Sensitivity Analysis of Zinc Dose-response Function according to Actual Standard Approach

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Abstract. One of the reasons for the decrease in reliability of constructions is the corrosion of carbon steel. Many members are made from carbon steel as embedded reinforcement in reinforced concrete (RC) members, steel structures, steel bearings, barriers, rails, etc. These members from carbon steel can be protected by zinc coating. In these cases, the zinc coating layer provides the passive stage during which the steel does not corrode. Therefore, the first-year corrosion rate, as well as the speed of the corrosion during many years, is a very significant parameter for determination of the decreasing the reliability of structure in time. The determination of the corrosivity of the atmosphere can be either on specimens exposed under outdoor conditions or by calculation, according to so-called dose-response function, based on environmental information observed from the public’s hydrometeorological institutes. The paper is focused on sensitivity analysis of zinc dose-response function \( r_{\text{cont,ZN}} \) in the range of input parameter recommended either in the standard STN EN ISO 9223 or in the range of measurement by Slovak Hydrometeorological Institute – SHMI.

1. Introduction
According to the actual standard approach, the resistance of the structure \( R \) is constant in time. So, the reliability margin \( \Delta G \) is also considered constant in time, see equation (1). Nevertheless, it can be seen the degradation of the material, especially corrosion, on various members like RC members (corrosion of reinforcement in superstructure or substructure) [1], steel members as bearings (Figure 1), rails or structural steel trussed footbridge (Figure 2) [2], [3]. A significant problem with material degradation is also in the case of the constructions of cultural heritage [4], [5].

Figure 1. Corrosion on bridge in city Bratislava, Slovakia a) corrosion of RC abutment, b) corrosion of steel bearing
Figure 2. Corrosion of structural steel trussed footbridge in town Prievidza, Slovakia, a) location of corrosion effect, b) detail of corrosion

The reliability margin $G$ in the cases [6], [7], when the corrosion is not detected, is given by equation

$$G = R - E \geq 0$$  \hspace{1cm} (1)

By substituting the time into equation (1), considering the corrosion, the reliability margin in time $G(t)$ can be written by the following formula [8]:

$$G(t) = R(t) - E(t) \geq 0$$  \hspace{1cm} (2)

where:
- $G$ is the reliability margin,
- $R$ is the random variable resistance,
- $E$ is the random variable load effects,
- $G(t)$ is the reliability margin in time,
- $R(t)$ is the random variable resistance in time,
- $E(t)$ is the random variable load effects in time.

The zinc coating is widely used not only on structural steel members, but also the embedded reinforcement steel in reinforced concrete structures is coated with zinc, mainly in areas with higher chloride ion concentration, see Figure 3 [9], [10], [11], [12].

Figure 3. Corrosion model of uncoated and galvanized rebar of RC member [9] a), installation of galvanized rebar on bridge in the USA [10] b)
The standard EN ISO 14657 [13] describes the minimum thickness of the zinc coating in Class A:
t = 84 μm for reinforcement ø > 6 mm and t = 69 μm for reinforcement ø ≤ 6 mm.

In the case of structural steel members, as well as RC members, the zinc coating offers the so-called passive stage during which the steel does not corrode. The time of the passive stage is a very significant parameter because during this time, the resistance of the structure is not reduced by corrosion. The calculation of the corrosion loss \( D_{corr,ZN} \) is based on the first-year corrosion rate \( r_{corr,ZN} \). The first-year corrosion rate can be determined either on the specimens (exposed under outdoor conditions during one year) or by environmental information observed from the public’s hydrometeorological institutes, see also Figure 4.

\[
\begin{align*}
    r_{corr,ZN} &= 0.0129 \cdot [SO_2]^{0.44} \cdot \exp(0.046 \cdot Rh + f_{ZN}) + 0.0175 \cdot [Cl^-]^{0.57} \cdot \\
    &\quad \cdot \exp(0.008 \cdot Rh + 0.085 \cdot T)
\end{align*}
\] (3)
where:
- $r_{corr,ZN}$ is the first-year corrosion rate of zinc [μm/year],
- $T$ is the temperature [°C],
- $Rh$ is the relative humidity [%],
- $SO_2$ is the sulphur dioxide deposition rate ($SO_2=0.8\cdot SO_{2\text{air}}$) [mg/(m²·day)],
- $Cl^-$ is the chloride deposition rate measured by the wet candle method [mg/(m²·day)].

Corrosion loss $D_{corr,ZN}$ for a period less than or equal to 20 years or period greater than 20 years can be calculated according to following equations [15]:

\[ D_{corr,ZN}(t_{as} \leq 20) = r_{corr,ZN} \cdot t_{as}^b \]  
\[ D_{corr,ZN}(t_{as} > 20) = r_{corr,ZN} \cdot \left(20^b + b \cdot (20^{b+1}) \cdot (t_{as} - 20)\right) \]

where:
- $D_{corr,ZN}(t_{as} \leq 20)$ is the corrosion loss up to 20 years [μm],
- $D_{corr,ZN}(t_{as} > 20)$ is the corrosion loss after 20 years [μm],
- $t_{as}$ is the length of the active stage of corrosion [years],
- $b$ is the metal-environment-specific time exponent [-].

The exponent $b$ is in the range from $b=0.813$ to $b=1.00$ (for zinc), depending on the deposition rate of chloride [15]. Thus, the model of corrosion loss of zinc is close to the linear model under 20 years of corrosion (exponent $b=0.813-1.00$, equation (4)), and after this time, the corrosion loss has a linear model (equation (5)).

On the other way, in equation (3) does not seem clear which one of the input parameter the most affect output parameter (first-year corrosion rate $r_{corr,ZN}$). The equation contains not only mathematical expressions like “times” or “plus” but also “exponential-functions” or “power functions”. In this case, the sensitivity analysis can offer the information which one from input parameters the most affect the range of the calculated first-year corrosion rate $r_{corr,ZN}$.

Sensitivity analysis was done in various ways. Firstly, the ranges of input parameters recommended in standard STN EN ISO 9223 [14] was used. Then the range from 30% to 70% of these parameters was chosen as input parameters into the dose-response function. Finally, the sensitivity analysis based on climatic data measured by Slovak Hydrometeorological Institute (SHMI), for simulation the conditions in Slovakia, was made.

### 2. Sensitivity analysis of dose-response function of zinc

#### 2.1. Fixed input values fixed on their mean value

In the first step of sensitivity analysis, the fixed input parameters are fixed on their mean values, and only one parameter is changing from their minimum (represented by 0% in the graphs) for their maximum (represented by 100% in the graphs), horizontal axis in figure 5. The intervals of input parameters, as well as, their mean values used in the analysis are summarized in tables 1, 2, and 3 below.

| Description                      | Symbol | Interval   | Mean value | Unit    |
|----------------------------------|--------|------------|------------|---------|
| Temperature                      | $T$    | -17.1 – 28.7 | 5.8        | [°C]    |
| Relative humidity                | $Rh$   | 34 – 93    | 63.50      | [%]     |
| Concentration of $SO_2$ in the air | $SO_{2\text{air}}$ | 0.88 – 188.0 | 94.44     | [μg/m³] |
| Deposition rate of sulphur dioxide | $SO_2$ | 0.7–150.4  | 75.55      | [mg/(m²·day)] |
| Deposition rate of chloride      | $Cl^-$ | 0.4–760.5  | 380.45     | [mg/(m²·day)] |
Table 2. Input parameters used in sensitivity analysis of zinc dose-response function in range of 30-70% values as is recommended in standard

| Description                          | Symbol | Interval      | Mean value | Unit    |
|--------------------------------------|--------|---------------|------------|---------|
| Temperature                          | T      | -11.97–20.09  | 4.06       | °C      |
| Relative humidity                    | Rh     | 44.20–65.10   | 54.65      | %       |
| Concentration of SO2 in the air      | SO2,air| 1.14–131.60   | 66.37      | [µg/m³] |
| Deposition rate of sulphur dioxide   | SO2    | 0.91–105.28   | 53.10      | [mg/(m².day)] |
| Deposition rate of chloride          | Cl⁻    | 0.52–532.35   | 266.44     | [mg/(m².day)] |

Table 3. Input parameters used in sensitivity analysis of zinc dose-response function in range measured by SHMI in Slovakia

| Description                          | Symbol | Interval      | Mean value | Unit    |
|--------------------------------------|--------|---------------|------------|---------|
| Temperature                          | T      | 2.38–15.00    | 8.69       | °C      |
| Relative humidity                    | Rh     | 68.85–86.00   | 77.43      | %       |
| Concentration of SO2 in the air      | SO2,air| 2.75–18.50    | 10.63      | [µg/m³] |
| Deposition rate of sulphur dioxide   | SO2    | 2.20–14.80    | 8.50       | [mg/(m².day)] |
| Deposition rate of chloride          | Cl⁻    | 0.40–22.00(760.50)³ | 11.20   | [mg/(m².day)] |

³ In the case of splashing transport mechanisms, the range of deposition rate of chloride is up to 760.50 mg/(m².day).

In Slovakia, the deposition rate of chloride has not been measured, so, the two ranges were chosen. The first is in the range from Cl⁻=0.40 mg/(m².day), which is minimum value recommended in standard, to Cl⁻=22.00 mg/(m².day). This interval represents the yearly average value of deposition rate of chloride transported on the zinc by spraying transport mechanisms of de-icing salt [16], [17]. The second interval (Cl⁻=0.40-760.50 mg/(m².day)) represents splashing transport mechanisms of de-icing salt [18]. The difference between these transport mechanisms is that in the first case the chloride reaches the structure by air while in the second by water containing de-icing salt.

Figure 5 shows the calculated first-year corrosion rate based on the four ranges of input parameters, i.e.:
- recommended range in standard (Figure 5 (a)),
- 30-70% of this recommended range in standard (Figure 5 (b)),
- ranges of parameters measured in Slovakia considered spraying transport mechanisms of de-icing salt (Figure 5 (c)),
- simulation of splashing transport mechanisms of de-icing salt in Slovakia (Figure 5 (d)).

The ranges of first-year corrosion rate from figure 5 are summarized in table 4, so that, the minimum value of calculated corrosion rate \( r_{corr,ZN} \) is subtracted from the maximum value (see vertical axis in Figure 5).

Table 4. Sensitivity of calculated first-year corrosion rate of zinc \( r_{corr,ZN} \)

| Changing parameter     | STN EN ISO 9223 (µm/year) | 30-70% of STN EN ISO 9223 (µm/year) | Slovak republic (SR) (µm/year) | SR with max. value of Cl⁻ (µm/year) |
|------------------------|---------------------------|------------------------------------|-------------------------------|-----------------------------------|
| Temperature            | 9.51                      | 3.52                               | 0.43                          | 2.21                              |
| Relative humidity      | 5.63                      | 0.68                               | 0.93                          | 1.17                              |
| Sulphur dioxide        | 1.68                      | 1.00                               | 0.80                          | 0.80                              |
| Chloride               | 2.06                      | 1.38                               | 0.36                          | 2.95                              |
Figure 5. Sensitivity of calculated first-year corrosion rate of zinc (a) recommended range of standard approach, (b) 30-70% of input parameter according to STN EN ISO 9223, (c) range of Slovak Republic, (d) range of Slovak Republic with maximum value of chloride deposition rate

In the range of input parameter recommended in standard (and in their 30-70%), the temperature is the most significant parameter that affects corrosion rate (range of $r_{corr,ZN}=9.51 \, \mu m/\text{year}$ and $r_{corr,ZN}=3.52 \, \mu m/\text{year}$).

The most interesting results are shown in the range of parameters measured in Slovakia. The study indicates that in the case of spraying transport mechanisms of de-icing salt, the range of calculated first-year corrosion rate is on the fourth place (range of $r_{corr,ZN}=0.36 \, \mu m/\text{year}$) but in the case of splashing transport mechanisms the scope of corrosion rate is on the first position (range of $r_{corr,ZN}=2.95 \, \mu m/\text{year}$). So, the scope of chloride deposition rate the most affect the first-year corrosion rate.

2.2. Fixed input values fixed on their minimum, maximum or mean position

In the first step of the sensitivity analysis, always three fixed values were fixed on their arithmetical mean, and one parameter was changing from its minimum to maximum value (Section 2.1 above). However, not only these combinations of input parameters may occur under outdoor conditions but also another combination. Hence, in the second step of the analysis, always one parameter was fixed on its minimum or maximum value, another two was fixed on their mean value, and the last was changing. The ranges of the first-year corrosion rate of zinc are summarized in table 5 (in the case of spraying transport mechanisms of de-icing salt) and in table 6 (in the case of splashing transport mechanisms of de-icing salt).
### Table 5. Range of calculated first-year corrosion rate of zinc $r_{\text{corr,ZN}}$ transported by spraying transport mechanisms in Slovakia

| Changing parameter       | $\text{SO}_2$ min. (µm/year) | $\text{SO}_2$ max. (µm/year) | $T$ min. (µm/year) | $T$ max. (µm/year) | $\text{Rh}$ min. (µm/year) | $\text{Rh}$ max. (µm/year) |
|-------------------------|-------------------------------|-------------------------------|-------------------|-------------------|---------------------------|---------------------------|
| Temperature             | 0.30                          | 0.51                          | -                 | -                 | 0.33                       | 0.58                       |
| Relative humidity       | 0.53                          | 1.18                          | 0.73              | 0.72              | -                         | -                         |
| Sulphur dioxide         | -                             | -                             | 0.63              | 0.59              | 0.54                       | 1.19                       |
| Chloride                | 0.36                          | 0.36                          | 0.21              | 0.61              | 0.33                       | 0.38                       |
| Order of Cl$^-$         | 2$^{\text{nd}}$               | 3$^{\text{rd}}$               | 3$^{\text{rd}}$   | 3$^{\text{rd}}$   | 2$^{\text{nd}}$            | 3$^{\text{rd}}$            |

### Table 6. Range of calculated first-year corrosion rate of zinc $r_{\text{corr,ZN}}$ transported by splashing transport mechanisms in Slovakia

| Changing parameter       | $\text{SO}_2$ min. (µm/year) | $\text{SO}_2$ max. (µm/year) | $T$ min. (µm/year) | $T$ max. (µm/year) | $\text{Rh}$ min. (µm/year) | $\text{Rh}$ max. (µm/year) |
|-------------------------|-------------------------------|-------------------------------|-------------------|-------------------|---------------------------|---------------------------|
| Temperature             | 2.23                          | 2.19                          | -                 | -                 | 2.08                       | 2.34                       |
| Relative humidity       | 0.77                          | 1.42                          | 0.87              | 1.13              | -                         | -                         |
| Sulphur dioxide         | -                             | -                             | 0.63              | 0.59              | 0.54                       | 1.19                       |
| Chloride                | 2.95                          | 2.95                          | 1.72              | 5.04              | 2.75                       | 3.15                       |
| Order of Cl$^-$         | 1$^{\text{st}}$               | 1$^{\text{st}}$               | 1$^{\text{st}}$   | 1$^{\text{st}}$   | 1$^{\text{st}}$            | 1$^{\text{st}}$            |

### 3. Conclusions

The zinc coating is widely used as a protected layer of carbon steel in structural steel members and reinforced concrete members, as well. Thus, it is useful to know the speed of the first-year corrosion rate in various areas. Based on this, the sensitivity analysis of the dose-response function of zinc was done. This analysis shows that in the case of input parameters recommended in standard STN EN ISO 9223 [14], the temperature the most affect the range of calculated output parameter.

In the second step of the analysis, the range of input parameters measured in Slovakia was used. SHMI has not measured only deposition rate of chloride, so, the two ranges of it were chosen. One represents the spraying transport mechanisms of de-icing salt, and another represents the splashing transport mechanisms of de-icing. In the case of spraying mechanisms, the dose-response function is more sensitive on the chloride ions when the sulphur dioxide or relative humidity is fixed on their minimum values (Table 5). So, in these areas, the change in chloride deposition rate more affect first-year corrosion rate $r_{\text{corr,ZN}}$. In the case of splashing transport mechanisms of de-icing salt, the range of chloride deposition rate the most affect the scope of calculated first-year corrosion rate, see Table 6. It means that in areas where de-icing salt is transported on zinc coating by water containing chloride ions, do not depend on which regions of Slovakia is the structure build, the chloride ions the most affect the range of $r_{\text{corr,ZN}}$. For example, when comparison areas where de-acing salt is not splashing on structure with areas where it is splashing on structure, the different in corrosion rate can be from $r_{\text{corr,ZN}}=1.72$ µm/year to $r_{\text{corr,ZN}}=5.04$ µm/year, see Table 6.

It leads to the conclusion, that is important to focus attention on structures, or part of it, where de-icing salt is splashing on structure, or the drainage system of the bridge is damaged and water flows on the structure.

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