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Effect of aggressive environments and stray currents on the corrosion resistance of corrugated metal pipes

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Abstract. The study aimed to investigate the role of corrosion damage to corrugated metal pipes in determining the durability, technical condition and operational reliability of transport structures. The methodology was based on methods of systematisation, engineering and theoretical analysis, illustrative calculation, and the analysis of practical examples. The study established that the corrosive degradation of metal corrugated pipes is predominantly of an electrochemical nature and is determined by the aggressiveness of the soil and water environments. Localised corrosion poses the greatest danger to such structures, as it reduces the shell's stiffness, local stability and the structure's remaining service life. In underground and water-saturated conditions, corrosion is accelerated by wetting-drying cycles, which destroy the protective coating and increase the metal's vulnerability. Stray currents in the vicinity of electrified transport systems constitute a separate man-made risk factor, causing localised anodic areas and accelerated metal damage. The study demonstrated that the corrosion resistance of metal corrugated pipes should be assessed not only by the aggressiveness of the environment, but also by a system of quantitative indicators reflecting the rate of metal loss, local damage, changes in stiffness and the residual service life of the structure. Quantitative assessment based on Faraday's law has shown that even a relatively small loss of wall thickness is of engineering significance, as it affects the durability, technical condition and operational safety of the transport structure. An engineering approach is proposed for the assessment of the corrosion degradation of corrugated metal pipes based on a corrosion weakening coefficient, which characterises the relative loss of thickness of the metal shell and its approach to a critical state. A simplified relationship linking the initial thickness, critical thickness and corrosion rate is used for the engineering assessment of the remaining service life. The practical significance lies in the possibility of applying the results by designers, operating organisations and diagnostic specialists during the design, operation, inspection and rehabilitation of corrugated metal pipes in transport structures

Keywords: degradation; remaining service life; durability; operation; structures

Introduction

Corrugated metal pipes are used in transport infrastructure as culverts, drainage structures and transition structures; consequently, their technical condition affects the reliability and safety of transport infrastructure. At the same time, such structures are operated in conditions of aggressive soil and water environments, cyclic wetting and drying, and in some cases are also subject to stray currents. The combined effect of these factors requires separate consideration, as this effect determines the intensity of corrosion degradation and must be addressed in the analysis of the durability, technical condition and methods of protection for such structures. This topic has already been extensively explored in academic discourse. The paper by E.M. Farahani *et al.* (2024) summarises the 21st-century definition of corrosion in steel pipelines under cathodic protection when exposed to alternating

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current. The authors emphasised that the influence of alternating current can cause significant corrosion damage to buried metal structures even in the presence of cathodic protection. This indicates the need to account for the influence of alternating stray currents when assessing corrosion risk and the effectiveness of cathodic protection systems. C. Wang *et al.* (2024a) proposed a model for assessing the area of influence of stray currents in the vicinity of a metro depot, which is based on current distribution and surface potential gradient and has been verified by modelling and experimentation. The results obtained can improve accuracy of localisation of areas of increased corrosion risk near electrified transport systems. The study by Y. Li *et al.* (2023) established that in stratified soil, the current corrosion of buried metal is less intense than in a homogeneous medium, decreases with an increase in the soil's specific resistance, and intensifies with a decrease in the distance to the rail. This contributes to the research on the role of the soil environment in the development of corrosion of buried metal under the influence of stray currents.

According to S. Rossi *et al.* (2022), elevated concentrations of chlorides and sulphates accelerate the degradation of the zinc coating on hot-dip galvanised steel, and their combined action has a pronounced synergistic effect. The authors' findings clarified the role of soil chemical composition in reducing the corrosion resistance of galvanised steel. In turn, the study by G.A. Gaber *et al.* (2023) demonstrates that in an aqueous environment, galvanised steel may be subject to pitting, galvanic and uniform corrosion, and the nature of the damage is determined by the concentration of active components, in particular sodium hypochlorite. This clarifies the influence of the composition of the aqueous environment on the corrosion behaviour of galvanised steel under conditions of wetting and water saturation. J.E. Torres *et al.* (2024) found that in simulated seawater, the corrosion behaviour of galvanised steel depends on the ambient temperature and the thickness of the zinc coating: as the thickness of the protective layer increases, the corrosion rate decreases, whilst at lower temperatures the kinetics of the process increase slightly. This approach quantifies the influence of temperature and the condition of the zinc coating on the corrosion resistance of galvanised steel. A study by E. Nakhostin *et al.* (2022) found that the combination of metal corrosion and erosion cavities in the soil alters the mechanical behaviour of buried corrugated steel pipes, and that the location of cavities at or above the spring line increases the risk of reaching critical conditions. This defines corrosion of corrugated metal pipes not merely as a materials science issue, but as a factor in the structural degradation of the "soil-structure" system, affecting the stiffness, load-bearing capacity and durability of the structure.

In Ukrainian academic discourse, Y.Y. Luchko & V.V. Kovalchuk (2021) summarised the challenges of ensuring the reliability and durability of transport structures made of corrugated metal and emphasised the need to assess their actual technical condition under operational conditions. This forms the engineering context for considering corrugated metal pipes as elements of transport infrastructure, the technical condition of which requires systematic monitoring. M.V. Harkusha (2023) noted that corrosion damage to road culverts is one of the causes of their loss of serviceability and the transition of structures to a defective or emergency condition, and attention is drawn to the importance of modern 21st-century repair technologies. The authors' findings highlight the practical need for timely diagnosis of corrosion degradation, assessment of the actual technical condition of the pipes, and the informed selection of methods for the repair and restoration of such structures.

At the same time, existing studies lack a comprehensive analysis in which aggressive environments and stray currents are considered jointly as factors in the corrosion degradation of corrugated metal pipes, affecting their technical condition, service life, operational reliability, remaining service life, and the selection of engineering measures for protection and rehabilitation. Therefore, the study aimed to summarise the factors and mechanisms of corrosion degradation of metal corrugated pipes to determine their impact on the durability and reliability of transport structures. To achieve this aim, the following tasks were set: to characterise the factors and mechanisms of corrosion degradation of metal corrugated pipes in aggressive environments and under the influence of stray currents; to systematise approaches to assessing corrosion resistance, its quantitative indicators and engineering significance for transport structures; to summarise the practical manifestations of corrosion degradation and engineering solutions for reinforcement and rehabilitation to determine approaches to ensuring the durability of corrugated metal pipes at the design, construction, operation and repair stages.

The scientific novelty of the study is determined by the proposal of an engineering approach to assessing the corrosion degradation of corrugated metal pipes, based on the introduction of a corrosion weakening coefficient and its relationship to changes in the shell stiffness and the residual service life of the structure. An approach to assessing corrosion resistance has been developed by combining the electrochemical parameters of the corrosion process with engineering indicators of technical condition – thickness loss, critical thickness and estimated remaining service life. Further development has been made in the engineering interpretation of the impact of metal loss on the structural behaviour of the "soil-structure" system, which provides a basis for the quantitative assessment of the technical condition and the justification of decisions regarding the rehabilitation of the structure.

Materials and Methods

The study was theoretical in nature and was based on a combination of methods, including systematisation, engineering and theoretical analysis, illustrative calculations, and the analysis of practical examples, with a view to comprehensively examining the factors contributing to the corrosion degradation of corrugated metal pipes and their consequences for transport infrastructure. The study's source base includes 32 scientific and scientific-practical sources published between 2015 and 2025, with the majority comprising works from 2021 to 2025. The period 2015-2025 was chosen to cover both contemporary 21st-century scientific approaches to assessing the corrosion degradation of corrugated metal pipes and earlier studies containing representative practical examples of their damage, reinforcement and rehabilitation. Sources were selected based on criteria of thematic relevance to the problem of corrosion degradation of metal corrugated pipes and buried metal structures, the availability of data on the effects of aggressive environments, stray currents, corrosion resistance indicators, technical condition, durability and remaining service life, as well as the engineering suitability of the results for assessing the load-bearing capacity, serviceability, reinforcement, rehabilitation and life-cycle management of transport structures. The analysis also includes studies on the corrosion of buried metal pipelines, as these elucidate the mechanisms of stray current action, the patterns of electrochemical degradation, and approaches to its quantitative assessment, all of which are methodologically relevant to corrugated metal pipes. Practical examples were included based on the representativeness of key scenarios for changes in the technical condition of corrugated metal pipes in transport infrastructure: corrosion damage and loss of serviceability, structural reinforcement, trenchless rehabilitation, and extension of the structure's safe service life. This interpreted the results of the applied methods in the context of assessing the technical condition, durability and remaining service life of corrugated metal pipes in transport infrastructure.

Using a systematic approach, the factors contributing to the corrosion degradation of corrugated metal pipes in aggressive environments – acidic and alkaline environments (Mundra & Provis, 2021), chlorides, sulphates, humidity and water saturation (Ezzeldin *et al.*, 2024a), and wetting-drying cycles (Ezzeldin *et al.*, 2024b). The selection of these specific factors is due to the fact that they are the most representative of the operating conditions for metal corrugated pipes in a soil-water environment and determine the intensity of electrochemical processes, the stability of the protective coating, and the development of general and localised corrosion. The generalisation was conducted according to the following criteria: the nature of the corrosive effect, the consequences for the metal corrugated pipe, and the significance for the transport structure. This approach has made it possible to systematise the main factors of the aggressive environment and form a basis for further assessment of their impact on the technical condition, durability, stiffness, remaining service life and operational reliability of the structure.

Using engineering analysis, this study examines the specific effects of stray currents on the corrosion degradation of corrugated metal pipes and identifies indicators for assessing this degradation in transport infrastructure: the rate of general corrosion (Chen *et al.*, 2025), mm/year, wall thickness loss, mm, depth and location of localised corrosion damage (Zou *et al.*, 2024), condition of the protective coating and the metal's ability to passivate, stray density/presence of anodic zones (Liang *et al.*, 2024), reduction in stiffness and load-bearing capacity of the shell, remaining service life and feasibility of rehabilitation. These indicators were selected as the most representative, as they correlate the intensity of the effect with the localisation of corrosion damage, the degree of structural weakening of the shell, and the consequences for the reliability and serviceability of the transport structure. The analysis was summarised according to the nature of the impact and its engineering significance for the transport structure. An analysis was also conducted to compare changes in the structural performance of the shell with the serviceability of the transport structure. This was done to consider stray currents as a separate engineering risk factor and to establish a basis for assessing the corrosion resistance, technical condition and serviceability of metal pipes.

Theoretical analysis has been used to derive analytical relationships describing the corrosion degradation of corrugated metal pipes. The formulas presented are used to illustrate, from an engineering perspective, the effect of metal loss on changes in the stiffness, load-bearing capacity and remaining service life of the structure. Faraday's law and its derivatives (ASTM International, 2023) have been chosen as the theoretical basis for this analysis, according to which the mass of metal dissolved as a result of an electrochemical process is proportional to the electric charge passing through the system (1):

$$m = \frac{I \times t \times M}{n \times F}, \tag{1}$$

where m – lost material mass; I – magnitude of the anodic or corrosion current; t – current duration; M – molar mass of the metal; n – number of electrons in the anode process; F – Faraday's constant (96,485 C/mol).

For engineering assessment, it is not the mass loss of metal that is most indicative, but the corresponding reduction in wall thickness. The transition to this parameter is described by equation (2):

$$\Delta h = \frac{m}{\rho \times A}, \tag{2}$$

where Δh – loss of thickness; ρ – metal density; A – area of affected surface.

Incorporating the expression for mass loss, the relationship for thickness loss takes the form (3):

$$\Delta h = \frac{I \times t \times M}{n \times F \times \rho \times A}, \tag{3}$$

where Δh – loss of metal thickness; I – magnitude of anodic or corrosion current; t – duration of the current; M – molar mass of the metal; n – number of electrons involved in anode process; F – Faraday's constant (96,485 C/mol); ρ – metal density; A – area of the affected surface.

Using current density , the rate of thickness loss can be expressed as in (4):

$$v_{\Delta h} = \frac{i \times M}{n \times F \times \rho}, \tag{4}$$

where $v_{\Delta h}$ – rate of metal thickness loss; i – current density; M – molar mass of the metal; n – number of electrons involved in anode process; F – Faraday's constant (96,485 C/mol); ρ – metal density.

These relationships make it possible to establish a direct correlation between the electrochemical parameters of the process and the rate of degradation of the metal coating. The equation for determining the corrosion rate from the corrosion current density, as used in electrochemical laboratory studies, is given by (5):

$$CR = \frac{K \times i_{corr} \times M}{n \times \rho}, \quad (5)$$

where K – unit conversion factor; i_{corr} – corrosion current density; M – molar mass of the metal; n – number of electrons in anode process; ρ – metal density.

This established a theoretical basis for further interpretation of the effect of corrosion on the shell stiffness, local stability and remaining service life of corrugated metal pipes. Furthermore, using an illustrative calculation based on Faraday's law and the relationship for wall thickness loss, the influence of the electrochemical parameters of the corrosion process on the rate of metal loss in corrugated metal pipes was quantitatively demonstrated. Conventional values for current intensity, affected surface area and duration of current exposure have been selected as representative examples to illustrate the transition from theoretical relationships to an engineering interpretation of wall thickness loss, changes in shell stiffness and reduction in the remaining service life of the structure (National Corrugated Steel Pipe Association, 2018). To transition from a qualitative assessment of corrosion degradation to an engineering-quantitative one, it is advisable to introduce the corrosion weakening coefficient , which characterises the relative loss of metal shell thickness (6):

$$K_O = \frac{\Delta t}{t_0} = \frac{t_0 - t}{t_0}, \quad (6)$$

where t_0 – initial wall thickness; t – remaining thickness; Δt – thickness loss due to corrosion.

This coefficient can be used to interpret corrosion degradation not merely as a material loss, but as a factor reducing the stiffness, local stability and load-bearing capacity of the corrugated pipe. It is appropriate to consider the attainment of a critical thickness t_{cr}, at which the condition of local stability or the load-bearing capacity of the shell is violated, as a criterion for the risk of corrosion damage. In equivalent form, this corresponds to condition (7):

$$t \le t_{cr} \text{ or } K_O \ge K_{O,cr} = 1 - \frac{t_{cr}}{t_0}, \quad (7)$$

where t_{cr} – critical wall thickness at which the structure reaches the limit state in terms of local stability or load-bearing capacity; K_O – corrosion reduction factor, which characterises the relative loss of thickness; $K_{O,cr}$ – limit value of the corrosion reduction factor corresponding to the attainment of the critical thickness.

Thus, the extent of corrosion degradation can be characterised not only by the rate of metal loss, but also by the structure's proximity to the limit state. The first condition, $t \le t_{cr}$, means that the residual wall thickness has become less than or equal to the critical value. The second condition, $K_O \ge K_{O,cr}$, is an equivalent form of expressing the same limit state in terms of the relative corrosion weakening of the shell. For the engineering assessment of the residual life of corrugated metal pipes, it is advisable to use the simplified relationship (8):

$$T_{rem} = \frac{t - t_{cr}}{v_{cor}}, \quad (8)$$

where T_{rem} – remaining service life of the structure, years; v_{cor} – average corrosion rate, mm/year.

This relationship exceeds the scope of corrosion damage identification to a simplified engineering assessment of the time remaining before a dangerous technical condition is reached, and justifies decisions regarding the monitoring, reinforcement or rehabilitation of the structure. This approach has been used to demonstrate the practical significance of a quantitative assessment of corrosion degradation in the context of evaluating the technical condition, durability and operational reliability of transport infrastructure.

Using a case-study approach, this paper analyses instances of corrosion-induced degradation, rehabilitation and reinforcement of corrugated metal pipes in transport infrastructure. The analysis includes examples of structural failure resulting from a combination of corrosion and soil degradation (Giresini *et al.*, 2015), and structural reinforcement of corrosion-damaged pipes using an internal composite liner (Taha & Murcia, 2021). Trenchless rehabilitation using GeoSpray geopolymer lining (Liao *et al.*, 2022) and the restoration of the load-bearing capacity of damaged structures under conditions of intensive operational loads (Liang *et al.*, 2024) were analysed. These examples were selected because they represent the main practical scenarios of changes in the technical condition of corrugated steel pipes, ranging from loss of serviceability to restoration of capacity and extension of service life. The analysis was conducted based on the following criteria: characteristics of the event, engineering solution and significance for transport infrastructure. This made it possible to demonstrate the practical manifestations of corrosion degradation, justify approaches to the rehabilitation and reinforcement of structures, and formulate practical recommendations for managing the technical condition, durability and life cycle of corrugated metal pipes as elements of transport infrastructure.

Results and Discussion

Assessment of the corrosion resistance of corrugated metal pipes

Corrosion degradation of corrugated metal pipes is predominantly electrochemical in nature and occurs as a result of the metal contacting an electrolyte, which, under operational conditions, is affected by groundwater, moist soil or saline solutions. The intensity of corrosion is determined by the chemical composition of the environment, the pH level, the oxygen content, the concentration of aggressive ions and the condition of the metal surface. In an alkaline environment, steel can become passivated; however, in the presence of chlorides, the protective layer is disrupted, whereas in an acidic environment, corrosion activity increases and localised damage intensifies (Mundra & Provis, 2021; Chenghui *et al.*, 2024). For corrugated metal pipes, localised corrosion is the most dangerous, as these structures function as thin-walled shells within the "soil-structure" system. This results in a reduction in effective wall thickness, leading to a decrease in stiffness, a loss of local stability, and a redistribution of stresses within the shell. Even minor local metal loss can cause the development of local deformations and a reduction in the structure's remaining service life (Alam *et al.*, 2021; Ezzeldin *et al.*, 2024b).

In underground and water-saturated conditions, corrosion is further accelerated by cycles of wetting and drying, which degrade the protective coating and increase the steel's susceptibility to corrosion (Ezzeldin *et al.*, 2024a). The most vulnerable areas of corrugated metal pipes are the lower part of the casing, the side sections and the crown, where corrosion-induced weakening has the greatest impact on the stress-strain state and geometric stability of the structure (Premasuriya *et al.*, 2025). In the presence of stray currents, the current entry and exit zones also become critical, as local anodic areas with accelerated metal degradation form there (Wang *et al.*, 2024b). From an engineering perspective, such degradation leads to a reduction in the structure's load-bearing capacity, an increased risk of roadbed deformation, and the structure entering a defective or emergency state. Consequently, the corrosion resistance of corrugated metal pipes should be regarded as an integral characteristic reflecting the technical condition, load-bearing capacity and operational safety of the transport structure (Table 1).

Table 1. Effect of aggressive environments on the service life of corrugated metal pipes

Environmental factor	Nature of corrosive effect	Consequences for corrugated metal pipes	Significance for a transport structure
Acidic environment	A decrease in pH accelerates anodic dissolution of steel and hinders the formation of stable corrosion protection products; in the presence of chlorides, the risk of localised damage increases	Both overall metal loss and the development of localised defects in the shell are accelerating	Service life of the pipe is reduced, its rigidity decreases, and the risk of the structure losing its operational reliability increases
Alkaline environment	At high pH values, temporary passivation of steel may occur; however, this effect is disrupted in the presence of chlorides, sulphide-containing compounds, moisture and media heterogeneity	When the passive state is disrupted, localised active areas with accelerated corrosion develop	The beneficial effects of an alkaline environment are not guaranteed and must be assessed based on actual operating conditions
Chlorides	They break down protective films and cause localised corrosion, particularly in acidic environments or those with fluctuating pH levels	They cause a disproportionate loss of rigidity in certain areas of the membrane	Increase the risk of localised damage, which determines the remaining service life of the structure
Sulphates and other harsh ingredients	Alter the electrochemical conditions on the steel surface and influence the composition of corrosion products	Contribute to the long-term development of corrosion in the soil environment	Chemical composition of groundwater is becoming one of the key factors determining a structure's durability
Moisture content and water saturation	Increase the electrical conductivity of the medium, enhance ion mass transfer and facilitate the formation of localised corrosion cells	Accelerate the deterioration of the metal and the protective coating	In areas with unstable water conditions, the risk of structural corrosion significantly increases
Moisturising and drying cycles	These cause periodic activation of the metal surface, changes in salt concentration and the depletion of protective corrosion products	Accelerate the deterioration of the coating and the development of localised corrosion sites	Seasonal fluctuations in humidity have a direct impact on the service life and technical condition of transport infrastructure

Source: compiled by the author based on S. Alam *et al.* (2021), S. Mundra & J. Provis (2021), I. Ezzeldin *et al.* (2024a; 2024b), H. Liang *et al.* (2024), Y.I. Chenghui *et al.* (2024), C. Wang *et al.* (2024a; 2024b)

A corrosive environment should be regarded not merely as a set of chemical characteristics of the soil or water, but as one of the key factors determining the durability of corrugated metal pipes in transport infrastructure. The greatest danger to thin-walled shells arises from conditions in which the chemical aggressiveness of the environment is combined with high humidity, cyclic wetting and damage to the protective coating. Under such conditions, corrosion progresses from material wear to structural weakening, as it reduces the rigidity of the shell and shortens the remaining service life of the structure. Stray currents are one of the most dangerous man-made factors contributing to the corrosion of underground metal structures. They most commonly occur in the vicinity of electrified railways, underground railways and other rail transport systems, where part of the return current is dissipated into the ground and may find a path through underground steel elements. For corrugated metal pipes, this risk is particularly relevant within transport corridors, near electrified tracks and urban rail systems (Liang *et al.*, 2024). The corrosion hazard arises because the current enters the metal in some areas and exits into the soil in others. Anode areas form at the points where the current exits, where intensive electrochemical dissolution of the metal occurs. In contrast to uniform corrosion, this process is localised; therefore, even with a small average metal loss, deep defects and wall breaches can rapidly develop in individual zones (Zou *et al.*, 2024).

For corrugated metal pipes, which act as thin-walled shells, this is dangerous, as local damage leads to a reduction in stiffness, a loss of local stability, and an accelerated transition of the structure to a defective or critical state. In transport infrastructure, this means a reduction in the structure's safe service life, even when the initial condition of the metal and coating is relatively satisfactory (Wang *et al.*, 2024b). Therefore, during the design and operation of corrugated metal pipes in the vicinity of electrified lines, stray currents should be considered as a separate engineering risk factor alongside soil and water aggressiveness, providing for the monitoring of potentials, inspection of the coating condition and assessment of areas of potential current influence (Liang *et al.*, 2024). In the context of transport infrastructure construction, it is advisable to assess the corrosion resistance of corrugated metal pipes not only in terms of the aggressiveness of the environment or the presence of stray currents, but also using a system of quantitative indicators reflecting the rate of metal loss, the degree of structural weakening of the casing and the remaining service life of the structure (Table 2).

Table 2. Indicators for assessing the corrosion resistance of corrugated metal pipes in aggressive environments and under the influence of stray currents

Indicator	Characteristic	Engineering significance for a transport structure
Rate of general corrosion, mm/year	The rate of uniform metal loss in a corrosive environment	Determines the rate at which the design wall thickness decreases and the projected service life of the pipe
Loss of wall thickness, mm	The cumulative reduction in the effective thickness of the metal casing during operation	Affects the stiffness of the shell, the load-bearing capacity and the remaining service life of the structure
Depth and location of localised corrosion damage	Uneven metal degradation; the development of localised, pitting or crevice corrosion	Local defects pose a risk to thin-walled corrugated shells, as they can lead to a loss of local stability and accelerated structural damage
Condition of the protective coating and the metal's ability to passivate	Effectiveness of corrosion protection in acidic, alkaline or chloride-containing environments	Damage to the coating or disruption of the passive state accelerates the onset of degradation and shortens the safe service life
Stray current density/ presence of anodic zones	Electrochemical intensity of the current acting on a metal structure	Can be used for the assessment of the risk of accelerated localised metal loss in the vicinity of electrified transport systems
Reduction in the stiffness and load-bearing capacity of the shell	Transition from material degradation to structural weakening of the pipe	Describes the impact of corrosion on the behaviour of the "soil-structure" system, structural deformation and the operational reliability of transport infrastructure
Remaining service life and the feasibility of refurbishment	The possibility of continued safe operation, reinforcement or restoration without the need to completely replace the structure	A basis for decision-making regarding monitoring, repair, rehabilitation using the pipe-in-pipe method, and the application of GeoSpray

Source: compiled by the author based on S. Alam *et al.* (2021), S. Mundra & J. Provis (2021), I. Ezzeldin *et al.* (2024a; 2024b), H. Zou *et al.* (2024), W. Liang *et al.* (2024), C. Wang *et al.* (2024a; 2024b)

The proposed system of indicators suggests that the corrosion resistance of corrugated metal pipes should be assessed not based on individual environmental factors but rather based on their impact on the rate of metal loss, the nature of localised damage, the degree of structural weakening of the pipe wall, and the remaining service life of the structure. This approach makes it possible to move from a description of corrosion factors to an engineering assessment of the technical condition and the justification of decisions regarding the further operation of the structure. The results of the study showed that the corrosion degradation of corrugated metal pipes in transport structures should be regarded not merely as an electrochemical process, but as a factor affecting the technical condition, durability and operational reliability of the structure, which is determined, in particular, by the pH of the environment and the chloride and sulphate content. This is consistent with the findings of N.T. Chung *et al.* (2021) established that the combination of pH, chlorides and sulphates influences the corrosion behaviour of steel in soil, and that chlorides and sulphates are factors that enhance corrosion activity. The aggressiveness of the environment should be considered as one of the basic parameters of the durability of metal corrugated pipes in transport infrastructure. At the same time, the research results indicate that the intensity of corrosion degradation is determined not only by the chemical composition of the environment but also by underground operating conditions, in particular water saturation, soil condition and damage to the protective coating. This correlates with the approach of G.M. Castro *et al.* (2025), who demonstrated that the degree of saturation, mineralogy and the content of the fine-grained fraction significantly influence corrosion processes in buried metal elements. In this context, the current results confirm that the most hazardous conditions for corrugated metal pipes are those in which the aggressiveness of the environment is combined with high humidity, an unstable water regime and degradation of the protective layer.

The study by S. Safari *et al.* (2024) examined a corrugated metal culvert prior to its rehabilitation using a geopolymer spray-applied lining. To assess its actual condition, the authors used installed sensors, visual measurement methods and diagnostic load tests in static and dynamic modes, which determined the maximum deformations, evaluated the actual behaviour of the structure under load and compared the obtained results with the calculated ones. This correlates with the results of the current study, which showed that for metal corrugated pipes as thin-walled shells, even insignificant local metal loss must be assessed not only in terms of metal loss but also in terms of its impact on the stiffness, local stability, deformation state and residual life of the transport structure. Stray currents pose a particular threat to corrugated metal pipes within transport corridors. The study's findings established that, in their presence, the areas where the current enters and exits become particularly hazardous, as local anodic zones form there, leading to accelerated electrochemical dissolution of the metal. C. Wang *et al.* (2024a) identified the influence of dynamic stray currents caused by underground rail infrastructure on the corrosion behaviour of buried metal elements. The authors demonstrated that such current effects intensify non-uniform and localised corrosion, altering the nature of the electrochemical damage to the metal. This conclusion is consistent with the findings of the current study, according to which stray currents should be regarded as a distinct man-made risk factor which, when combined with a corrosive environment, can significantly reduce the safe service life of a structure.

C. Bryden & A. Valsangkar (2025) examined the long-term assessment of the design service life of a corrugated metal pipe following rehabilitation with a geopolymer lining, focusing on how the rehabilitation solution affects the structure's subsequent structural performance. The proposed study presented rehabilitation not merely as a means of repairing existing damage, but as an engineering approach to restoring functional reliability and extending the service life of the structure in the long term. In this context, the authors' findings align with the conclusions of the current study, according to which the corrosion degradation of metal corrugated pipes in transport infrastructure should be considered as a basis for decision-making regarding monitoring, reinforcement, rehabilitation and the extension of the structure's safe service life. Thus, the corrosion degradation of metal corrugated pipes in transport structures should be regarded not merely as an electrochemical process, but as a factor in structural weakening, arising under the influence of an aggressive environment, water saturation, damage to the protective coating and stray currents. In this regard, it is advisable to assess the corrosion resistance of such pipes in terms of the degree of structural weakening of the shell and the remaining service life of the structure.

Engineering assessment of corrosion damage to corrugated metal pipes

For thin-walled corrugated pipes, the quantitative assessment of corrosion degradation is critical, as even a slight loss of wall thickness affects the stiffness of the pipe, its local stability and the performance of the "soil-structure" system. The theoretical basis for such an assessment is Faraday's law and its derivatives (equations 1-4), which link the electrochemical process to mass loss of metal, reduction in wall thickness and the rate of its further decrease. In the case of non-uniform corrosion damage, this can lead to local deformations, stress concentrations and a reduction in the structure's remaining service life. Consequently, these relationships make it possible to interpret the electrochemical parameters of corrosion in terms of engineering-relevant indicators of the technical condition of corrugated metal pipes.

To assess the impact of corrosion processes, it is advisable to move from a qualitative characterisation of the aggressiveness of the environment and the mechanisms of stray current action to a quantitative assessment of the rate of metal degradation. A numerical example based on Faraday's law is illustrative in this context. Assuming that an anode current of $I = 1$ A acts uniformly on an area of $A = 1$ m² over the course of one year, the calculated loss of steel wall thickness will be approximately 1.16 mm/year. For corrugated metal pipes with a typical wall thickness of 3-6 mm, such metal loss is of engineering significance, as even over a relatively short period of operation, it can lead to a reduction in the shell's stiffness and a loss of local stability. Even at a lower current density, for example, 0.25 A/m², the calculated thickness loss is approximately 0.29 mm/year, which is also a significant figure for the long-term operation of a transport structure (Liang *et al.*, 2024). Given the possibility of localised current concentration in certain surface areas, the actual rate of metal loss under real-world conditions may be even higher. Thus, a quantitative assessment of corrosion losses is an essential link between the electrochemical description of the process and the engineering evaluation of the structure's technical condition.

An interpretation of the relationship (equation 5) shows that the corrosion rate is directly related to the corrosion current density, i_{corr}; consequently, as the electrochemical activity of the medium increases, the rate of metal degradation increases. For corrugated metal pipes, this means that in acidic environments, where i_{corr} values are generally higher, the corrosive weakening of the casing occurs more intensively, whereas in an alkaline environment, the corrosion process may slow down. At the same time, the engineering significance of this relationship lies not only in determining the corrosion rate, but also in the ability to assess the degree of structural weakening via the corrosion weakening coefficient K_O (equation 6), to establish the time at which a dangerous state is reached according to the criterion (equation 7), and to perform a simplified assessment of the remaining service life based on the relationship (equation 8). Thus, as i_{corr} increases, not only does the loss of wall thickness accelerate, but the metal shell also approaches the critical thickness t_{cr}, at which the conditions for local stability or load-bearing capacity are violated. This ensures a transition from an electrochemical description of the process to a quantitative assessment of the remaining service life and the justification of decisions regarding the strengthening or rehabilitation of the structure. In practical terms, this approach links laboratory-determined electrochemical parameters with the assessment of the rate of metal loss, the degree of structural weakening of the shell, and the remaining service life of the structure. The practical significance of corrosion-induced degradation of corrugated metal pipes in transport infrastructure is illustrated by the examples given in Table 3.

Table 3. Examples of corrosion damage, rehabilitation and reinforcement of corrugated metal pipes

Event description	Subject of analysis / engineering solution	Engineering value for transport infrastructure
Damage to the corrugated pipe during heavy rainfall; corrosion of the invert, combined with soil erosion and softening	Analysis of the causes of the building's collapse	Localised corrosion, combined with soil degradation, can lead to structural failure and the collapse of the structure
A metal pipe damaged by corrosion that required repair without being completely replaced	Reinforcement by installing an internal fibreglass composite liner, followed by load-bearing tests; the technology was regarded as a way of extending the service life by 50-100 years	Confirms that the service life of the pipe can be extended through structural reinforcement
Corrosion-damaged corrugated metal culverts, for which traditional replacement was too expensive or would have had a significant impact on traffic	The rehabilitation was conducted by applying GeoSpray geopolymer coating to the actual transport infrastructure	The effectiveness of trenchless solutions for restoring a structure's functionality without significantly impacting the operation of the infrastructure
Damaged metal corrugated culverts on sections of heavy-haul railways exhibiting structural damage, reduced load-bearing capacity and durability under heavy axial loads	Technology for reinforcing corrugated plates has been proposed and investigated	The issue of damaged pipes is viewed as a matter of service life, load-bearing capacity and the safety of transport infrastructure

Source: compiled by the author based on L. Giresini *et al.* (2015), M.R. Taha & D.H. Murcia (2021), H. Liao *et al.* (2022), M.V. Harkusha (2023)

The presented examples have shown that the corrosion-induced degradation of corrugated metal pipes is not merely a process of material wear and tear, but also a factor contributing to the loss of serviceability and a reduction in the structural reliability of the structure. In particular, the collapse of a corrugated pipe due to a combination of localised pitting corrosion and degradation of the soil environment demonstrated that such damage could lead to a complete loss of serviceability and the need for immediate engineering intervention (Giresini *et al.*, 2015). At the same time, the use of an internal composite liner confirmed the possibility of restoring the pipe's structural integrity without its complete replacement and extending its service life (Taha & Murcia, 2021). Rehabilitation using GeoSpray geopolymer coating has demonstrated the effectiveness of trenchless restoration in situations where traditional replacement would be prohibitively expensive or would entail significant operational restrictions (Liao *et al.*, 2022). The necessity of reinforcing damaged corrugated structures, especially under intensive operational loads, highlights that corrosion-induced weakening must be considered in the context of restoring load-bearing capacity and ensuring the overall safety of transport infrastructure (Luchko & Kovalchuk, 2021; Harkusha, 2023). Thus, the analysed cases confirm that corrosion damage to metal corrugated pipes provides grounds for decisions regarding the reinforcement, rehabilitation or restriction of a structure's operation. As an example of practical application, a field project is presented involving the rehabilitation of a corrosion-damaged corrugated metal pipe using GeoSpray geopolymer coating (Fig. 1).

Figure 1. A practical example of the restoration of a corrosion-damaged corrugated metal pipe using GeoSpray geopolymer coating
Source: H. Liao *et al.* (2022)

The durability of corrugated metal pipes is determined throughout the entire life cycle of the structure and must be ensured as early as the design stage. At this stage, it is necessary to assess the aggressiveness of soils and water, based on pH, chloride and sulphate content, degree of water saturation, moisture regime and the environment's capacity to support electrochemical processes. For structures located within the influence zone of electrified transport systems, this assessment should additionally include the risk of stray currents. The selection of material, protective coating and design allowance for metal loss must be conducted based on the expected aggressiveness of the environment, the service life and the reliability requirements of the structure (Ezzeldin *et al.*, 2024b).

During the construction phase, the quality of the implementation of design solutions, monitoring of the condition of the protective coating and adherence to installation procedures are crucial. For thin-walled corrugated pipes, even localised damage to the casing or the anti-corrosion layer during transport, assembly, backfilling or soil compaction can become the starting point for subsequent accelerated degradation. Therefore, construction supervision must focus not only on checking geometry and joints, but also on preventing initial defects, on which the actual service life of the structure depends (Ezzeldin *et al.*, 2024a; Rahmaninezhad *et al.*, 2025). During operation, the main task is the timely detection of signs of degradation and the assessment of remaining service life. This requires periodic inspections, instrumental diagnostics of thickness loss and shell deformations, and, for structures near electrified lines, monitoring of potentials and areas of possible current influence. Under these conditions, corrosion damage should be viewed not merely as a loss of material, but as a source of operational risks that may manifest as ballast settlement, deformations of the track bed or track area, and a reduction in the intervals between repairs. This approach makes it possible to move from simply recording damage to predicting the technical condition and justifying decisions regarding repair or rehabilitation.

In the event of corrosion-induced degradation, engineering measures should combine structural repair with the restoration of anti-corrosion protection. In the case of localised damage, it may be advisable to reinforce specific areas of the casing, whereas for more advanced degradation, internal lining and rehabilitation using the liner pipe method are effective, as they can restore the structure's functionality without complete dismantling. For structures within the vicinity of electrified transport systems, rehabilitation must also include measures to counteract stray currents. Consequently, ensuring the longevity of metal corrugated pipes requires systematic risk management during the design, construction, operation and repair phases. For the designer, this means the need to account for the aggressiveness of the environment and the risk of stray currents when selecting materials, protective coatings and design allowances for metal loss (Zou *et al.*, 2024). For the operating organisation, this means the need for risk-oriented monitoring of the structure's technical condition, including checks on wall thickness loss, shell deformations, the condition of the invert and, in the event of potential current influence, potentials and areas of anodic corrosion (Ezzeldin *et al.*, 2024b). When selecting a repair method, a differentiated approach is advisable – ranging from local reinforcement to the use of trenchless rehabilitation technologies, depending on the degree of degradation and the remaining service life of the structure.

The results of the study showed that the invert and the lower section of the casing are among the most vulnerable areas of corrugated steel pipes in terms of corrosion degradation, and damage in these specific areas can significantly affect the casing's stiffness, remaining service life and the operational safety of the transport structure. This is consistent with the approach of B. Lassy & A. Hain (2025), who investigated methods for installing invert linings made of ultra-high-strength concrete in corrugated metal pipes and focused on the rehabilitation of the lower part of the structure as the area most vulnerable to moisture accumulation, corrosion products and localised damage. In this context, the authors' results confirm the conclusions of the present study regarding the advisability of considering local repair of the invert as one of the practical engineering solutions in the rehabilitation of corrugated metal pipes.

K. Żakowski *et al.* (2025) summarised methods for assessing the risk of corrosion caused by constant stray currents in underground pipelines, particularly in the vicinity of rail transport systems. The authors demonstrated that the identification of current-affected zones, the assessment of anodic areas, and the organisation of a system for monitoring electrochemical parameters are of key importance. This is consistent with the results of the presented study, where stray currents are considered one of the most dangerous man-made factors in the corrosive degradation of corrugated metal pipes, and the monitoring of potentials, coating condition and areas of possible current influence is identified as an essential component of operational supervision. Consequently, for structures located near electrified transport systems, the corrosion risk must be assessed not only based on the characteristics of the soil environment, but also incorporating external current influence.

The results of the current study have shown that internal lining and rehabilitation using the liner pipe method are effective approaches to the restoration of corrosion-damaged corrugated metal pipes. Their application makes it possible to restore the structure's functionality and extend its safe service life without the need for complete replacement. This is confirmed by Z.K. Kouchesfehani *et al.* (2021), who, based on field data, examined the rehabilitation of culverts using cement-geopolymer sprayed lining and assessed the actual condition of the structure following the rehabilitation. The authors analysed the field characteristics of the structure, the specifics of the lining installation, and the results of the post-repair inspection, which addressed the suitability of this technology for the practical rehabilitation of the culvert without significantly disrupting the structure's operation. The results showed that cement-geopolymer sprayed lining can perform not only a repair function but also a structural restoration function, ensuring an extension of the pipeline structure's service life. It is advisable to transition from the identification of corrosion damage to the justification of decisions regarding the reinforcement, rehabilitation and extension of the structure's service life.

In a study by S. Raut *et al.* (2024), three-dimensional finite-element modelling was conducted on corrugated metal pipes repaired using sprayed linings, with an analysis of their performance under shallow burial conditions. The authors concluded that the use of sprayed pipe linings can alter the pipe's deformation behaviour, reduce deformations and improve the structural performance of the system following damage. This is consistent with the results of the present study, in which rehabilitation without complete pipe replacement is considered substantial for the engineering management of residual life. In cases of significant corrosion degradation, it is advisable to assess not only the extent of metal loss but also the effect of the rehabilitation solution on reducing deformations and extending the structure's safe service life.

The study found that the greatest risk to metal corrugated pipes stems from a combination of a corrosive environment, high humidity, damage to the protective coating and the effects of stray currents; under such conditions, corrosion degradation becomes localised and escalates from material wear to a structural issue. This correlates with the findings of W. Lan *et al.* (2025), who analysed the mechanisms of pipeline corrosion in the presence of coating defects under alternating current conditions and examined in detail the interphase processes developing in the zone of the damaged protective layer. The authors established that the combination of a coating defect and electrical influence creates conditions for the intensification of local electrochemical damage to the metal, altering the nature of the corrosion process and increasing the risk of its accelerated development. Coating degradation should be regarded not as a secondary defect, but as one of the key factors in the reduction of corrosion resistance and operational reliability of corrugated metal pipes.

Thus, the impact of aggressive environments and stray currents should be regarded not only as a cause of corrosive wear of metal, but also as a factor contributing to the structural weakening of transport infrastructure. For corrugated metal pipes, this manifests itself in accelerated metal loss, the development of localised defects, a reduction in the shell's stiffness, and a shortening of the structure's remaining service life. In practical terms, this can deform the carriageway or track structure, result in a reduction in the intervals between repairs, and necessitate operational restrictions. For this reason, the corrosion resistance of such pipes should be assessed in terms of the degree of structural weakening of the shell and the remaining service life of the structure.

Conclusions

The results of the study established that the key factors contributing to the corrosion degradation of corrugated metal pipes are the aggressiveness of the soil-water environment, high humidity, damage to the protective coating, and the effects of stray currents. For thin-walled corrugated casings, localised metal loss is the most dangerous, as it leads to a disproportionate reduction in stiffness, a loss of local stability and a reduction in the structure's remaining service life. The most vulnerable areas are the lower zone of the casing, the invert, the side sections and the crown, where corrosion-induced weakening has the greatest impact on the structural performance of the "soil-structure" system. The assessment of the corrosion resistance of corrugated metal pipes should be conducted not only based on environmental characteristics, but also using a system of engineering-relevant indicators, which include the rate of metal loss, loss of wall thickness, localisation of damage, condition of the coating, presence of anodic zones, change in stiffness and remaining service life.

A theoretical analysis based on Faraday's law has shown that even a relatively small reduction in wall thickness is significant for pipes with a metal thickness of 3-6 mm and must be considered when assessing the technical condition of the structure. This paper proposes an engineering approach to assessing the corrosion degradation of corrugated metal pipes based on the corrosion weakening coefficient and critical wall thickness as criteria for transition to a hazardous technical condition. This approach makes it possible to link the electrochemical characteristics of corrosion with the parameters of stiffness, local stability and the remaining service life of the structure. The practical significance of the proposed approach lies in the ability to assess the technical condition, predict the remaining service life and justify decisions regarding the monitoring, reinforcement and rehabilitation of metal corrugated pipes. A limitation of the study is its theoretical nature, without experimental, field or numerical verification of the influence of corrosive factors on the condition of metal corrugated pipes. Future research should focus on developing predictive models of service life, risk-oriented monitoring systems, and criteria for selecting effective methods of strengthening and trenchless rehabilitation of corrugated metal pipes in real-world transport infrastructure conditions.

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Вплив агресивних середовищ та блукаючих струмів на корозійну стійкість металевих гофрованих труб

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Анотація. Метою дослідження було з'ясування ролі корозійного пошкодження металевих гофрованих труб у формуванні довговічності, технічного стану й експлуатаційної надійності транспортних споруд. Методологія базувалась на методах систематизації, інженерного, теоретичного аналізу, ілюстративного розрахунку, аналізу практичних прикладів. Встановлено, що корозійна деградація металевих гофрованих труб має переважно електрохімічну природу й визначається агресивністю ґрунтового та водного середовища. Найбільшу небезпеку для таких конструкцій становить локальна корозія, оскільки вона безпосередньо знижує жорсткість оболонки, місцеву стійкість і залишковий ресурс споруди. У підземних і водонасичених умовах корозія прискорюється через цикли зволоження-висушування, які руйнують захисне покриття та підвищують вразливість металу. Блукаючі струми в зоні електрифікованих транспортних систем є окремим техногенним чинником ризику, що викликає локальні анодні ділянки та прискорене ураження металу. Показано, що корозійну стійкість металевих гофрованих труб слід оцінювати не лише за агресивністю середовища, а й за системою кількісних показників, що відображають швидкість металовтрати, локальні пошкодження, зміну жорсткості та залишковий ресурс споруди. Кількісне оцінювання на основі закону Фарадея показало, що навіть відносно невелика втрата товщини стінки є інженерно значущою, оскільки впливає на довговічність, технічний стан і безпеку експлуатації транспортної споруди. Запропоновано інженерний підхід до оцінювання корозійної деградації металевих гофрованих труб на основі коефіцієнта корозійного ослаблення, який характеризує відносну втрату товщини металевої оболонки та її наближення до критичного стану. Для інженерного оцінювання залишкового ресурсу використано спрощену залежність, що пов'язує початкову товщину, критичну товщину та швидкість корозії. Практична значимість полягає у можливості застосування результатів проєктувальниками, експлуатуючими організаціями та фахівцями з діагностики під час проєктування, експлуатації, обстеження та реабілітації металевих гофрованих труб у транспортних спорудах

Ключові слова: деградація; залишковий ресурс; стійкість; експлуатація; споруди