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# APPLICATION OF GROUND-PENETRATING RADAR IN THE INDIRECT ASSESSMENT OF STEEL CORROSION IN REINFORCED CONCRETE STRUCTURES

***Abstract:***

Corrosion of steel reinforcement reduces the durability of reinforced and prestressed concrete structures. Ground-penetrating radar (GPR) enables rapid nondestructive inspection and indirect identification of corrosion-prone zones. This paper reviews the physical mechanisms linking corrosion-induced changes in moisture and conductivity to electromagnetic signal variations. Signal-based indicators and quantitative approaches, including depth correction and artificial intelligence–based interpretation, are summarized. Practical limitations related to environmental variability are discussed. GPR is identified as an effective probabilistic tool for preventive infrastructure management.

*Keywords: Ground-penetrating radar (GPR), reinforcement corrosion, nondestructive testing (NDT), structural health monitoring.*

# ПРИМЕНА ГЕОРАДАРА У ИНДИРЕКТНОЈ ПРОЦЕНИ КОРОЗИЈЕ ЧЕЛИКА У АРМИРАНОБЕТОНСКИМ КОНСТРУКЦИЈАМА

***Сажетак:***

Корозија челичне арматуре смањује трајност армиранобетонских и преднапрегнутих бетонских конструкција. Георадара (GPR) омогућава брзу недеструктивну инспекцију и индиректну идентификацију зона подложних корозији. У раду се разматрају физички механизми који повезују промене влаге и проводљивости изазване корозијом са варијацијама електромагнетног сигнала. Приказани су сигнални показатељи и квантитативни приступи, укључујући корекцију дубине и интерпретацију засновану на вештачкој интелигенцији. Дискутују се и практична ограничења повезана са утицајем променљивих услова околине. Георадар је идентификован као ефикасан пробабилистички алат за превентивно управљање инфраструктуром.

*Кључне ријечи: Георадар, корозија арматуре, недеструктивна испитивања, мониторинг стања конструкција.*

# 1. INTRODUCTION

Corrosion of steel reinforcement represents one of the primary causes of deterioration in reinforced and prestressed concrete infrastructure. The economic and structural implications of corrosion extend beyond material degradation, directly affecting service life, maintenance strategies, and lifecycle costs of infrastructure systems. Modern asset management frameworks emphasize the transition from reactive repair to preventive and predictive maintenance models [1].

Service-life prediction models for reinforced concrete structures incorporate chloride ingress modeling, carbonation mechanisms, and probabilistic durability assessment [2]. However, theoretical prediction models must be complemented by reliable in-situ diagnostic techniques capable of identifying ongoing degradation during the operational phase.

Among nondestructive testing (NDT) techniques, GPR has emerged as one of the most efficient tools for large-area inspection of reinforced concrete elements. Compared to other nondestructive testing methods, such as half-cell potential measurements, resistivity testing, and ultrasonic-based techniques, GPR offers significantly faster inspection and spatial coverage. However, unlike electrochemical methods that provide direct information on reinforcement corrosion activity, GPR only detects indirect changes in material properties. Therefore, GPR is most effective when used in combination with complementary diagnostic techniques. GPR enables rapid scanning of structural surfaces, identification of reinforcement layout, cover thickness estimation, and detection of subsurface anomalies without destructive intervention [3].

Early studies demonstrated that variations in reflection amplitude at reinforcement depth may correlate with chloride contamination and corrosion activity [4]. Subsequent investigations confirmed that GPR can be used for corrosion mapping of bridge decks when properly calibrated with electrochemical measurements [5].

Nevertheless, it is essential to emphasize that GPR does not directly measure corrosion rate or steel mass loss. Instead, it detects electromagnetic changes in the surrounding concrete matrix caused by variations in moisture, ionic concentration, and microstructural degradation [6]. Therefore, GPR-based corrosion detection must be regarded as an indirect assessment method.

Recent studies have shown that variations in GPR reflection amplitudes and signal characteristics can be used to assess reinforcement corrosion in concrete structures [7].

However, despite extensive research, a consistent framework linking physical steel corrosion mechanisms with measurable GPR signal features is still lacking, particularly in distinguishing the effects of moisture, chloride content, and material heterogeneity.

These developments have significantly expanded the interpretative capabilities of GPR. Quantitative approaches now attempt to relate signal attenuation, frequency-domain characteristics, and pattern recognition algorithms to corrosion probability levels.

Despite these developments, interpretation remains complex due to environmental variability and multi-factor coupling effects. Consequently, a systematic review of the physical mechanisms, signal-based indicators, quantitative frameworks, and practical limitations is necessary.

The objective of this paper is to provide a comprehensive and structured review of GPR-based corrosion assessment in reinforced and prestressed concrete structures, focusing on:

- Physical mechanisms linking corrosion and electromagnetic response,
- Signal-based corrosion indicators,
- Quantitative and advanced interpretation methodologies,
- Practical implications and limitations in field applications.

The novelty of the paper is that it accents the integrated analysis of corrosion mechanisms, electromagnetic signal behavior, and interpretation methodologies in GPR testing of steel corrosion. Unlike previous studies that focus on isolated aspects, this work provides a structured synthesis linking physical processes with measurable GPR indicators and advanced data interpretation approaches.

# 2. PHYSICAL BACKGROUND

GPR–based corrosion assessment relies on the interaction between electrochemical degradation processes in reinforced concrete and electromagnetic wave propagation within heterogeneous cementitious media. Understanding this interaction is essential for interpreting radargram features as indirect indicators of corrosion.

This section first outlines the fundamental corrosion mechanisms in reinforced concrete and then summarizes the key electromagnetic principles governing GPR signal behavior.

## 2.1. STEEL CORROSION MECHANISMS IN REINFORCED CONCRETE

Steel reinforcement embedded in concrete is normally protected by a passive oxide layer formed in the highly alkaline pore solution (pH ≈ 12.5–13.5). Under these conditions, corrosion is thermodynamically unfavorable. However, depassivation may occur due to chloride ingress or carbonation, initiating electrochemical reactions at the steel surface [2].

### 2.1.1. Chloride-Induced Corrosion

Chloride-induced corrosion is the dominant deterioration mechanism in marine environments and bridge decks exposed to de-icing salts. Chloride ions penetrate concrete through diffusion and capillary absorption, gradually reaching the reinforcement level. Once the chloride threshold concentration at the steel surface is exceeded, localized pitting corrosion may initiate [8].

Experimental investigations under cyclic wet–dry exposure demonstrate that corrosion initiation and propagation depend not only on chloride concentration but also on moisture availability and oxygen diffusion [8]. In practice, non-uniform chloride distribution may create electrochemical potential differences along the reinforcement, leading to spatial variability of corrosion activity.

Long-term studies of chloride-exposed reinforced concrete structures confirm that corrosion products accumulate at the steel–concrete interface, generating expansive pressure and leading to cracking and delamination [9]. These structural changes significantly modify the microstructure of concrete surrounding the reinforcement.

### 2.1.2. Carbonation-Induced Corrosion

Carbonation occurs when atmospheric $CO_2$ diffuses into concrete pores and reacts with calcium hydroxide, reducing alkalinity. When the carbonation front reaches reinforcement depth, the passive layer may be destabilized [2]. Compared to chloride-induced pitting corrosion, carbonation-induced corrosion often results in more uniform steel degradation.

### 2.1.3. Steel–Concrete Interface and Microstructural Changes

Corrosion progression alters the steel–concrete interface through:

- Increased porosity,
- Microcrack formation,
- Redistribution of moisture,
- Accumulation of corrosion products.

Experimental studies show that corrosion-induced cracking significantly affects bond behavior and interface integrity [10]. These microstructural changes are particularly relevant for electromagnetic wave propagation, as they modify local dielectric and conductive properties of concrete.

Thus, corrosion processes do not only reduce steel cross-section but also alter the electromagnetic characteristics of the surrounding material. These alterations form the physical basis for indirect detection using GPR.

## 2.2. ELECTROMAGNETIC PRINCIPLES RELEVANT TO GPR IN CONCRETE

GPR operates by transmitting short electromagnetic pulses into the material and recording reflections from interfaces characterized by contrasting dielectric properties.

### 2.2.1. Wave Velocity and Dielectric Permittivity

The propagation velocity $v$ [m/s] of electromagnetic waves in concrete is governed by:

$$\nu = \frac{c}{\sqrt{\varepsilon_r}} \quad (1)$$

where:

- $c$ is the speed of light in vacuum [m/s],
- $\varepsilon_r$ is the relative dielectric permittivity of concrete.

Concrete permittivity strongly depends on moisture content and material composition. Experimental studies using different antenna frequencies (1.6 GHz and 2.6 GHz) demonstrate that dielectric properties evolve with hydration and are highly sensitive to water content [11].

An increase in moisture content leads to higher permittivity and electrical conductivity, which reduces wave velocity and increases attenuation. Since corrosion-prone zones often exhibit higher moisture and ionic concentration, electromagnetic properties are indirectly affected.

### 2.2.2. Signal Attenuation and Conductivity

Signal attenuation in conductive media follows an exponential decay law:

$$A(d) = A_0 e^{-\alpha d} \quad (2)$$

where:

- $A_0$ is the initial amplitude (typically normalized during signal processing and dependent on antenna power and acquisition settings),
- $d$ is the propagation depth (corresponding to the distance between antenna and the reflecting interface) [cm],
- $\alpha$ is the attenuation coefficient [dB/cm], (typically ranging from approximately 0.05–0.4 dB/cm).

Numerical simulations based on the finite-difference time-domain (FDTD) method confirm that increased electrical conductivity significantly amplifies attenuation rates in reinforced concrete systems [12]. Therefore, chloride contamination and moisture accumulation—both associated with corrosion-contribute to measurable amplitude reduction.

Parametric studies investigating the influence of chloride-induced corrosion parameters on GPR response further demonstrate that variations in conductivity and crack width alter reflection characteristics [13].

#### 2.2.3. Reflection at Reinforcement

Steel reinforcement acts as a strong electromagnetic reflector due to its high conductivity relative to concrete. Cylindrical reinforcement bars produce characteristic hyperbolic signatures in B-scan radargrams [14].

The geometry of the hyperbola depends on wave velocity, while peak amplitude is influenced by:

- Impedance contrast,
- Cover thickness,
- Reinforcement diameter,
- Signal attenuation along the propagation path.

Interpretation guidelines emphasize the importance of appropriate gain correction, filtering, and migration to enhance hyperbolic clarity and reduce background noise [14].

#### 2.2.4. Synthesis of the Physical Background

Corrosion processes alter:

- Moisture distribution,
- Ionic concentration,
- Steel–concrete interface properties,
- Crack development patterns.

These changes modify:

- Dielectric permittivity,
- Electrical conductivity,
- Signal velocity,
- Attenuation rate,
- Reflection amplitude.

Because GPR responds to electromagnetic properties rather than electrochemical reactions directly, corrosion detection remains indirect. Nevertheless, understanding the coupling between corrosion mechanisms and electromagnetic behavior provides the theoretical foundation for signal-based corrosion indicators, which are discussed in the next section.

## 3. GPR SIGNAL-BASED INDICATORS OF CORROSION

Several studies have investigated signal-based indicators such as amplitude reduction, scattering patterns, and waveform distortion for identifying corrosion-prone zones in reinforced concrete structures [15], [16], [17], [18].

Signal-based interpretation represents the most widely applied approach in practical GPR corrosion assessment. Since GPR does not directly measure corrosion rate or steel mass loss, interpretation relies on identifying changes in radargram characteristics that are associated with corrosion-related modifications of concrete properties.

These characteristics include:

- Reflection amplitude variation,
- Signal attenuation with depth,

- Hyperbolic signature distortion,
- Travel time shifts,
- Frequency-domain changes,
- Texture and pattern features.

However, all these indicators are influenced by multi-factor coupling effects, including moisture variability, reinforcement depth, cover thickness, and concrete heterogeneity.

### 3.1. REFLECTION AMPLITUDE REDUCTION

Reflection amplitude at reinforcement depth is the most frequently used qualitative indicator of potential corrosion.

Early bridge deck investigations reported that zones with reduced reflection amplitude often corresponded to areas with higher chloride concentration and negative half-cell potential values [4]. Similar conclusions were reported in experimental bridge deck studies using 1.6 GHz antennas [7].

Large-area corrosion mapping studies demonstrated that spatial amplitude distribution can be used to generate corrosion risk maps when combined with electrochemical validation [6]. In these studies, amplitude reduction was interpreted as a consequence of increased attenuation caused by elevated moisture and ionic concentration.

Quantitative assessment studies further confirmed that amplitude values correlate with chloride-induced corrosion probability when depth normalization is properly applied [8].

However, it is important to emphasize that amplitude reduction is not exclusively caused by corrosion. Moisture variation alone may produce similar attenuation patterns [19]. Therefore, amplitude must be interpreted in context.

### 3.2. ATTENUATION WITH DEPTH

Amplitude decay with increasing depth provides additional insight into material conductivity. Instead of evaluating raw amplitude values, several researchers proposed analyzing the attenuation rate along the propagation distance.

Experimental monitoring of chloride-induced corrosion demonstrated that signal attenuation increases progressively as corrosion evolves [9]. Parametric numerical modeling also confirmed that conductivity increase due to chloride contamination significantly enhances attenuation rate [13].

The attenuation-based approach is advantageous because it partially compensates for geometric spreading effects. Nevertheless, accurate velocity estimation and cover thickness determination remain critical.

### 3.3. HYPERBOLIC SIGNATURE DISTORTION

Reinforcement bars produce characteristic hyperbolic reflections in B-scan radargrams (two-dimensional radar images obtained by moving the antenna along the surface) [14]. Corrosion-induced microcracking and localized moisture accumulation may distort these signatures.

Experimental detection studies reported that corrosion may lead to:

- Blurred hyperbola apex,
- Reduced peak amplitude,
- Asymmetric shape,
- Increased background scattering (Figure 1.) [5].

Figure 1 illustrates the degradation of hyperbolic reflections in a corrosion-prone zone. The reduced clarity and increased background noise indicate higher attenuation and scattering caused by increased moisture and microcracking around the reinforcement.

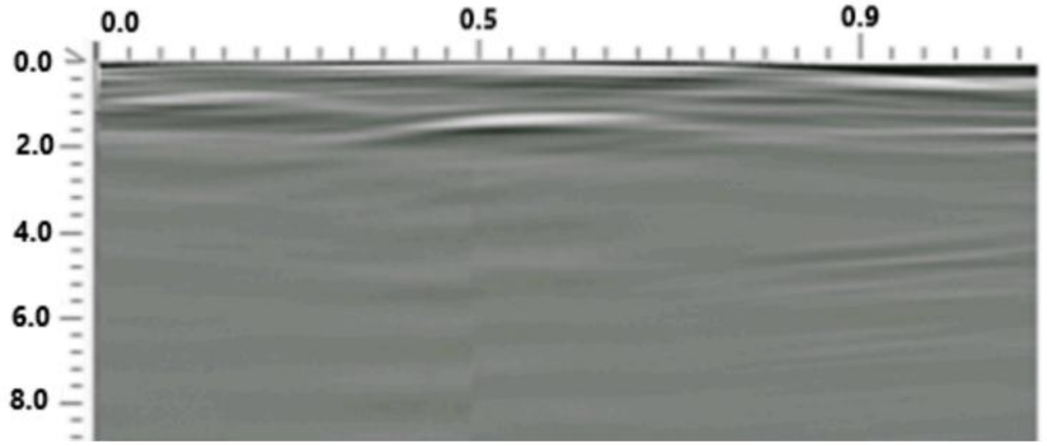


*Figure 3. GPR B-scan showing increased background scattering and reduced hyperbolic clarity in a corrosion-prone reinforcement zone [5].*

In early corrosion stages, localized cracking may temporarily increase impedance contrast, producing subtle amplitude enhancement before attenuation becomes dominant. This explains why conflicting amplitude trends are sometimes reported.

### 3.4. TRAVEL TIME AND VELOCITY VARIATIONS

Changes in dielectric permittivity due to moisture accumulation may affect electromagnetic wave velocity in concrete. Experimental dielectric characterization confirms that permittivity is highly sensitive to water content [11].

Since corrosion processes are often accompanied by increased moisture and ionic concentration in the vicinity of the reinforcement, these changes may indirectly influence wave propagation velocity.

### 3.5. TEXTURE AND IMAGE-BASED INDICATORS

With advances in digital processing, radargram interpretation increasingly relies on texture analysis and automated image processing.

Image-based corrosion mapping approaches demonstrated that pixel intensity distribution and pattern recognition improve classification accuracy compared to manual amplitude thresholding [6]. Automated evaluation frameworks have also been proposed to process large bridge deck datasets and reduce operator subjectivity during corrosion mapping.

More recent studies integrate GPR imaging with artificial intelligence techniques to extract high-dimensional features from B-scan images [19], [20], [21]. These methods reduce operator subjectivity and enhance reproducibility.

### 3.6. MULTI-FREQUENCY AND SPECTRAL CHARACTERISTICS

Traditional time-domain amplitude analysis may overlook subtle conductivity-related effects. Frequency-domain approaches examine spectral energy distribution shifts associated with material degradation.

Recent frameworks analyzing frequency-domain features demonstrate improved discrimination between corrosion-prone and intact zones (Figure 2.) [22]. Figure 2 demonstrates the shift in frequency-domain characteristics between intact and corroded zones. The attenuation of higher-frequency components reflects increased conductivity and energy dissipation associated with corrosion processes. Spectral attenuation of higher-frequency components is particularly sensitive to increased conductivity. Field investigations of existing reinforced concrete structures confirm that combined diagnostic approaches and condition assessment methods remain essential for reliable evaluation of corrosion-related deterioration [23].

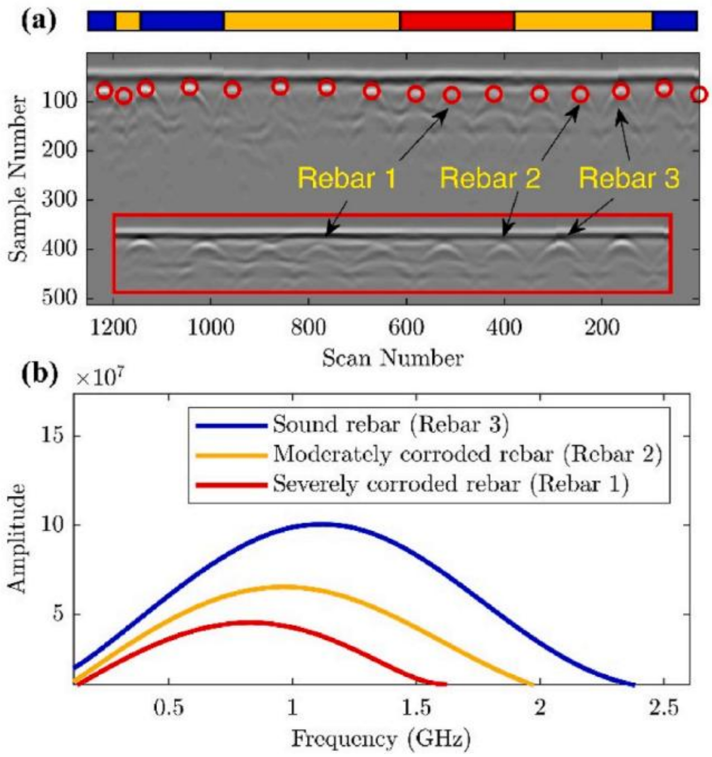


*Figure 4. Frequency-domain spectrum comparison between intact and corroded zones [22].*

### 3.7. INFLUENCE OF MOISTURE AS A CONFOUNDING FACTOR

Moisture represents one of the dominant confounding variables in signal-based corrosion interpretation. Investigations in heritage and reinforced concrete structures show that increased moisture alone significantly reduces reflection amplitude [19].

Therefore, interpretation should prioritize:

- Comparative intra-structure analysis,
- Repeated measurements under controlled conditions,
- Integration with complementary techniques.

### 3.8. SUMMARY OF SIGNAL-BASED INDICATORS

Signal-based corrosion assessment primarily relies on:

- Amplitude reduction,
- Attenuation increase,
- Hyperbolic signature distortion,
- Texture pattern changes,
- Frequency-domain shifts.

However, no single parameter uniquely identifies corrosion severity. Reliable interpretation requires multi-parameter analysis and calibration. Although various signal-based indicators have been proposed, their reliability varies significantly depending on environmental conditions and structural characteristics. Amplitude-based methods are simple and widely used but highly sensitive to moisture variations. Attenuation-based approaches provide more physically grounded insight but require accurate depth estimation. Image-based and AI-driven methods offer improved objectivity; however, they often lack transparency and require large calibrated datasets. Therefore, no single indicator can be considered universally reliable, and combined approaches are necessary.

A comparative summary of the main signal-based indicators, including their physical basis, advantages, and limitations, is presented in Table 1. This overview highlights the necessity of combining multiple indicators in order to improve the reliability of GPR-based corrosion assessment.

This motivates the development of quantitative and advanced interpretation frameworks, discussed in the following section.

*Table 1. Comparative Overview of Quantitative Methods*

| Indicator | Physical Basis | Advantages | Limitations |
|---|---|---|---|
| Amplitude reduction | Conductivity increase | Simple, fast | Sensitive to moisture |
| Attenuation rate | Energy loss | More robust | Needs calibration |
| Hyperbola distortion | Cracking, moisture | Visual interpretation | Subjective |
| Frequency analysis | Spectral shift | Sensitive to corrosion | Complex processing |
| AI/image methods | Pattern recognition | Automated | Needs large datasets |

## 4. BASIS FOR THE QUANTITATIVE AND ADVANCED INTERPRETATION

While traditional GPR corrosion assessment relies primarily on qualitative amplitude interpretation, recent research has explored quantitative approaches and machine learning techniques for automated data analysis. These developments demonstrate significant potential for improving objectivity of corrosion assessment; however, their practical implementation still requires further validation and will be the subject of future research.

Despite their potential, artificial intelligence–based approaches face several limitations. These include the need for large labeled datasets, sensitivity to training bias, and limited interpretability of results. In many cases, models trained on specific structures cannot be directly generalized to different environmental conditions or structural configurations. Consequently, AI-based methods should currently be regarded as complementary tools rather than standalone solutions.

## 5. CONCLUSIONS

GPR has established itself as one of the most effective nondestructive tools for large-area assessment of reinforced and prestressed concrete structures. Based on the reviewed literature and synthesized findings, several key conclusions can be drawn regarding its role in corrosion detection.

First, corrosion in reinforced concrete fundamentally alters the physical properties of the surrounding concrete matrix rather than being directly measurable by electromagnetic methods. Chloride ingress, carbonation, moisture redistribution, and corrosion-induced cracking modify dielectric permittivity and electrical conductivity, which in turn affect GPR signal attenuation and reflection behavior [2], [10]. This coupling between electrochemical degradation and electromagnetic response forms the theoretical foundation of indirect corrosion assessment.

Second, signal-based indicators-particularly reflection amplitude reduction and increased attenuation-remain the most widely applied approaches. Numerous bridge deck and laboratory studies confirm that amplitude variations correlate with chloride contamination and corrosion probability when interpreted within structural context [4], [8], [9]. However, amplitude alone cannot uniquely determine corrosion severity due to multi-factor influences including moisture and cover thickness.

Third, several studies suggest that advanced signal processing and normalization techniques may improve the reliability of GPR-based corrosion interpretation [8], [13]. Numerical simulations further clarify the relative influence of conductivity, crack width, and reinforcement depth on GPR response [12]. These advancements represent important steps toward more objective corrosion risk assessment.

Fourth, moisture variability remains the most significant confounding factor in practical applications [19]. Because GPR measures electromagnetic properties rather than electrochemical corrosion current, integration with complementary diagnostic techniques remains essential for validation.

Overall, GPR-based corrosion assessment should be regarded as a probabilistic risk-mapping tool rather than a direct quantification method. Its primary advantages include:

- Rapid large-area scanning capability,
- Nondestructive operation,
- Early identification of corrosion-prone zones,

- Support for targeted destructive testing and maintenance planning.

Future research directions should focus on:

- Standardization of signal processing workflows,
- Multi-frequency and multi-domain integration,
- Hybrid sensor fusion strategies,
- Development of calibrated probabilistic corrosion indices,
- Expansion of long-term monitoring datasets for improved calibration of corrosion assessment methods.

In conclusion, when applied with proper physical understanding, quantitative correction methods, and complementary validation techniques, GPR represents a powerful component of modern structural health monitoring and preventive infrastructure management strategies.

Despite significant progress, several research gaps remain. In particular, the lack of standardized interpretation procedures and the strong influence of environmental variability limit the reliability of GPR-based corrosion assessment. Future research should focus on developing calibrated multi-parameter frameworks and integrating GPR with complementary sensing techniques to improve robustness and consistency.

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