Civil and Environmental Engineering
Vol. 0, Issue 0, DOI: 10.2478/cee-2026-0070

Update of Corrosion Maps in Slovakia and Prediction of Reinforced Concrete Beam Service Life Using Dose-response Functions (2017–2024)

Michal ZAHURANEC[1,*], Peter KOTEŠ[1], Martin VAVRUŠ[1], Andrej KRIŠTOF[1]

[1] Department of Structures and Bridges, Faculty of Civil Engineering, University of Žilina, Univerzitná 8215/1, 010 26 Žilina, Slovakia.

* corresponding author: michal.zahuranec@uniza.sk

Date of Submission: 26 November 2025
Revision Date: 09 December 2025
Date of Acceptance: 09 December 2025

Civil and Environmental Engineering
Journal of the Faculty of Civil Engineering | University of Žilina

Abstract
Reinforcement corrosion is an increasingly serious issue worldwide. The structures gradually lose their load-bearing capacity, reliability and service life of the buildings decrease. Humankind should monitor and solve the problem of corrosion. From this reason, the research is focused on effect of corrosion on the structures not only in Slovak Republic. This study continues the previous work (Strieška et al., 2018), where were investigated corrosion maps of carbon steel (reinforcement in Slovakia between years 2004-2017. A dose-response function was used to evaluate the effect of corrosion on steel rebar. Input data for the corrosion models were obtained from the Slovak hydrometeorological institute database. Corrosion losses for individual monitoring stations across the Slovak Republic were determined by calculation. Corrosion maps were visualizing in programs Gimp and Qgis. The results were processed in the coordinate system WGS 84. The results are corrosion maps of corrosion losses per year between years 2017-2024 in Slovak Republic. Following, the effect of corrosion was applied on the structural beam subjected to bending and exposed in the aggressive corrosion environment. These examples were developed for the monitoring stations, where corrosion risk was the highest, and lowest in Slovak Republic and for the station Žilina. The graphs illustrate expected reduction in beam capacity subjected to bending caused by the corrosion of reinforcement over a 100-year period. The research demonstrates that the effect of corrosion significantly affects the structural reliability and durability. The analysed beam demonstrates reduced load-bearing capacity and does not achieve the required load-bearing capacity over a 100-year period.

Keywords
Corrosion maps; Dose-response function; Effect of corrosion; Corrosion rate.

1. Introduction

Corrosion of reinforcement and prestressing steel in concrete and prestressed concrete structures is among the most significant factors affecting their durability and reliability. Although carbon steel, which include reinforcement and prestressing steel, benefits from the protective alkaline environment of concrete, the ingress of aggressive agents such as chlorides or CO_2 leads to depassivation of the passive layer and initiation of corrosion processes (Strieška et al., 2018), (Ni et al., 2025), (Wang et al., 2025), (Haššová et al., 2025). The subsequent corrosion causes expansion of corrosion products

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(rust), the formation of cracks in the concrete cover, spalling, and a reduction of the reinforcement cross-section, which results in a decrease in load-bearing capacity and eventual structural failure (Angst et al., 2009), (Bertolini et al., 2013), (Barradas-Hernández et al., 2025), (Ding et al., 2025), (Li et al., 2025).

It is therefore essential to study this issue thoroughly from multiple perspectives — including materials engineering, structural design, and operational maintenance. In practice, neglecting timely corrosion diagnostics can have tragic consequences. Notable examples include bridge collapses that have already resulted in loss of life — such as the infamous collapse of the Morandi Bridge in Genoa in 2018 — as well as less publicized failures of smaller bridges and buildings, where advanced reinforcement corrosion was the main contributing factor. Even in Central Europe, traffic restrictions due to reduced load-bearing capacity, and in some cases the unplanned closure of bridges caused by diagnosed corrosion-induced loss of structural capacity, have repeatedly been necessary, leading to serious economic and logistical impacts.

As Moravčík and Kraľovanec (Moravcik and Kralovanec, 2024) points out, corrosion is a “silent killer” of structures – it acts inconspicuously over time but gradually undermines the integrity of elements, reduces their load-bearing capacity reserve, and increases the risk of sudden failure. From the perspective of public safety, it is therefore not sufficient merely to design structures with an assumed service life; it is essential to continuously monitor their condition and the aggressiveness of the environment to which they are exposed. This is even more significant in the era of climate change and increasing traffic loads, which intensify the exposure of structures to aggressive substances (particularly chlorides from winter road maintenance).

Corrosion maps are a fundamental tool for understanding the spatial variability of environmental aggressiveness, for planning effective maintenance, and for minimizing the risk of catastrophic infrastructure failures. Without their regular updating, the process of designing and managing civil structures cannot be sufficiently safe or economically sustainable.

To manage these risks effectively, the concept of corrosion maps has been developed, enabling the geographic representation of the average or expected corrosion aggressiveness of the environment. Corrosion maps serve as an essential basis for designing durable structures, planning protective measures, determining maintenance intervals, and managing the overall life cycle of built assets (Morcillo et al., 2015).

Historically, the first systematic corrosion maps emerged as early as the mid-20th century, particularly in Europe and North America. The rapid growth of industrial production during the 1950s and 1960s led to high concentrations of sulphur dioxide (SO_2) and a dramatically increased aggressiveness of urban atmospheres. Pioneering studies in Sweden and the United Kingdom included the exposure of carbon steel and zinc at out-door testing stations and produced the first maps of annual material loss (Tidblad et al., 2014), (Recha, 2025), (J. Kozak et al., 2014).

These early maps were relatively coarse in resolution and based on simple averaging of measurements. Over time, however, the need arose for a methodologically consistent assessment, which led to the development of ISO 9223 (ISO 9223:2012), introducing atmospheric corrosivity categories (C1–CX) based on measured or estimated metal loss rates. Standards such as ISO 9224–9226 (ISO 9224:2023), (ISO 9225:2012), (ISO 9226:2012) subsequently define how these losses are deter-mined and modelled (ISO 9223: 2012).

Modern approaches make use of the availability of environmental data (such as SO_2 and chloride concentrations, as well as meteorological variables) and geographic information systems (GIS) to create interpolated maps of environmental aggressiveness. Geo-statistical methods such as kriging or inverse distance weighting (IDW) allow the estimation of values between measurement points with a controlled degree of uncertainty. The result is higher-resolution maps that can be used for maintenance planning in urban, industrial, and coastal areas exposed to marine aerosols (Morcillo et al., 2015).

Studies conducted abroad have also shown that more sensitive and modern methods can reveal higher levels of aggressiveness than earlier assessments suggested. For example, in Colombia, a recent mapping campaign demonstrated that areas originally classified as having a metal loss rate of 2 μm/year in fact reached values exceeding 5 μm/year when finer interpolation and actual surface humidity were considered (Morcillo et al., 2015), (Santa, et al., 2022). In Mauritius, kriging interpolation combined with climatic data identified “hot spots” where the ISO category increased from C2 to C3, which has a significant impact on the design of protective systems (King, F.; et al., 2024).

A new trend is the development of probabilistic corrosion maps, which indicate not only the average expected material loss but also the probability of exceeding a given threshold value. This approach was recently applied, for instance, on the island of Oahu (Hawaii, USA), where the high variability of marine aerosols caused differences ranging from 4 μm/year to more than 10 μm/year depending on exposure and humidity. Detailed probabilistic modelling demonstrated that the risk of exceeding the limit values in some areas was up to twice as high as originally expected (Ghosh, R. et al., 2024).

In Slovakia as well, there is an increasing need for a systematic update of corrosion maps that would reflect changing environmental conditions—namely, the decline in industrial SO_2 emissions, the growing chloride load resulting from winter road maintenance, and the effects of climate change on temperature and precipitation. The corrosion maps available from 2004–2017 provided a valuable foundation, but their data no longer account for recent trends or regional variations that indicate an increased risk of corrosion in certain parts of Slovakia (J. Kozak, et al., 2015).

The paper, therefore, aims to present an updated corrosion map for Slovakia, developed using dose–response functions to calculate annual carbon steel loss. This approach, recommended by ISO 9223 (ISO 9223:2012), links environmental factors (SO_2 concentrations, chloride deposition, humidity, and temperature) with empirically verified relationships to corrosion rates. Accordingly, the paper focuses on the processing of current national measurement data, their analytical evaluation, and spatial representation within a GIS environment, resulting in a map with finer resolution and higher predictive value.

The outcome is a tool that can be used by designers and managers of transport and civil infrastructure for reliable determination of concrete cover thickness, maintenance planning, and decision-making regarding protective measures. At the same time, this approach supports systematic monitoring of atmospheric aggressiveness and enables prompt responses to environmental changes. Updated corrosion maps thus represent one of the key prerequisites for improving the durability, safety, and cost-effective operation of reinforced and prestressed concrete structures in Slovakia.

2. Materials and Methods

2.1. Input Environmental Data and Resources from the Slovak Hydrometeorological Institute

To update the corrosion maps of Slovakia, the first step involved obtaining current and representative environmental data from the Slovak Hydrometeorological Institute (SHMÚ). The key variables for calculating annual corrosion losses according to ISO 9223 (ISO 9223:2012) and ISO 9224 (ISO 9224:2023) include: sulphur dioxide (SO_2) concentration, carbon monoxide (CO) content as an indicator of traffic-related pollution, relative humidity (RH), average air temperature (T), and the rate of chloride deposition on surfaces.

These data were provided as monthly averages for individual monitoring stations across Slovakia. Since the objective is to track the annual corrosion rate of carbon steel (reinforcement), it is sufficient to average the monthly values at each station to obtain a representative annual mean for each variable. This approach follows ISO requirements, where annual average values are directly used in dose–response equations to estimate corrosion loss.

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2.2. Assumptions for Calculating Corrosion Losses

The current standard, STN EN ISO 9223 (ISO 9223:2012), describes two methods for determining the corrosive aggressiveness of the atmosphere (i.e., its potential to cause corrosion): either measuring the corrosion effect on standard specimens or assessing corrosion activity based on environmental information.

In this paper, corrosion loss is calculated using the dose–response function. This method is based on considering the average values of input parameters such as SO_2 (sulphur dioxide), CO (carbon monoxide), relative humidity (RH), temperature (T), and the rate of chloride deposition.

Over the years, several dose–response functions have been developed for basic construction materials such as carbon steel, zinc, copper, aluminium, masonry, and stone (sandstone, limestone – particularly in the context of historical buildings). This paper focuses on the effects of aggressive atmospheric corrosion on reinforced concrete structures; therefore, the subsequent analysis is restricted to carbon steel. The dose–response function for carbon steel is expressed by Equation (1).

The dose–response function for metal corrosion rate according to the current standard STN EN ISO 9223 (ISO 9223:2012) is expressed as follows:

$$r_{corr,CS} = 1.77 \times [SO_2]^{0.52} \times \exp(0.02 \times Rh + f_{CS}) + 0.102 \times [Cl^-]^{0.62} \times \exp\,(0.033 \times Rh + 0.04 \times T) \qquad (1)$$

$$f_{CS} = 0.15 \times (T - 10)\ for\ T \leq 10°C \qquad (2)$$

$$f_{CS} = -0.054 \times (T - 10) for\ T > 10°C \qquad (3)$$

Then, the approximate formula for the relationship between the sulphur dioxide deposition rate (SO_2) and the sulphur dioxide concentration in air (SO_2, air) is determined by (ISO 9223:2012):

$$SO_2[mg/m^2 \times d] = 0.8 \times SO_{2,air}[\mu m/m^2] \rightarrow SO_{2,air}[\mu m/m^2] = \frac{SO_2[mg/m^2 \times d]}{0.8} \qquad (4)$$

The relationship between the corrosion rate in the first year (r_{corr}) and the mass loss in the first year (ML) is expressed as:

$$r_{corr}[\mu m/year] = \frac{ML[g/m^2 \times year]}{\rho[g/cm^3]} \qquad (5)$$

2.3. Methodology for Modelling and Visualizing Corrosion Maps

The software tools Surfer and QGIS were used for processing and visualizing the resulting annual corrosion loss values. The input data consisted of point values of corrosion loss assigned to the geographic coordinates of monitoring stations in the WGS 84 coordinate system (GPS). In Excel, a table was created with three columns: longitude (λ), latitude (ϕ), and the measured or calculated corrosion loss value (r_{corr}).

For data interpolation, the geostatistical method of kriging was applied in Surfer, allowing the creation of a regular grid of values with a defined resolution. The grid parameters were set to cover the entire territory of Slovakia with some margin, and the optimal cell size was determined as 5 × 5 meters (spacing = 0.005°). This resolution ensures sufficiently detailed yet still comprehensible maps. After defining the grid boundaries and parameters, the computation was executed, resulting in an interpolated grid saved in XYZ format.

The data were then imported into QGIS and loaded as a raster layer. Visualization was set up using a single-band pseudo colour display with linear interpolation and the Spectral colour scale (including an inverted colour map for better differentiation of values). To ensure the map accurately represented the territory of Slovakia, administrative boundaries (e.g., country outline, regions, districts) from the GADM layer were added to the project. The outline symbology was set to a thin black or blue line with a width of 0.1 mm, providing clear and legible boundaries.

The resulting map thus visualizes the predicted or calculated annual corrosion loss values of carbon steel across Slovakia in accordance with the environmental input data and interpolation. The map was exported from QGIS as a publication-ready image file, suitable for further analysis if needed.

2.4. Selected Coordinate System for Corrosion Map Development

For the development of corrosion maps, the geodetic reference system WGS 84 (World Geodetic System 1984) was selected, as it represents a global standard for geolocation and satellite-based applications (e.g., GPS). This system uses geographic coordinates (latitude and longitude) and provides a unified reference framework for processing and comparing spatial data at an international level.

Data visualization in WGS 84 is commonly based on a simple equirectangular projection, which may cause minor visual distortions in regions with a predominantly horizontal extent, such as Slovakia. These distortions are purely graphical and do not affect the accuracy of spatial calculations, interpolation procedures, or the resulting corrosion rate estimates.

The selection of WGS 84 was motivated by its global compatibility, wide support in GIS software (QGIS, ArcGIS, Surfer), and its frequent use in international corrosion and environmental studies. Although the S-JTSK coordinate system is traditionally used at the national level in Slovakia and is better suited for planar representation of the territory, WGS 84 was considered more appropriate for scientific analysis and international data integration. For practical engineering applications or national-level presentations, projection of the results into S-JTSK or UTM may be applied to facilitate interpretation.

3. Discussion

3.1. Average Annual Corrosion Rate (r_{corr}) in Slovakia for 2017

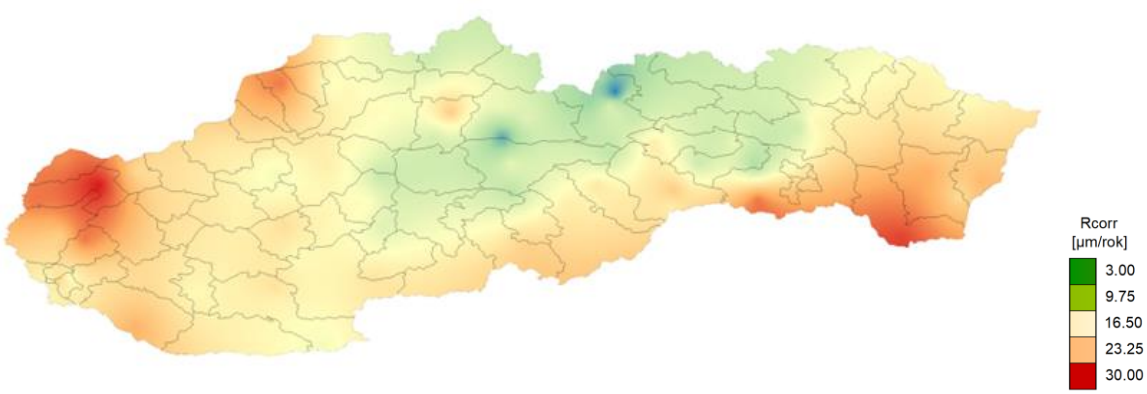


Figure 1: Average annual corrosion rate (r_{corr}) in Slovakia for 2017 (μm/year)

The most affected area in Slovakia in 2017 (Figure 1) was found to be the vicinity of the town of Senica, where corrosion losses reached up to r_{corr} = 30.75 μm/year. Significant corrosion losses were also observed in the eastern part of Slovakia, around the town of Trebišov and the municipalities of Somotor and Moldava nad Bodvou, where corrosion rates ranged between the values r_{corr} = 24-28 μm/year.

The lowest recorded value in Slovakia was measured in the High Tatras, specifically at Lomnický Štít, where the corrosion loss was r_{corr} = 3.22 μm/year. Due to the area's pristine fauna and flora and minimal human access, except for a few tourist hotels, air pollution is significantly reduced. This location therefore represents the most favourable conditions for corrosion resistance of reinforced concrete structures.

3.2. Average Annual Corrosion Rate (r_{corr}) in Slovakia for 2018

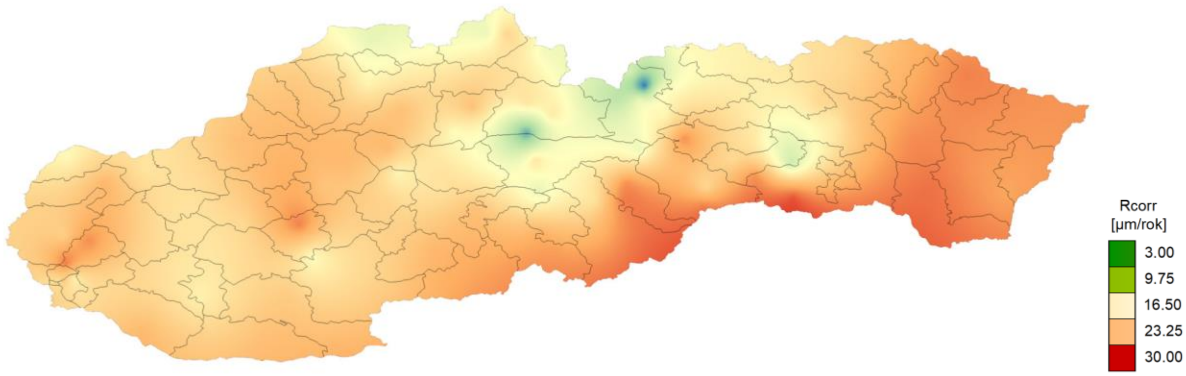


Figure 2: Average annual corrosion rate (r_{corr}) in Slovakia for 2018 (μm/year)

The corrosion map for 2018 (Figure 2) demonstrates values ranging from r_{corr} = 4.38-26-82 μm/year. The most affected areas in Slovakia were recorded in the southern and eastern regions. The highest calculated corrosion loss was observed at the Moldava nad Bodvou monitoring station, where r_{corr} = 26.82 μm/year. In contrast, the lowest corrosion loss in 2018 was recorded at the Lomnický Štít station, with a value of r_{corr} = 4.39 μm/year. The most favourable conditions across the entire region were again found in the Tatras and Liptov areas.

3.3. Average Annual Corrosion Rate (r_{corr}) in Slovakia for 2019

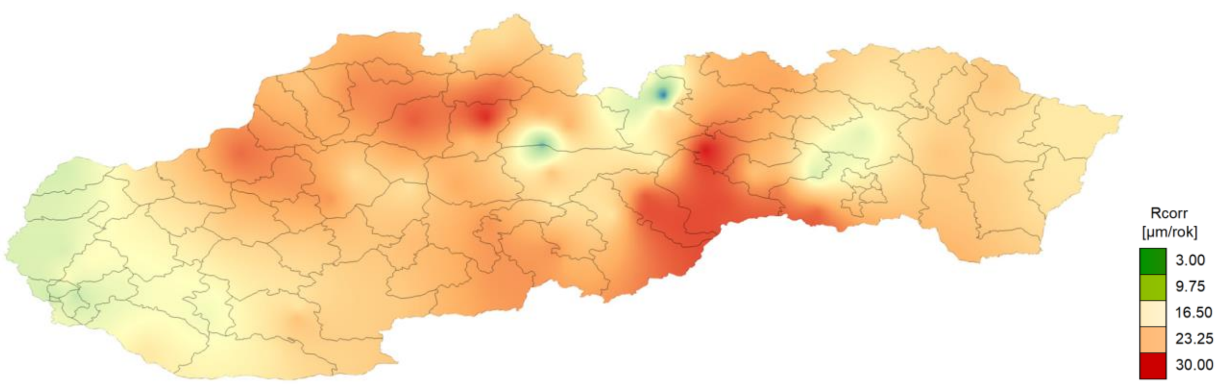


Figure 3: Average annual corrosion rate (r_{corr}) in Slovakia for 2019 (μm/year)

In 2019 (Figure 3), corrosion loss values ranged from r_{corr} = 4.65-25.29 μm/year. The corrosion map for 2019 shows slight changes compared to previous years. The most affected areas in Slovakia during 2017 and 2018 were located in the eastern part of the country. In 2019, however, measured values in these regions slightly improved. While Somotor and Moldava nad Bodvou were among the most heavily impacted areas in previous years, in 2019 the corrosion rates there ranged between r_{corr} = 19.17- 22.44 μm/year. The highest calculated corrosion loss in 2019 was recorded at the Krompachy monitoring station, reaching r_{corr} = 25.29 μm/year. Notable locations include the vicinity of Rožňava, where corrosion caused a loss of up to 23.38 μm of reinforcing steel, and the municipality of Ratková, Revúca District, in southeastern Slovakia, where r_{corr} = 23.08 μm/year. The lowest calculated values continued to be observed in the High and Low Tatras, with rates around r_{corr} = 12.29 μm/year.

3.4. Average Annual Corrosion Rate (r_{corr}) in Slovakia for 2020

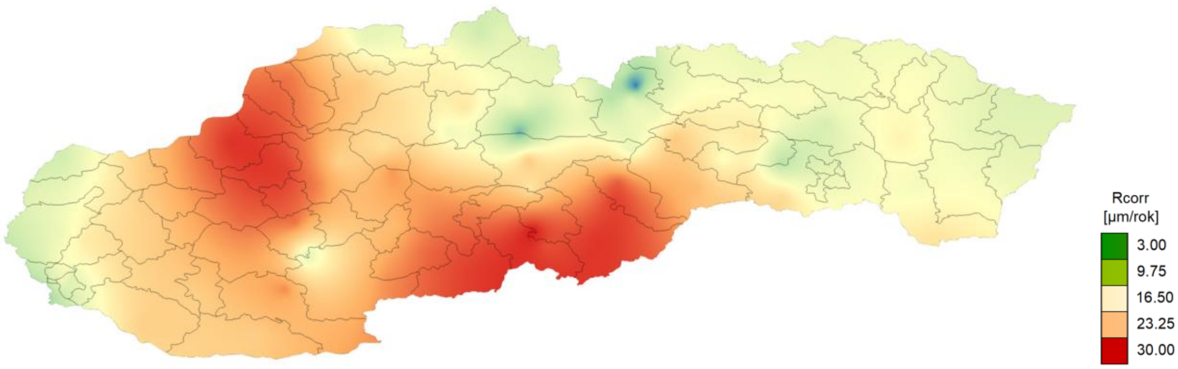


Figure 4: Average annual corrosion rate (r_{corr}) in Slovakia for 2020 (μm/year)

In 2020 (Figure 4), the most affected areas included the regions around the towns of Zvolen, Lučenec, and Rimavská Sobota, where corrosion losses r_{corr} reached up to 24.14 μm/year. Notably high corrosion intensities were also observed in the areas surrounding Trenčín, Bánovce nad Bebravou, and Prievidza.

The lowest corrosion losses were again recorded in the Low and High Tatras. This phenomenon is partly influenced by elevation: higher altitudes experience lower air pollution due to reduced human activity, while rapid wind flow between the mountain peaks ensures quick air exchange, significantly reducing local pollution and its impact on corrosion. Primarily, these areas are relatively untouched by human activity compared to the lower, more urbanized regions of Slovakia.

3.5. Average Annual Corrosion Rate (r_{corr}) in Slovakia for 2021

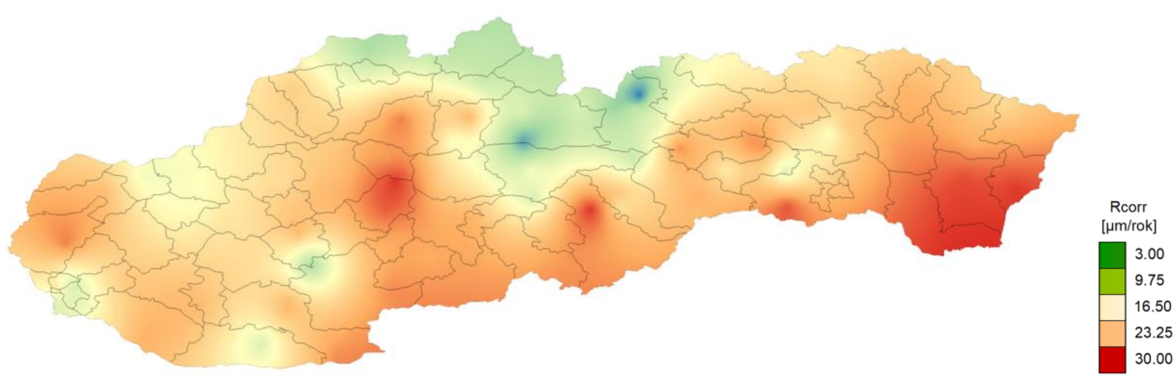


Figure 5: Average annual corrosion rate (r_{corr}) in Slovakia for 2021 (μm/year)

In 2021 (Figure 5), the corrosion map shows areas with elevated corrosion losses, particularly in central Slovakia. The most affected locations are around Banská Bystrica, Zvolen, and Žiar nad Hronom, where local steel loss values range from r_{corr} = 21.61-22.91 μm/year. Another significant area is located near the municipality of Tisovec in the Brezno District. The highest corrosion losses in 2021 are again observed in eastern Slovakia, in the Eastern Slovak Lowland. Representative examples include the towns of Trebišov and Sobrance. For instance, the Trebišov monitoring station recorded a corrosion loss of r_{corr} = 21.54 μm/year, while the area of Orechová, Sobrance District, showed r_{corr} = 22.80 μm/year.

The Tatras remained the least affected, with corrosion rates ranging from r_{corr} = 2.90-7.60 μm/year. Conditions in northern Slovakia also improved compared to previous years, with lower corrosion rates observed in Kysuce, Orava, Martin, and Žilina. Elevated corrosion risk persists in the Western Kysuce area, where higher values have been recorded for a long time. Corrosion losses there typically range from r_{corr} = 16.63-26.00 μm/year. It should be noted, however, that the situation is gradually improving. For example, in 2017, the town of Turzovka, Čadca District, recorded r_{corr} = 26.00 μm/year, whereas by 2021, corrosion losses had decreased to r_{corr} = 16.60 μm/year, representing an improvement of nearly 37%.

3.6. Average Annual Corrosion Rate (r_{corr}) in Slovakia for 2022

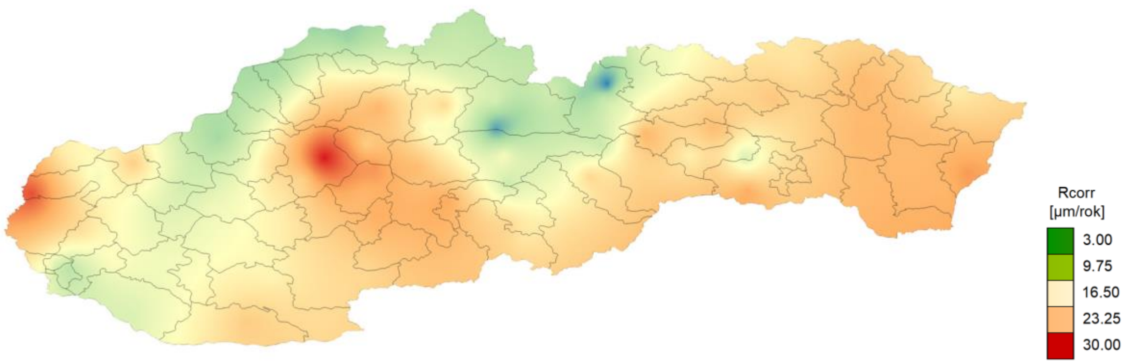


Figure 6: Average annual corrosion rate (r_{corr}) in Slovakia for 2022 (μm/year)

Across Slovakia in 2022 (Figure 6), a general decrease in r_{corr} values were observed. The expanding areas of reduced corrosion intensity indicate an overall slowdown in the corrosion processes, and the regions with the highest corrosion rates have also diminished. The highest corrosion loss in 2022 was calculated for the Bystričany monitoring station, Prievidza District, where r_{corr} = 26.20 μm/year. Conversely, the lowest corrosion losses were, as usual, recorded in the Tatras. For example, at the Lomnický Štít station, corrosion losses in 2022 reached r_{corr} = 3.23 μm/year, and at Chopok, r_{corr} = 5.17 μm/year.

Improvements were also observed in other areas. For instance, in the Kysuce region, the town of Turzovka showed a calculated corrosion loss of r_{corr} = 9.40 μm/year in 2022, representing further improvement compared to previous years. Similar improvements were noted along the D1 motorway corridor. If this trend continues, it could reduce structural degradation in the area over the long term and have a particularly significant impact on bridge structures, especially highway bridges.

3.7. Average Annual Corrosion Rate (r_{corr}) in Slovakia for 2023

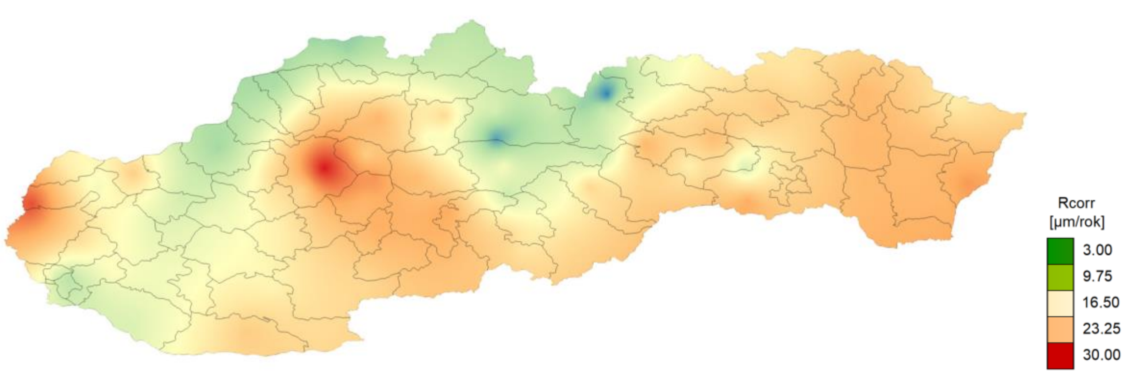


Figure 7: Average annual corrosion rate (r_{corr}) in Slovakia for 2023 (μm/year)

In 2023 (Figure 7), the annual corrosion rate values across Slovakia ranged approximately from r_{corr} = 4.40–26.10 μm/year. The most affected areas were in central Slovakia, particularly around the towns of Banská Bystrica, Prievidza, and Žiar nad Hronom, with the highest corrosion loss again recorded at the Bystričany monitoring station, Prievidza District, r_{corr} = 26.10 μm/year. Conversely, the lowest corrosion losses were traditionally observed in the High Tatras. For example, at the Lomnický Štít station, r_{corr} = 4.40 μm/year, making this area once again one of the most favourable locations for the long-term durability of reinforced concrete structures.

Regionally, there was a slight increase in corrosion aggressiveness in eastern Slovakia, in areas such as Trebišov and Sobrance, where r_{corr} again approached 20 μm/year. In the Kysuce region, specifically in Turzovka, the value was r_{corr} = 10.20 μm/year, representing a slight deterioration compared to 2022, when the value was lower.

Overall, 2023 confirmed the trend of increased corrosion aggressiveness in central Slovakia, while the northern mountainous regions and the Tatras continued to maintain low r_{corr} values.

3.8. Average Annual Corrosion Rate (r_{corr}) in Slovakia for 2024

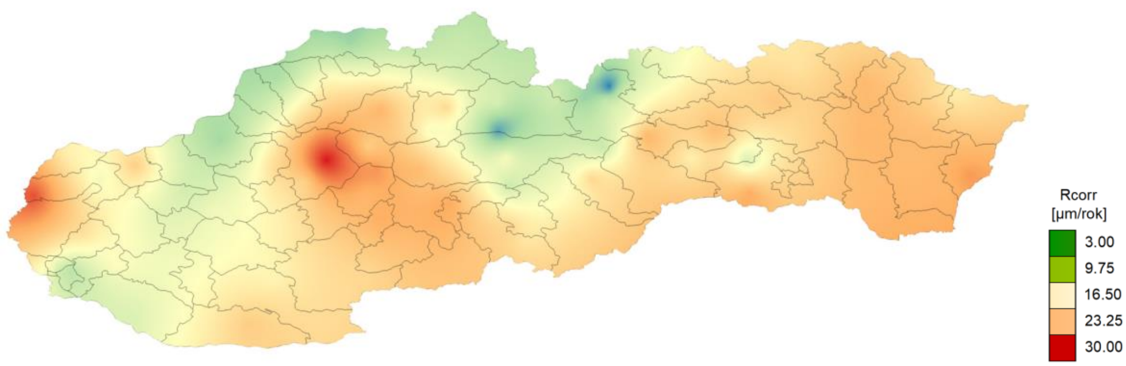


Figure 8: Average annual corrosion rate (r_{corr}) in Slovakia for 2024 (μm/year)

The corrosion loss map for 2024 (Figure 8) shows a continuation of the favourable trend, with a slight decrease in annual steel loss values. The r_{corr} values ranged from 3.80 to 24.60 μm/year. The highest value was again recorded in the Bystričany area, Prievidza District, known for its high corrosion aggressiveness, reaching r_{corr} = 24.60 μm/year. This represents an improvement compared to previous years, when values exceeded 26 μm/year.

The lowest annual corrosion loss was again observed at the Lomnický Štít monitoring station, with r_{corr} = 3.80 μm/year, making this area consistently the most stable in terms of minimal corrosion exposure. Positive developments were also noted in the Turzovka area, where the corrosion loss decreased to r_{corr} = 8.70 μm/year, indicating improvement in the Kysuce region. More significant improvements were observed near Košice, where r_{corr} values decreased compared to 2023.

These observations indicate that 2024 saw improvements in several critical areas, with corrosion levels beginning to stabilize even in regions previously characterized by high aggressiveness. This trend is favourable not only for extending the service life of construction structures but also from an environmental perspective.

3.9. Effect of Corrosion on Durability of Structural Elements over time

In this section, we focus on analysing the impact of the calculated annual corrosion rate on the reduction of flexural capacity of reinforced concrete elements over time. Calculations will be presented for each year from 2017 to 2024, with the aim of evaluating the varying influence of the corrosive environment on the long-term load-bearing capacity of the structures.

For this purpose, three representative locations were selected for each year to cover the full range of conditions across Slovakia:

- Area with the highest r_{corr} value (representing extremely unfavourable conditions).
- Area with a medium r_{corr} value (representing favourable conditions, e.g. mountainous regions).
- Area with the lowest r_{corr} value (representing favourable conditions, e.g., mountainous regions).

The low-aggressiveness reference area was chosen as Lomnický Štít, which has consistently exhibited the lowest corrosion losses. Žilina was selected as the reference area due to its location, availability of environmental data, and connection to the university's academic environment. Areas with the highest corrosion aggressiveness were represented by Krompachy or Bystričany, where the annual corrosion rate has historically reached its highest values.

This set of selected locations allows for a comparison of the durability development of reinforced concrete structures across different regions of Slovakia and enables estimation of their service life in the context of atmospheric aggressiveness. Additionally, accounting for year-to-year changes in r_{corr} allows for tracking trends in corrosion exposure over time and observing regional differences.

The calculation of flexural capacity is based on the formulas derived by Strieška (Strieška, 2019), which follow the principles outlined in the STN EN ISO 9224 standard (ISO 9224:2023) and consider the time-dependent progression of reinforcement corrosion.

The model assumes that during the first approximately 20 years, corrosion develops according to a power-law increase, while beyond this period, the degradation follows a linear trend. This approach allows for a realistic representation of the behaviour of steel reinforcement under long-term exposure to a corrosive environment.

The bending resistance at time t=0, i.e., at the time of construction, is calculated as:

$$M_{Rd} = M_{Rd}(0) = A \times \emptyset^2 - B \times \emptyset^4 \tag{6}$$

The calculation of the bending resistance for the period up to 20 years will be carried out using the following formula:

$$M_{Rd}(t_{as} \leq 20) = M_{Rd}(0) + k_{m1} \times (t - t_0)^b + k_{m2} \times (t - t_0)^{2\times b} + k_{m3} \times (t - t_0)^{3\times b} + k_{m4} \times (t - t_0)^{4\times b} \tag{7}$$

The calculation of the bending resistance for the period beyond 20 years will be carried out using the following formula:

$$M_{Rd}(t_{as} > 20) = k_{m5} + k_{m6} \times (t^*) + k_{m7} \times (t^*)^2 + k_{m8} \times (t^*)^3 + k_{m9} \times (t^*)^4 \tag{8}$$

Where:
M_{Rd}: is a bending capacity of the structure,
Φ: is the diameter of the reinforcement,
t: is time (in years),
k_{m1} – k_{m9}: are empirical coefficients, derived from numerical analysis in Strieška's dissertation (Strieška et al., 2018, Strieška et al., 2019),
b: exponent describing the shape of the corrosion curve,

t_0: initial exposure time,

$t^* = t - 20$: time beyond the 20-year threshold.

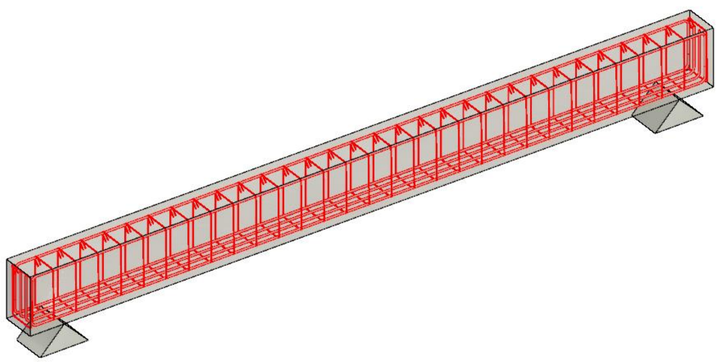
The model therefore accounts for the power-law–linear progression of reinforcement corrosion loss, based on observations reported in ISO 9224 (ISO 9224:2023) and subsequently adapted to the conditions of reinforced concrete elements by Strieška (Strieška, 2019).

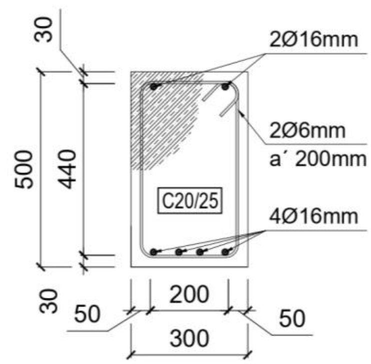
3.9.1. Effect of Corrosion on the Bending Resistance of Beam over Time

The example presented is purely theoretical and does not account for the existence of a passive stage of reinforcement. It is assumed that corrosion of the reinforcement begins immediately upon exposure to a corrosive environment. The duration of the passive stage is neglected (i.e., considered to be zero), and therefore, under real conditions where the passive stage may be significantly prolonged, the actual service life of the structure would likely be longer than predicted by this model.

3.9.2. Effect of Corrosion on the Bending Resistance of Beam over Time

Taking corrosion into account, a reinforced concrete beam model was created with cross-sectional dimensions of 300 × 500 mm and a length of 6000 mm. The beam was designed using C20/25 concrete and reinforced with B 500B reinforcing steel, with 4ϕ16 bars placed at the bottom face (Figure 9).





a) b)

Figure 9: Illustration of the designed beam a) axonometric view; b) cross-section

The structural capacity calculation was carried out based on STN EN 1992-1-1+A1 (Eurocode 2) Design of Concrete Structures (STN EN 1992-1-1+A1,2015). The aim was to design a beam that closely represents real-world examples from construction practice; therefore, a standard reinforcement cover c_{nom}=30 mm was considered in the calculation. The beam was designed to reach 98 % of the ultimate limit state capacity, meaning that the structure was reliably and economically designed while fully complying with the standard's requirements.

The findings confirm that corrosion has a significant long-term effect on the reduction of structural capacity: the higher the r_{corr} value, the faster M_{Rd} decreases. In the case of Senica, with r_{corr} = 30.75 μm/year, the beam's capacity falls below the ultimate limit state after approximately 35 years, indicating that a structure designed for a 50-year service life would not meet reliability requirements in this area.

3.9.3. Effect of Corrosion on the Time-Dependent Resistance of the Element in 2017

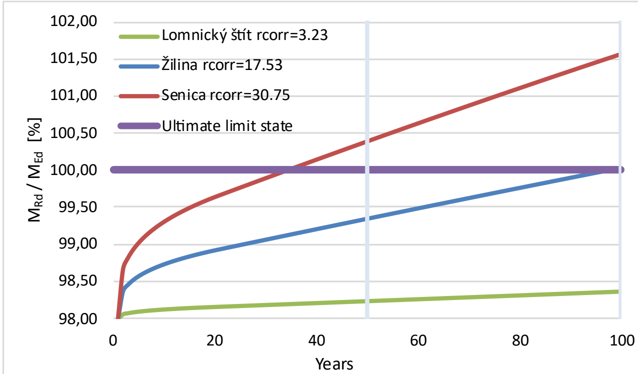


Figure 10: Development of the bending resistance M_{Rd} of the reinforcement concrete beam over 100 years of reinforcement corrosion at different r_{corr} rates depending on location, for the year 2017

Conversely, for the location with the lowest corrosion aggressiveness, Lomnický Štít (r_{corr} = 3.23 μm/year), the reduction in capacity over time is minimal, and even after 100 years, the cross-section remains within the safe range. The location of Žilina, representing average conditions in Slovakia r_{corr} = 17.53 μm/year, lies at the borderline: capacity decreases more slowly, but just before the 100th year, the ultimate limit state may be reached.

3.9.4. Effect of Corrosion on the Time-dependent Resistance of the Element in 2018

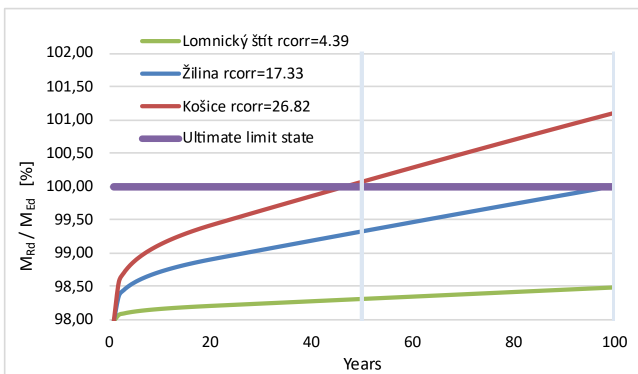


Figure 11: Development of the bending resistance M_{Rd} of the reinforcement concrete beam over 100 years of reinforcement corrosion at different r_{corr} rates depending on location, for the year 2018

Based on the calculated corrosion rates r_{corr} for 2018 (Figure 11), three representative locations with different levels of corrosion aggressiveness were selected: Lomnický Štít as the area with the lowest corrosion rate r_{corr} = 4.39 μm/year, Žilina with a medium rate r_{corr} = 17.33 μm/year, and Košice representing the area with the highest corrosion loss for that year - r_{corr} = 26.82 μm/year.

The calculated development of bending resistance M_{Rd} shows that the impact of reinforcement corrosion differs significantly depending on the location. In Košice, the capacity decreases rapidly, approaching the ultimate limit state before 50 years of service life. At this corrosion rate, the service life of the structure without additional protection would be significantly reduced, which is critical for bridges or other key engineering structures.

Conversely, Lomnický Štít, which traditionally exhibits the lowest corrosion losses, again demonstrates a stable situation. The reduction in capacity over time is negligible, and M_{Rd} remains within the safe range even after 100 years.

Žilina, representing an area with medium corrosion aggressiveness, exhibits a similar trend as in the previous year. The decrease in capacity is gradual and does not exceed the limit values even after 100 years. For a structure designed for a typical service life (e.g., 50 years), an adequate safety margin is maintained.

3.9.5. Effect of Corrosion on the Time-Dependent Resistance of the Element in 2019

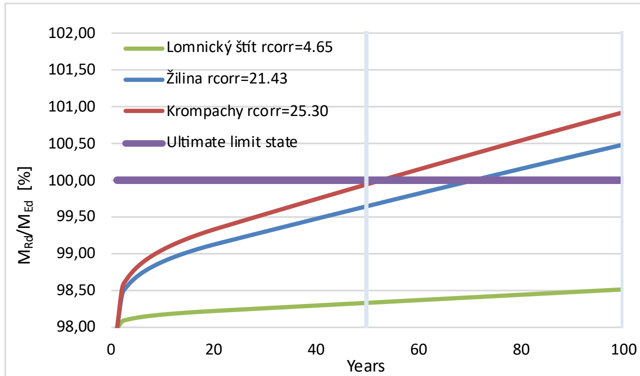


Figure 12: Development of the bending resistance M_{Rd} of the reinforcement concrete beam over 100 years of reinforcement corrosion at different r_{corr} rates depending on location, for the year 2019

For the assessment of the effect of corrosion on the mechanical resistance of the structure in 2019 (Figure 12), three characteristic locations were again selected, representing low, medium, and high levels of corrosion aggressiveness.

Lomnický štít exhibits the lowest corrosion rate r_{corr} = 4.65 μm/year, with Žilina represent-ing medium aggressivity with r_{corr} = 21.43 μm/year, while Krompachy belongs to the re-gions with the highest corrosion rate, specifically r_{corr} = 25.30 μm/year.

The graphical representation demonstrates that the degradation of the structural load-bearing capacity exhibits a distinct local character. In the case of Krompachy, the decrease in resistance occurs more rapidly, with the ultimate limit state being exceeded after approximately 60 years of service life. Such a corrosion rate represents a serious threat to structures designed for a 100-year service life unless appropriate reinforcement protection or an increased concrete cover is provided.

In the Žilina region, which regularly falls within the zone of medium aggressivity, a significant reduction in load-bearing capacity was also observed; however, a structure de-signed with adequate safety reserves should still meet the requirements even after 100 years. Conversely, Lomnický štít once again confirms favorable environmental conditions in terms of atmospheric corrosion. The reduction in resistance is minimal and remains within safe limits throughout the entire period analyzed.

For the year 2020 (Figure 13), three locations representing different levels of corrosion exposure were again analyzed.

Lomnický štít, as the area with the lowest aggressivity, exhibited a corrosion rate of r_{corr} = 3.65 μm/year. Žilina represents a moderately exposed area with r_{corr} = 17.92 μm/year, while Málinec was classified as a high-risk location with r_{corr} = 25.15 μm/year.

The results indicate that, at the highest corrosion rate in Málinec, a significant reduction in the bending resistance occurs over time, with the ultimate limit state being exceeded before 60 years of service life. For structures designed for a 50-year service life, the load-bearing capacity could already be at risk in this location without additional reinforcement protection.

3.9.6. Effect of Corrosion on the Time-Dependent Resistance of the Element in 2020

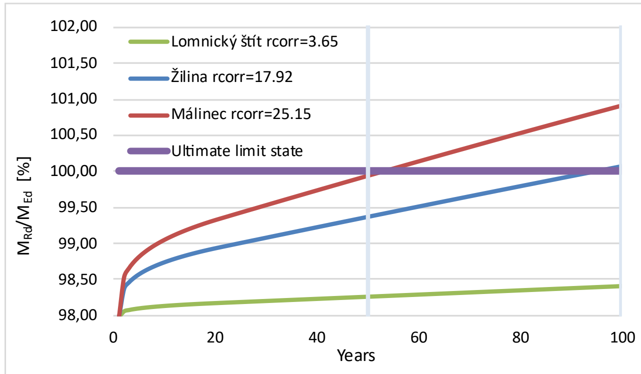


Figure 13: Development of the bending resistance M_{Rd} of the reinforcement concrete beam over 100 years of reinforcement corrosion at different r_{corr} rates depending on location, for the year 2020

In the Žilina area, a gradual decrease in resistance was observed, with the design safety margin remaining sufficient nearly up to the end of the 100-year period. Despite the medium-high corrosion aggressivity, the expected service life can be achieved with proper structural design. Lomnický štít again confirms a stable and favorable environment for reinforced concrete structures. Corrosion-induced degradation is minimal, and the reduction in resistance is negligible, supporting the long-term durability of structures in this area.

3.9.7. Effect of Corrosion on the Time-Dependent Resistance of the Element in 2021

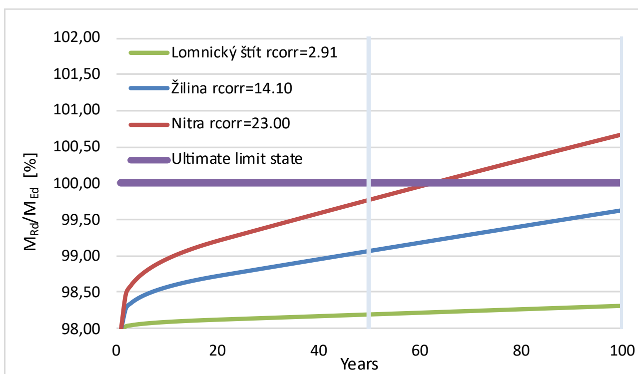


Figure 14: Development of the bending resistance M_{Rd} of the reinforcement concrete beam over 100 years of reinforcement corrosion at different r_{corr} rates depending on location, for the year 2021

For the year 2021 (Figure 14), three locations representing different levels of corrosion aggressivity were selected. Lomnický štít exhibited the lowest annual corrosion rate of r_{corr} = 2.91 μm/year, Žilina, representing an area of moderate intensity, showed a value of r_{corr} = 14.10 μm/year; and Nitra was identified as the most affected location, with r_{corr} = 23.00 μm/year.

The graphical comparison clearly indicates that the highest corrosion rate in the Nitra region leads to the fastest decrease in the bending resistance. The ultimate limit state is reached after approximately 70 years, which may have significant implications for the assessment of the service life of bridge or frame structures designed for higher durability without additional protection.

In the case of Žilina, the decrease in load-bearing capacity is more gradual, and the structure remains functional even after 100 years, although only slightly above the ultimate limit state. For this area, it is advisable to consider preventive measures or more detailed monitoring of reinforcement conditions throughout the service life.

The Lomnický štít location confirms the most favorable conditions in terms of corrosion exposure, as the decrease in load-bearing capacity is negligible and remains well above the ultimate limit state throughout the entire period.

3.9.8. Effect of Corrosion on the Time-Dependent Resistance of the Element in 2022

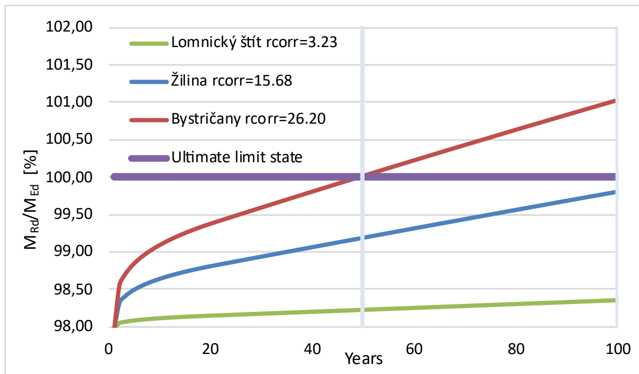


Figure 15: Development of the bending resistance M_{Rd} of the reinforcement concrete beam over 100 years of reinforcement corrosion at different r_{corr} rates depending on location, for the year 2022

As part of the corrosion load assessment for the year 2022 (Figure 15), three representative locations were analyzed. The lowest corrosion rate was again identified at Lomnický štít, with a value of r_{corr} = 3.23 μm/year, the medium level was represented by Žilina with r_{corr} = 15.68 μm/year and the most severe conditions were recorded in Bystričany, where the corrosion rate reached r_{corr} = 26.20 μm/year.

Based on the calculated bending resistance, it is evident that the structure exposed to the corrosion conditions in Bystričany exceeds the ultimate limit state after approximately 50 years, indicating a high level of risk for the long-term durability of reinforced concrete structures in this area.

The moderately aggressive environment in the Žilina region results in a slower decrease in load-bearing capacity; after 100 years, the structure remains slightly above the ultimate limit state, though with a limited safety margin. In this case, it is advisable to consider protective measures already during the design phase, particularly for structures expected to have an extended service life.

In the Lomnický štít area, corrosion practically does not affect the load-bearing capacity over a 100-year period, confirming that it represents one of the most favorable environments in terms of steel corrosion in concrete.

For the year 2023 (Figure 16), three representative locations with varying levels of corrosion exposure were selected: Lomnický štít, with the lowest corrosion rate of r_{corr} = 3.99 μm/year, Žilina, serving as the medium reference location with r_{corr} = 22.91 μm/year; and Prievidza, which in this year exhibited the highest measured corrosion intensity, specifically r_{corr} = 28.41 μm/year.

Based on the calculated bending resistance, it is evident that in the case of Prievidza, the structural element would not reach a 50-year service life, as the bending resistance falls below the ultimate limit state after approximately 45 years. This represents a highly critical area where additional reinforcement protection or a shorter design service life must be considered.

3.9.9. Effect of Corrosion on the Time-Dependent Resistance of the Element in 2023

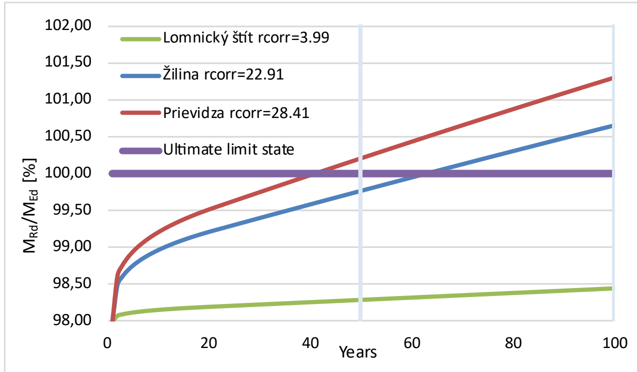


Figure 16: Development of the bending resistance M_{Rd} of the reinforcement concrete beam over 100 years of reinforcement corrosion at different r_{corr} rates depending on location, for the year 2023

The Žilina region shows a more favorable trend yet still represents a moderately aggressive environment; the model indicates that the ultimate limit state is exceeded after about 90 years. In this case, a thicker concrete cover or preventive protective measures at the design stage may be sufficient.

In the case of Lomnický štít, the load-bearing capacity remains virtually unchanged throughout the entire 100-year period, confirming that this location represents an environment with a minimal impact of atmospheric corrosion on the reinforcement.

3.9.10. Effect of Corrosion on the Time-dependent Resistance of the Element in 2024

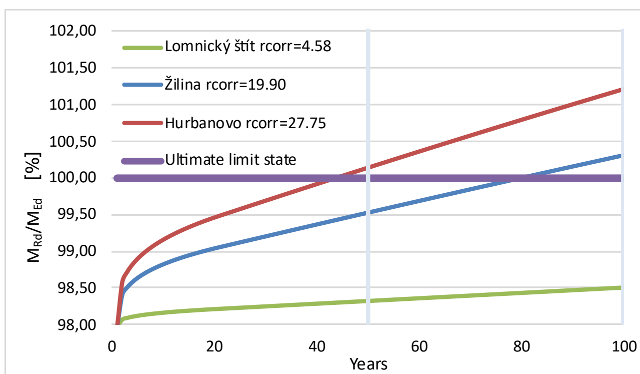


Figure 17: Development of the bending resistance M_{Rd} of the reinforcement concrete beam over 100 years of reinforce-ment corrosion at different r_{corr} rates depending on location, for the year 2024

For the assessment of the effect of corrosion on the bending resistance of elements in 2024 (Figure 17), three characteristic locations were again selected to represent both extremes and the average conditions: Lomnický štít (minimal corrosion exposure r_{corr} = 4.58 μm/year,), Žilina (reference medium value r_{corr} = 19.90 μm/year), and Hurbanovo as the location with the highest corrosion exposure in that year (r_{corr} = 27.75 μm/year).

The results of the bending resistance calculation indicate that in the Hurbanovo region, the load-bearing capacity of the structure would fall below the ultimate limit state after approximately 55 years of service, which necessitates additional design measures or a reduction of the intended service life.

In the case of Žilina, the decrease in resistance is more gradual, with the ultimate limit state reached after approximately 95 years. This scenario represents conditions requiring preventive monitoring; however, if design principles such as adequate concrete cover are properly maintained, a 100-year service life can still be achieved.

At Lomnický štít, virtually no significant reduction in bending resistance is observed even after 100 years, confirming the very favorable environmental conditions in terms of atmospheric corrosion of reinforcement.

4. Conclusion

Based on the results of the processed corrosion maps and the subsequent analysis of the effect of reinforcement corrosion on the load-bearing capacity of reinforced concrete elements, the following conclusions can be drawn:

1. The spatial variability of corrosion aggressivity in Slovakia is significant.

The highest corrosion loss values have been consistently observed in the central and eastern regions of Slovakia (around Prievidza, Bystričany, Trebišov, and Košice), while the lowest aggressivity levels occur in the high-mountain areas of the Tatras. This trend remained stable throughout the analysed period from 2017 to 2024.

2. The overall trend of corrosion aggressivity is slightly decreasing.

Year-on-year comparisons indicate a gradual reduction in r_{corr} values, particularly after 2020. This development is associated with the decline in industrial emissions and improved air pollution control, as confirmed by the shrinking ex-tent of areas with the highest corrosion intensity.

3. In the most at-risk areas, a significant reduction in load-bearing capacity occurs within 40–60 years.

In locations where the annual measured value of r_{corr} exceeds 25 μm/year (e.g., Bystričany, Senica, Hurbanovo), the ultimate limit state of the beam is reached considerably earlier than the standard 100-year design life. This highlights the need for preventive measures already at the design stage, particularly increasing the reinforcement cover or applying additional anti-corrosion protection.

4. Updating corrosion maps represents an effective tool for structural durability management.

The application of dose-response models according to ISO 9223 (ISO 9223:2012) and ISO 9224 (ISO 9224:2023) enables an effective linkage between environmental data (SO_2, chlorides, temperature, humidity) and material corrosion loss. The resulting maps can serve as a basis for design, assessment, and maintenance planning of bridges, tunnels, and other civil engineering structures.

5. The impacts of climate change and traffic loads are manifested regionally.

Increased r_{corr} values in urban areas and near heavily trafficked roads indicate that traffic-related factors (chlorides from winter maintenance, dust, CO) have become a more significant source of corrosion than traditional industrial emissions.

6. Recommendations for Practice. Based on the updated corrosion maps, it can be stated that the majority of Slovakia's territory falls, according to ISO 9223 (ISO 9223:2012), into category C2, corresponding to an average annual steel corrosion rate of up to 25 μm/year. However, the results indicate that in certain regions, particularly in industrial and lowland areas, these values have been consistently exceeded over the long term. Therefore, it would be appropriate to extend future corrosion maps with an additional zone of elevated atmospheric corrosivity that would clearly delineate these areas. When designing structures in such highly exposed environments, it is recommended to increase the concrete cover or use

stainless steel reinforcement to ensure the required reliability and service life of the structure even under above-average corrosion loads.

Acknowledgements

„Funded by the EU NextGenerationEU through the Recovery and Resilience Plan for Slovakia under the project No. 09I03-03-V05-00002".

Author Contributions

P.K. conceived the research idea and supervised the overall study. **M.Z.** was responsible for the methodology development, data analysis, structural calculations, preparation of figures and graphs, and for writing the main manuscript draft. **A.K.** contributed to the processing and visualization of bending resistance results and assisted with data interpretation. **M.V.** contributed to manuscript proofreading, formatting, and preparation of the final version according to the journal template.

All authors critically reviewed and approved the final version of the manuscript and agreed to be accountable for all aspects of the work.

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How to Cite This Article

Zahuranec, M., Koteš, P., Vavruš, M., & Krištof, A. (2026). Update of Corrosion Maps in Slovakia and Prediction of Reinforced Concrete Beam Service Life Using Dose-response Functions (2017–2024). Civil and Environmental Engineering, 0 (0). https://doi.org/10.2478/cee-2026-0070