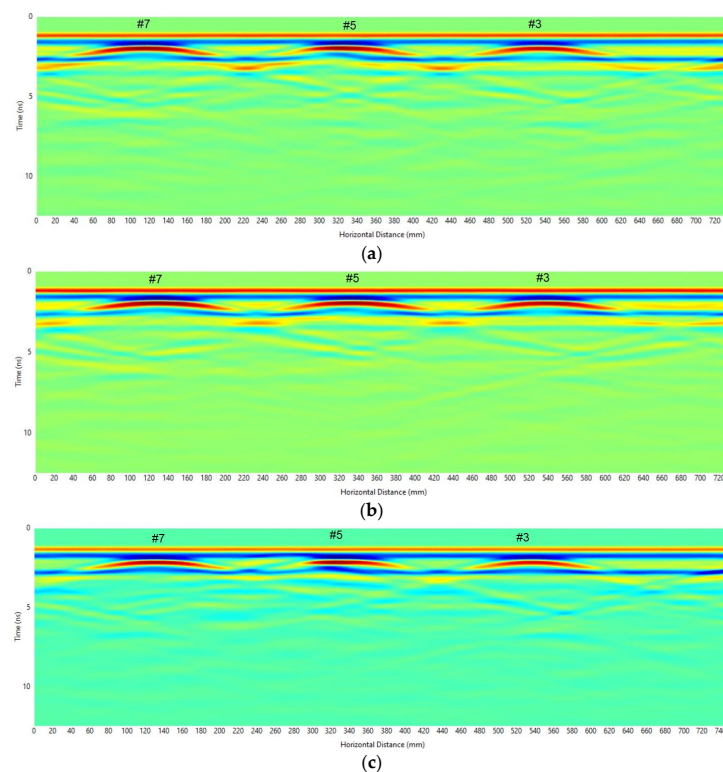
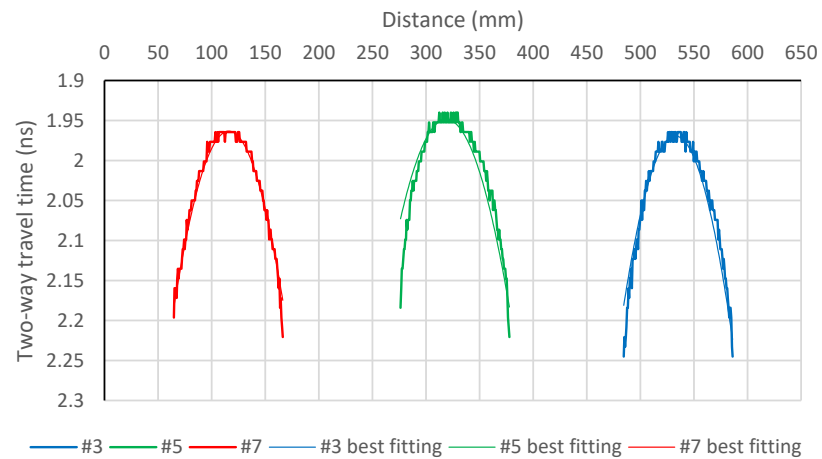
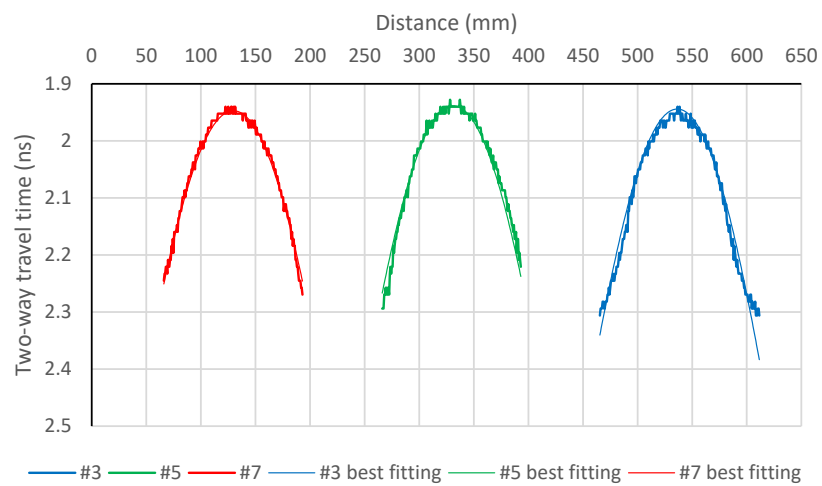


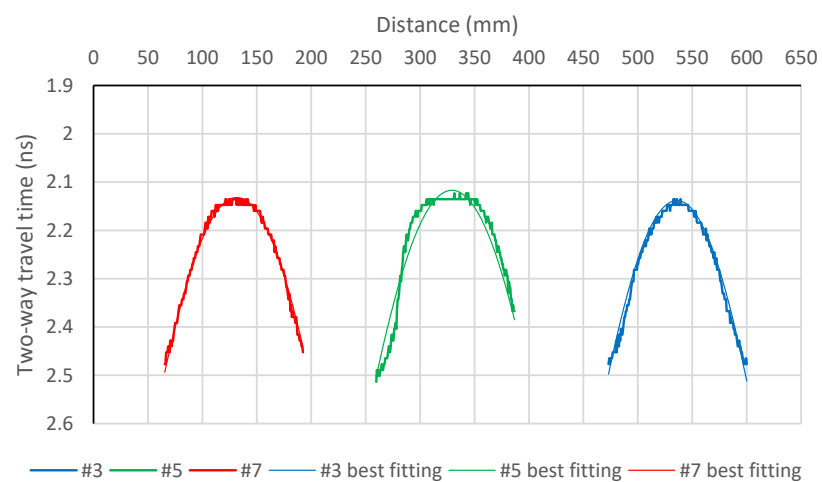
Figure 8. Radargram of slab specimens S1-1, S1-2, and S1-3. (a) Radargram of Specimen S1-1. (b) Radargram of Specimen S1-2. (c) Radargram of Specimen S1-3.



(a)

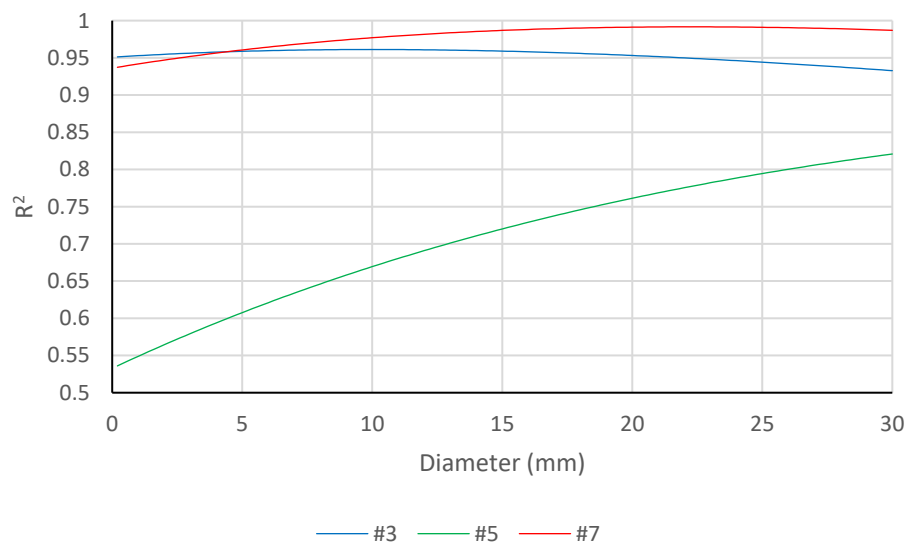


(b)

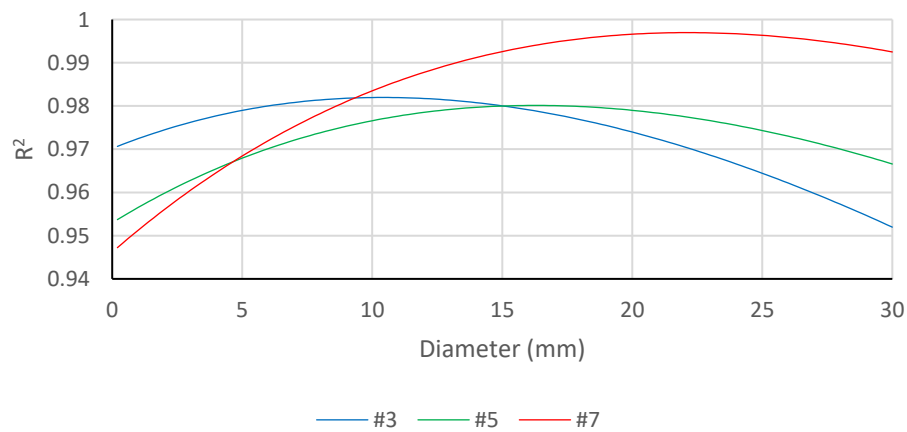


(c)

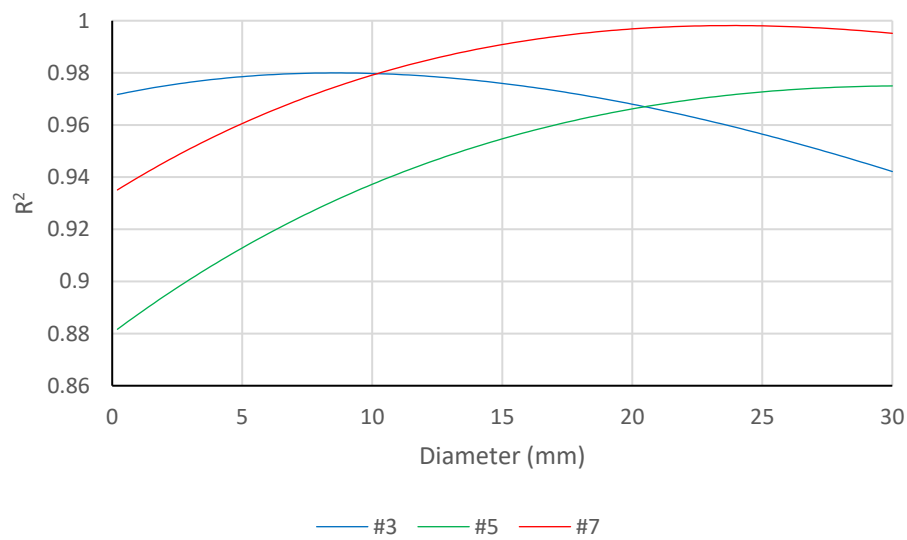
Figure 9. Hyperbolas and best fit curves for rebars of slab specimens S1-1, S1-2 and S1-3. (a) Hyperbolas and best fit curves for rebars of Specimen S1-1. (b) Hyperbolas and best fit curves for rebars of Specimen S1-2. (c) Hyperbolas and best fit curves for rebars of Specimen S1-3.



(a)



(b)



(c)

Figure 10. R² for slab specimens S1-1, S1-2, and S1-3. (a) S1-1. (b) S1-2. (c) S1-3.

The wave velocity of 133 mm/ns is determined from the reflection of the bottom of the 89 mm thick slab. With this known wave velocity, the depths of the rebars can be calculated by utilizing Equation (5). Subsequently, the rebar diameter is estimated by identifying the diameter corresponding to the maximum R-squared values in Figure 10. This analysis provides valuable insights into the composition and characteristics of the slabs, aiding in further understanding and decision-making.

The comparison of the rebar depth and diameter is detailed in Table 2. After examining the comparison of rebar diameters, the variations are typically under 10 percent. However, accurately estimating the #5 rebars in S1-1 and S1-3 slabs proves to be challenging due to the asymmetrical signal reflections, deviating from the typical hyperbolic pattern. This deviation is supported by evidence in Figures 8a,c and 9a,c. The reflections of the #5 rebars on the left side are notably impacted by adjacent surface void reflections, which affect the clarity of the #5 rebar's reflections. Despite this, the predicted rebar depth using the proposed approach closely aligns with the designed depths with high accuracy, typically less than 8 percent.

Table 2. Rebar diameters and depths for S1-1, S1-2, and S1-3 slabs.

Slab	Rebar No./Diameter (mm)	Designed Depth (mm)	Calculated Diameter/Depth (mm)	Diameter/Depth Differences (%)
S1-1	#3/9.525	50.8	10/48	5.0/5.5
	#5/15.875	50.8	(-)/47	(-)/7.5
	#7/22.225	50.8	22.2/48	0.1/5.5
S1-2	#3/9.525	50.8	10.4/49	9.2/3.5
	#5/15.875	50.8	16/48	0.8/5.5
	#7/22.225	50.8	22.2/49	0.1/3.5
S1-3	#3/9.525	50.8	8.6/47	9.7/7.5
	#5/15.875	50.8	(-)/48	(-)/5.5
	#7/22.225	50.8	23.8/47	7.1/7.5

The proposed method's reliability is demonstrated by comparing the determined spacing with the designed rebar spacing, as detailed in Table 3. The rebar spacings closely match the designed spacing, with minimal deviations of less than 6 percent. The variations in the calculated spacings point to actual spacings primarily influenced by uncontrolled factors, such as assembly and construction errors. These results strongly affirm the efficiency and reliability of the proposed method, especially when utilizing the biquadratic equation to determine the peak coordinates of the hyperbola.

Table 3. Rebar spacing for S1-1, S1-2, and S1-3 slabs.

Slab	Adjacent Rebar	Calculated Spacing (mm)	Difference (%)
S1-1	#3–#5	214	5.4
	#5–#7	202	0.5
S1-2	#3–#5	205	1.0
	#5–#7	202	0.5
S1-3	#3–#5	206	1.5
	#5–#7	198	2.5

The radargram and hyperbolas of the rebars for the S2 slab specimen, subjected to a rigorous analysis, can be seen in Figures 11 and 12, respectively. It is evident that the hyperbolas partially overlap due to the small spacings between them. To address the

perception of overlap, the number of data points of the hyperbolas was reduced, effectively eliminating data points in the overlapping zone. However, while the diameters of rebars #3, #7, and #8 were estimated with very high accuracy, a lower accuracy was obtained for rebar #5. Additionally, the diameters of rebars #4 and #6 could not be approximated, as summarized in Table 4 and Figure 13.

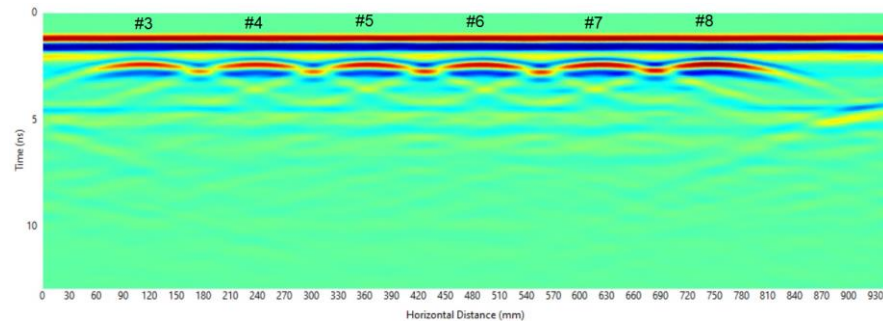


Figure 11. Radargram of slab specimen S2.

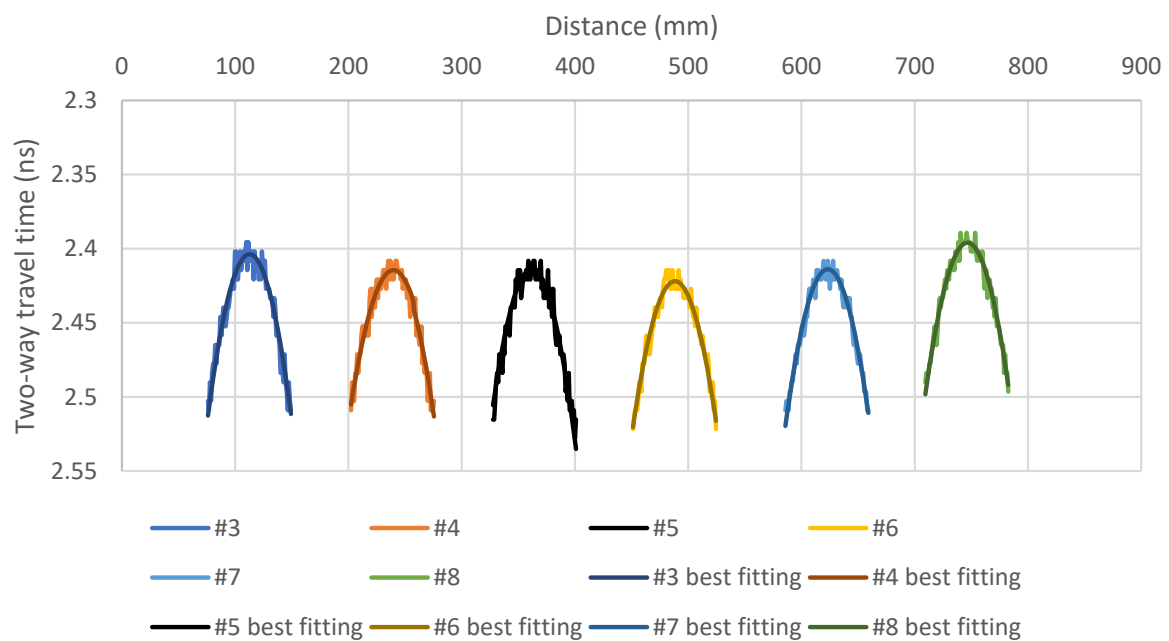


Figure 12. Hyperbolas and best fit curves for rebars for specimen S2.

Table 4. Rebar diameter and depth for specimen S2.

Rebar No./Diameter (mm)	Designed Depth (mm)	Calculated Diameter/Depth (mm)	Diameter/Depth Differences (%)
#3/9.525	62.5	10/68	5.0/8.8
#4/12.700	62.5	(-)/68	(-)/8.8
#5/15.875	62.5	13.2/68	16.6/8.8
#6/19.050	62.5	(-)/68	(-)/8.8
#7/22.225	62.5	21/68	5.5/8.8
#8/25.400	62.5	27/67	6.0/7.2

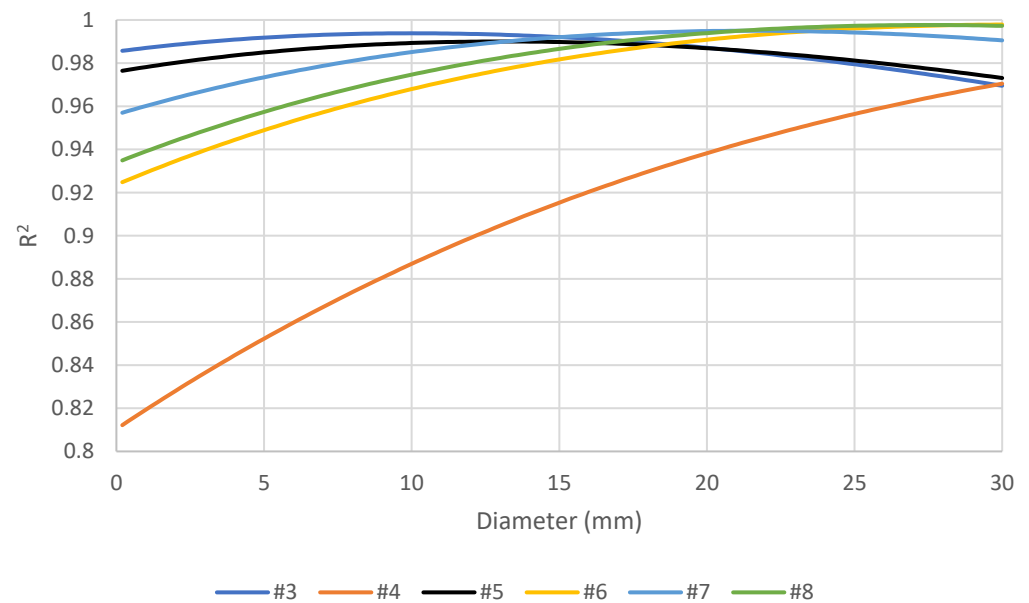


Figure 13. R^2 for specimen S2.

The rebars positioned on the side, such as #3, or larger rebars like #7 and #8, were less affected by small spacing compared to the inside rebars (#4, #5, and #6). This finding has significant implications for the design and construction of concrete slabs. Upon comparing the first three slab specimens, S1-1 to S1-3, it is noted that the overlapping zone may not occur if the minimum spacing of the rebar is around 150 mm for rebars #3 to #8. The rebar depth is not significantly affected by spacing, as shown in Table 5. The predicted spacing remained consistent, with discrepancies of around 8.8 percent for most rebars.

Table 5. Rebar spacing for specimen S2.

Adjacent Rebar	Calculated Spacing (mm)	Difference (%)
#3–#4	127	0.0
#4–#5	122	3.9
#5–#6	127	0.0
#6–#7	135	6.3
#7–#8	123	3.1

6. Conclusions

This study focused on determining the rebar depth and size in reinforced concrete structures using Ground Penetrating Radar (GPR) data. The approach involved developing a theoretical equation for the two-wave travel time, based on the assumptions of positive peak reflection corresponding to the negative peaks of the transmitting wave and the shortest two-wave travel path. A biquadratic equation was adopted to approximate the rebar reflection curve obtained from the radargram, facilitating the determination of the peak coordinates of the hyperbola, which represent rebar spacing and depth. The rebar size was then determined by matching the theoretical equation with the rebar reflection curve. The study concluded the following:

- Time zero can be accurately determined based on the negative peak of the transmitted signal in the air.
- The thickness of the concrete slab was a reliable indicator for determining the electromagnetic wave.
- The biquadratic equation proved to be an efficient method for fitting hyperbolas and estimating both the horizontal location and depth of the rebar.

- The rebar size was successfully estimated with high accuracy using the proposed theoretical equation, provided the reflected hyperbola remained unaffected by adjacent embedded objects.
- The overlapping zone of the rebar reflections may not occur if the minimum spacing of the rebar is approximately 150 mm for rebars #3 to #8.

Compared with existing methods in the literature, the proposed method efficiently processes signals and accurately and reliably determines rebar information.

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