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Geostatistic analysis of corrosion in reinforced concrete slabs

Análise geoestatística da corrosão em lajes de concreto armado

Felipe da Silva Barreto[1], Marco Aurélio Chaves Ferro[1]

[1]Universidade Federal Fluminense, Programa de Pós-Graduação em Engenharia Civil. Rua Passo da Pátria, 156, Bloco D, 24210-240, São Domingos. Niterói, RJ, Brasil.

e-mail: fsbarreto@id.uff.br, marcoferro@id.uff.br

ABSTRACT

The objective of this work is to study the behavior of corrosion in reinforced concrete slabs from the point of view of geostatistics. To this end, measurements of electrochemical potentials (reinforcement corrosion potentials) were taken in regions of a reinforced concrete slab, which was divided into smaller areas of the same dimensions in the "x" and "y" directions, respectively. In order to make the study feasible, a sub-region of this slab was separated where the corrosive activity was already more aggressive and the variograms were calculated for the "x" and "y" directions, according to the distances from the measurement points. After a detailed analysis of the results and the creation of graphs for each axis, the equations that best fitted the curves were obtained, in particular the polynomial for the "x" direction and the logarithmic for the "y" direction. From the data obtained, it is possible to understand the spatial extent of the problem, identify the corrosion bands in which each region of the structure studied is located and know the zone of influence of the sub-region used for analysis. The results can be used to choose the best technique for mitigating and combating slab corrosion, as well as for future work.

Keywords: Corrosion in reinforced concrete; Geostatistics; Corrosion in slabs; Corrosion potential.

1. INTRODUCTION

According to the British Cement Association Reinforcement corrosion is the main cause of the degradation of concrete structures. In order to detect damages and avoid this kind of problem, non-destructive testing (NDT) methods are used, and a better estimation of the corrosion spatial and temporal distribution are mandatory for a successful repair project. LI [1] studied the importance of the spatial information involving chloride-induced corrosion, and he showed a considerable effect on the failure risk of the structure. Actual researches have focused corrosion mainly on three approaches, which are spatial distribution with random field modelling, splitting the structure in small elements or considering areas with common properties.

Spatial information about Reinforced Concrete (RC) can be obtained from NDT, for example ground penetrating radar (GPR), rebound hammer, electrical resistivity measurements, concrete cover depth measurements as well as half-cell potential (HCP) mapping. Many of these methods provide information about the spatial distribution of RC parameters or damage. The spatial analysis of such data allows for describing the variation of a parameter in space or estimate the extent of damage for degradation processes with stochastic analysis.

AHSANA *et al.* [2] proposed a Stochastic Analysis of Flexural Strength of RC Beams Subjected to Chloride Induced Corrosion. In this article, it is assumed that the spatial characteristic of HCP can be used as an approximation to describe the spatial variability of the corrosion condition of the reinforcement. The working principle of the HCP is that actively corroding and passive areas of the embedded rebars show a different electrochemical potential, resulting in potential gradients detectable at the concrete surface. Generally, a two dimensional grid (with x and y coordinates) is used to scan the area of interest on the RC structures. It is common to find anisotropy in the HCP field, which has been attributed to material no homogeneity or variable environmental exposure conditions of the corrosion state. The interpretation of measured HCP data is generally based on statistical analysis by evaluating potential gradients or by applying potential threshold values. In summary, data on the spatial variability of deterioration processes in RC structures are needed for different scientific and engineering purposes, for instance, for reliability modelling of the structural condition (random fields)

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or for the optimization of inspection measurements with respect to the number of single measurement points and their distribution over a structure (grid spacing). The present paper focuses on an approach to analyze the spatial variability of corrosion processes by potential mapping (HCP data) using geostatistical techniques. Based on these results, decisions about further repair actions can be made and evaluated from an economical point of view.

2. METHODOLOGY OF DATA GENERATION

2.1. Corrosion of steel

In their initial state, the reinforcements inside the concrete are protected against corrosion by the phenomenon of passivation of the steel, provided if they are in favorable environments and conditions. In environments with alkalinity at normal levels, a microscopic impermeable layer of iron oxide, called passivating film, forms on the surface of steel bars. This film tends to protect corrosion in steel, if there is no contamination [3, 4].

Absorption of water, chlorides, CO_2 and other pollutants are very common to happen in various types of concrete structures, consequently the reinforcements become depassivated and the corrosion process in the structures begins [5]. It is known that water, chlorides and pollutants in general decrease the electrical resistivity of concrete, enabling and facilitating the corrosive process. In addition, the absorption of CO_2 causes the carbonation of concrete, lowering the pH and depassivating the steel in question [6–8].

CASCUDO [9], pointed out that there is a limit deterioration for the reinforcement, which represents the loss of load capacity and the consequent decrease in the useful life of the structure. Considering the importance of the integrity of a structural element, one should seek to combat such deterioration caused by corrosion, which is only possible by recognizing the corrosion rates of the reinforcements embedded in the concrete.

A survey of corrosion potentials is done to identify locations where corrosion is active in existing concrete if there are no external visual indicators. The process of measuring and analyzing corrosion potentials is conducted according to **ASTM C876** (Standard Test Method for Corrosion Potentials of Uncoated Reinforcing Steel in Concrete) [10, 11]. In the field, the procedure should be performed by measuring the potential difference between the steel (rebar) of the structural element in concrete and a reference electrode placed on the pre-moistened concrete surface at the specific locations for measurements [12, 13].

2.2. Electrical corrosion potential

When a metal is placed in an electrolyte, as soil, water, concrete or some other, an electric potential is generated that can be measured with the use of a voltmeter and a reference electrode (Figure 1). This reference electrode, also known as a half-cell, is a piece of equipment that when it turns into contact with the electrolyte closes the electrical contact through the circuit. In this way a potential difference is created between the reference electrode and the metal studied, allowing the verification of the electric potential through the correct procedure [15–17].

The measurement of the electrical corrosion potential, in the case of reinforced concrete structures, is based on the potential difference between the reinforcement and a reference electrode. Typically, a copper-copper sulfate electrode ($Cu/CuSO_4$) or a silver-silver chloride electrode (Ag/AgCl) is used, the first option

Figure 1: $Cu/CuSO_4$ Reference Electrode, examples of electrodes. Source: adapted from TINKER & RASOR [14].

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being best accepted by most engineers. This electrode is positioned on the surface of the concrete, connected to the negative pole of a voltmeter (or multimeter) of high impedance, while the positive pole of this voltmeter (or multimeter) is connected to the reinforcement as can be seen in Figure 2. This measurement process should be carried out with caution, as it can be altered by several factors [18].

Some of these factors are: the Moisture Content of the Concrete; the Armor Covering Thickness; the possible Erratic Currents (the presence of external electrical interferences, which can cause changes in the measurements of potentials); Concrete Carbonation (a physicochemical process between the carbon dioxide present in the atmosphere and the cement paste compounds, acting from the outside into the reinforced concrete, causing errors in the measurements); and Amount of Salts in Concrete (the presence of dissolved salts in the pores of the concrete facilitates the flow of current, allowing a measurement in an altered way). These measurements must present reliable results, as they can classify the state of corrosion of the steel of a given structural element [19–21].

2.3. Procedures and evaluation of potentials

As described in some technical documents, the technique of measuring potentials in concrete structures is the main and most advantageous method available for a non-destructive evaluation of the concrete surface, in relation to the probability of corrosion in the reinforcements. This can be affirmed by several authors, when it is verified that this technique, besides being non-destructive, is non-perturbative, simple, low cost and easy and fast to apply [22, 23].

According to DUTRA and NUNES [13], it is necessary to carry out a mapping of potentials along the concrete surface, taking some additional care since the measurements can be carried out in the most different types of existing structures (Figure 3 is an example of potential measurement in concrete, taking the necessary care). Such additional precautions are:

1. Use only voltmeters with impedance equal to or greater than 10M.Ω;
2. Use an appropriate reference electrode, in this case $Cu/CuSO_4$;

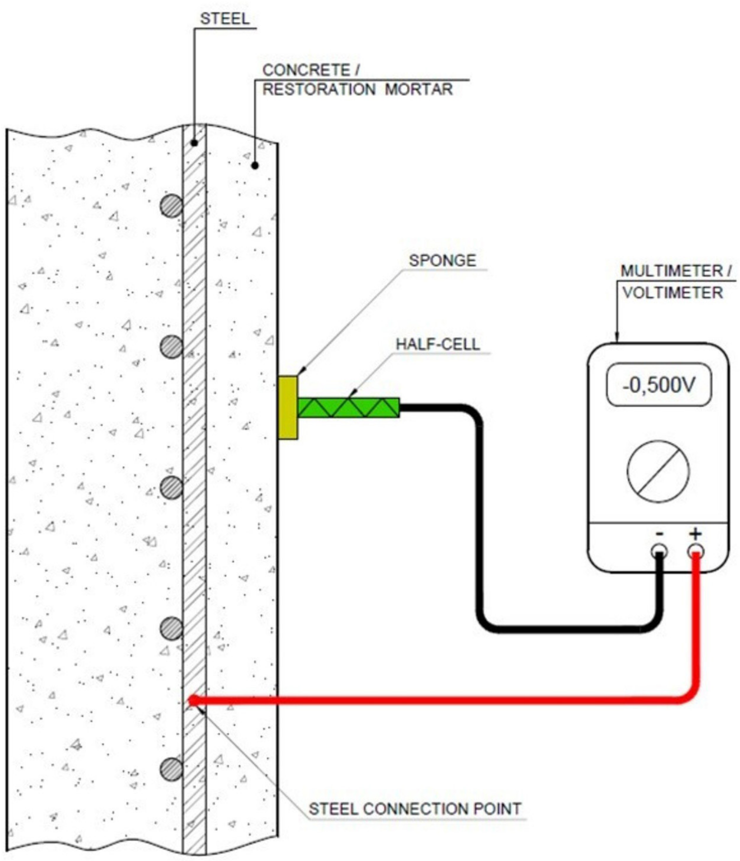

Figure 2: Schematic drawing on the measurement of corrosion potential. Source: the authors.

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3. The reference electrode has a porous tip (in ceramic), at this end it is recommended that a moistened sponge be inserted in order to increase and better the electrical contact of this circuit;
4. Where necessary, the concrete at the measuring site should be pre-moistened;
5. If necessary, seeking to reduce the electrical resistivity of the concrete in the piece, it is allowed to apply a saline solution on the face of the concrete in the specific places for measurements.

In reinforced concrete structures, the beginning of the corrosion process on the steel is not always visible since the reinforcement has a concrete covering. Therefore, the possibility of corrosion in each structure must be analyzed in the conditions most conducive to corrosive actions or in the conditions in which the structural element will be found most of the time [9].

After the mapping of potentials on the concrete surface is completed, the values obtained at each measuring point should be compared and diagnosed according to the probability of corrosion in the steel used (Table 1).

Analyzing Table 1 (based on the ASTM C876 standard) [10], which uses as a parameter a reference electrode of $Cu/CuSO_4$, the values of potentials more negative than –350 mV indicate an active state, with a probability of corrosion greater than 90%. On the other hand, more positive that –200 mV indicate that

Figure 3: Image courtesy of IEC Engenharia, potential measurement in reinforced concrete structure. Source: IEC Engineering, 2019.

Table 1: Classification of corrosion potentials according to ASTM C 876.

MEASURED POTENTIAL – V (mV)	PROBABILITY OF CORROSION
V > –200	< 10%
–200 ≥ V ≥ –350	Uncertainty about corrosion
V < –350	> 90%

Source: adapted from ASTM [10, 20].

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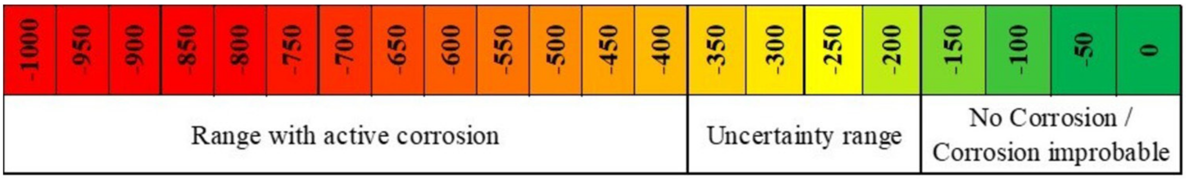

Figure 4: Color scale, for classification and mapping of potentials. Source: the authors.

the reinforcement is protected or passivated, with a probability of corrosion of less than 10%. The range of potentials between –200 mV and –350 mV is a transition region, where the probability of corrosion is considered uncertain. From this analysis it is possible to generate a color scale to classify and identify the potentials in a more understandable way (Figure 4), seeking to map the regions that should be studied and/or worked with greater brevity.

The values obtained from the equipment during the corrosion potential measurement procedures depend, among other things, on the positioning of the half-cell on the concrete surface. The application of this technique is very useful for inspecting and monitoring concrete structures, given its practicality and the possibility of monitoring the corrosion process over time in various types of structural elements [22, 23].

3. GEOSTATISTIC ANALYSIS

To understand the spatial variation of the corrosion potential as a random process, it is necessary to consider the possibility that the value of each point in space is related to values obtained from other points, located at a certain distance, and it is reasonable to assume that the influence is greater the smaller the distance between the points. Consequently, inference of the spatial continuity of a regionalized variable can be made with sample values based on two-point statistics. Considering the definitions of the covariance function and variogram function, it turns out that they depend only on two points x1 and x2. situated at a distance h = X1 – X2, between them, where X1 and X2 are x1 and x2 coordinates. Each pair of points is a different realization, which makes possible the statistical inference of these functions. To determine the spatial correlation model of the regionalized variable, this correlation is experimentally calculated using the sample points and then a theoretical model is adjusted. This theoretical model allows to determine the value of the spatial correlation for any distance within the sampled space.

The set of random variables {Z (xi), i = 1,n} correlated with each other constitutes a random function whose sampling provides a realization Z (xi) with Expected Value expressed as Equation 1.

$$E[Z(x_1)] = E[Z(x2)] = \cdots E[Z(xn)] = E[Z(x)] = m \tag{1}$$

Thus, the mean m becomes independent of the location and obtained as an arithmetic mean of the achievements of the random variables, as shown in Equation 2.

$$m = E[Z(x)] = \frac{1}{n} \sum_{i=1}^{n} Z(x_i) \tag{2}$$

The variance associated with the mean is calculated as seen in Equation 3.

$$Var[Z(x)] = E\{[Z(x) - m]^2\} \tag{3}$$

In statistics, covariance is a measure of the mutual relationship between two distinct random variables, for example, X and Y. In geostatistics, covariance measures the relationship between values of the same variable, obtained at points separated by a distance h, according to a certain direction. In this paper, directions x and y are considered. If the material is anisotropic, the covariance changes according to any direction and there are cases where the covariance is the same in any direction, and therefore the spatial phenomenon is isotropic. Thus, to detect whether the spatial phenomenon presents anisotropy or not, the covariance is calculated for several directions. If the phenomenon under study is distributed in 2D, the covariances are calculated generally in four horizontal directions: 0º, 45º, 90º and 135º.The covariance of a regionalized variable for points separated by a distance h can be calculated as shown in Equation 4.

$$C(h) = E\{[Z(x+h) - m]\,[Z(x) - m]\} \tag{4}$$

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Where h represents a vector between two points x1 and x2 in two-dimensional space. It is easy to conclude that the covariance for null distance (h = 0) is equal to the variance of the regionalized variable Z (x).

The variogram function γ(h) is defined as the variance of the increment ΔZ, shown in Equations 5 and 6

$$\Delta Z = [Z(x+h) - Z(x)] \tag{5}$$

$$\gamma(h) = \frac{1}{2}E[\Delta Z]^2 = \frac{1}{2}E\{[Z(x+h)\ -\ Z(x)]^2\} \tag{6}$$

For all vectors h, the increment [Z (x + h) – Z (x)] has a finite variance, which calculation is shown in Equation 7.

$$Var[Z(x+h) - Z(x)] = E\{[Z(x+h)\ -\ Z(x)]^2\} = 2\gamma(h) \tag{7}$$

4. EXAMPLE OF APPLICATION

The case studied is a reinforced concrete slab with different levels of corrosion in the reinforcements, caused by the conditions of the electrolyte (concrete) in the structure in question. In some regions of the slab there was a higher content of chloride contamination, which intensified the corrosive process, while in other regions the presence of chlorides was lower and had less moisture in the concrete.

In the Figure 5 is shown a sketch of the analyzed structure, with the dimensions and characteristics identified during the field study.

The slab was subdivided into smaller sections with dimensions of 4.80 m × 4.90 m (as can be seen in the Figure 6, where 27 points of measurement of corrosion potential were determined for each slab. Thus, it became possible to study in more detail each region of the slab, which already had corrosive effects on the reinforcements, but there was no identification of the points where corrosion is more intense.

To identify the corrosion bands existing in the reinforcements of the studied structure, the mapping of potentials on the lower surface of the slab was made, according to the parameters indicated in the ASTM C876 standard [10, 20]. Fragmenting it proportionally (in 27 measuring points for each of the 16 slabs), corrosion

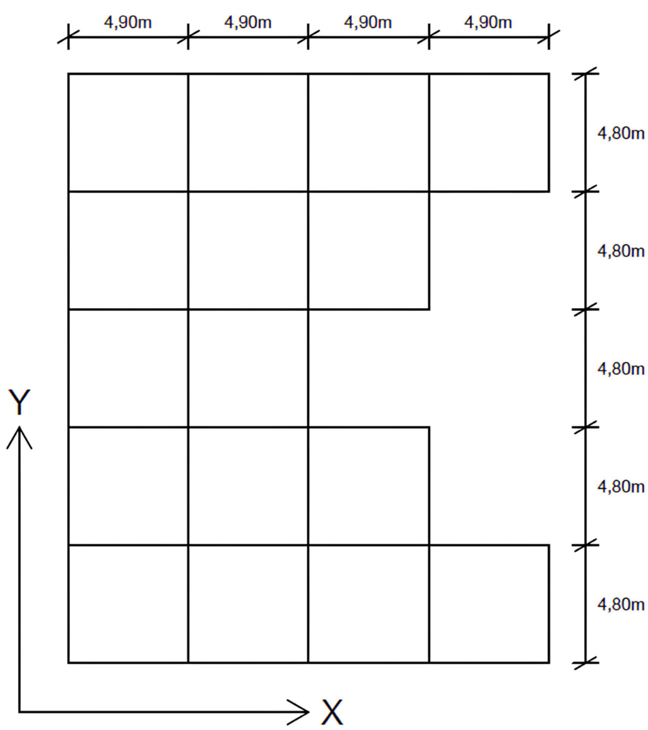

Figure 5: Sketch of the slab. Source: the authors.

potential measurements were made at a total of 432 different points, making it possible to understand the behavior of the corrosive activity throughout the structure.

For all 16 slabs, the same amount of potential measurement points were assigned and respecting the spacing between the measurement points, 1.63 m for horizontal and 0.53 m for vertical (as shown in Figure 6), which allowed the analysis of the entire area raised in this study in an equal and detailed way.

During the procedures for mapping the potential reinforcement/concrete in the slabs, the values obtained were critically analyzed and recorded, in order to identify possible contact failures, obstructions in the measurements, errors in the equipment or any other reason that could cause inconsistencies in the values obtained. In case of error or doubt, the recorded value was immediately discarded, and a new measurement of potentials was performed at the same point where the problem has occurred.

To properly perform these potential measurements on the concrete face of the slab, the following equipment were required:

- Digital Multimeter, with impedance greater than 10M.Ω;
- Reference electrode (half-cell) of $Cu/CuSO_4$ with porous nib in ceramic, at its end there was a moistened sponge to improve the contact in the concrete face;
- Electric cables of 2.50 mm^2, in sufficient lengths to reach the slab at all desirable points;
- Equipment to moisten the lower face of the slab at the necessary points.

In this specific case, the measurements of potential reinforcement/concrete were made with the reference electrode in the vertical position with the nib facing up, that is, over the head of the man who took the measure. It is important to note that the solution inside the reference electrode was always in simultaneous contact with the porous plug and the internal metal rod of this equipment. This allows greater confidence in the collected data and clarity for the analyses performed.

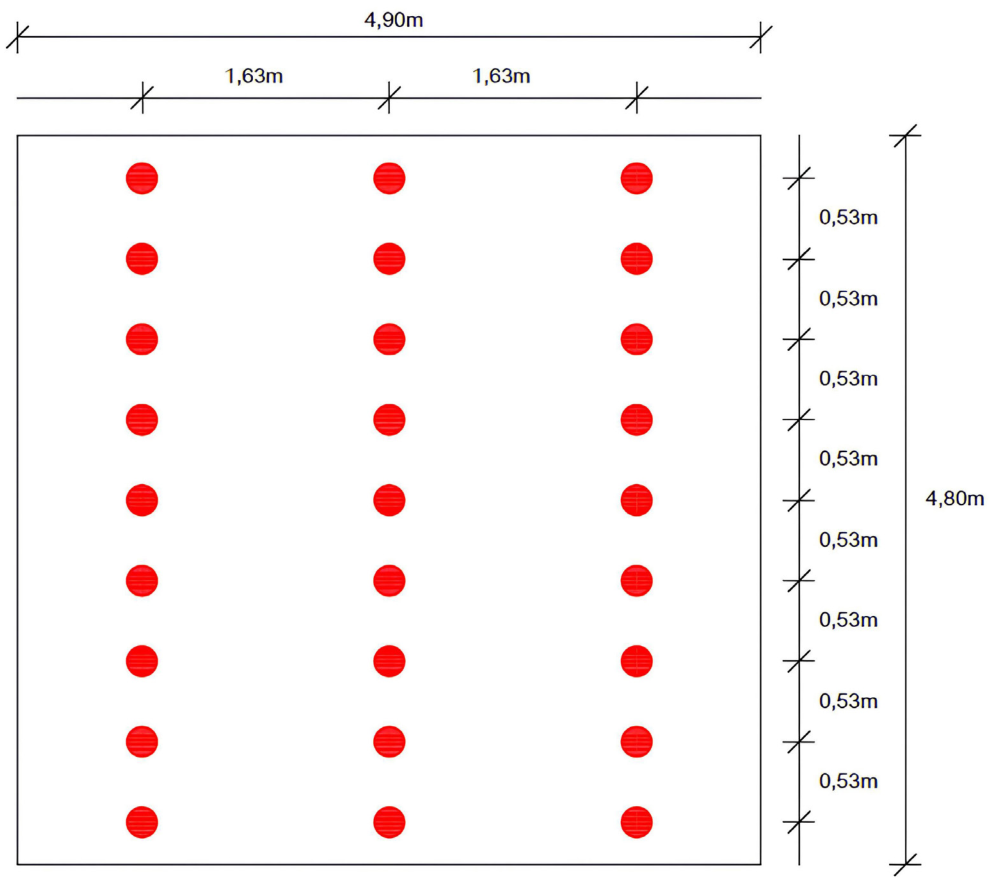

Figure 6: Spacing between the measurement points. Source: the authors.

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In possession of the data obtained during the potential measurements, in addition to the location of each measurement point, it was possible to generate the Figure 7, based on the color scale presented in Figure 4 of this work (used for classification and mapping of the verified potentials).

Corrosion is a complex process and often influenced by random factors, such as variations in environmental aggressiveness, concrete and reinforcement characteristics, and other external factors. Therefore, the phenomenon is considered a stochastic process, where events are treated as random, subject to uncertainty and variability. Stochastic analysis for corrosion in slabs involves the application of stochastic principles and methods to understand and model the corrosion process that affects concrete structures in each environment. Thus, in order to analyze the corrosivity in the structure and the influence of other regions for the potentials

-583	-695	-505	-417	-423	-400	-272	-382	-423	-301	-480	-471
-630	-512	-511	-344	-380	-368	-244	-314	-334	-322	-503	-441
-695	-476	-519	-326	-411	-386	-261	-360	-314	-435	-518	-422
-493	-620	-637	-627	-598	-593	-531	-531	-497	-272	-322	-263
-540	-638	-439	-649	-566	-539	-451	-562	-497	-236	-362	-370
-553	-628	-490	-613	-601	-535	-477	-414	-395	-350	-229	-399
-464	-799	-619	-626	-495	-630	-581	-483	-720	-266	-466	-372
-698	-649	-634	-511	-505	-604	-542	-534	-576	-364	-299	-381
-548	-562	-864	-533	-457	-512	-448	-598	-533	-563	-579	-308
-767	-778	-815	-717	-409	-532	-346	-203	-163			
-804	-797	-725	-507	-425	-527	-309	-124	-210			
-852	-893	-855	-425	-515	-453	-296	-126	-169			
-605	-659	-812	-444	-506	-624	-173	-113	-235			
-571	-671	-805	-456	-798	-432	-160	-133	-198			
-787	-921	-967	-507	-456	-398	-153	-248	-327			
-615	-755	-570	-472	-444	-453	-298	-207	-404			
-709	-569	-638	-507	-461	-531	-345	-294	-240			
-613	-624	-633	-576	-480	-474	-328	-444	-413			
-646	-505	-460	-355	-318	-411						
-490	-557	-449	-352	-540	-362						
-437	-478	-429	-301	-404	-333						
-220	-549	-619	-553	-473	-452						
-577	-558	-608	-489	-556	-525						
-520	-596	-786	-490	-489	-424						
-385	-516	-321	-513	-529	-484						
-343	-391	-417	-552	-514	-455						
-307	-398	-530	-591	-444	-519						
-279	-330	-350	-599	-428	-317	-349	-363	-225			
-248	-351	-339	-387	-341	-550	-305	-397	-265			
-316	-381	-252	-448	-541	-386	-301	-176	-247			
-531	-487	-409	-422	-429	-357	-300	-335	-448			
-540	-494	-413	-402	-419	-469	-322	-346	-320			
-537	-514	-499	-436	-408	-495	-360	-491	-345			
-372	-353	-299	-317	-388	-303	-410	-370	-298			
-395	-390	-479	-323	-319	-330	-267	-325	-348			
-312	-390	-479	-403	-354	-404	-377	-282	-424			
-459	-426	-447	-454	-473	-380	-437	-567	-451	-146	-136	-162
-477	-482	-458	-389	-566	-387	-595	-522	-491	-133	-139	-182
-497	-396	-422	-430	-521	-549	-458	-533	-422	-159	-105	-255
-481	-461	-361	-414	-450	-516	-431	-454	-471	-126	-103	-161
-456	-430	-456	-591	-455	-269	-457	-658	-443	-197	-115	-172
-444	-523	-502	-371	-356	-272	-407	-511	-463	-199	-145	-193
-434	-477	-364	-441	-520	-434	-847	-856	-832	-290	-237	-316
-455	-462	-297	-493	-527	-500	-787	-880	-827	-301	-234	-347
-500	-280	-385	-503	-470	-446	-969	-828	-948	-436	-302	-335

Figure 7: Values and mapping of the potentials identified on the slab. Source: the authors.

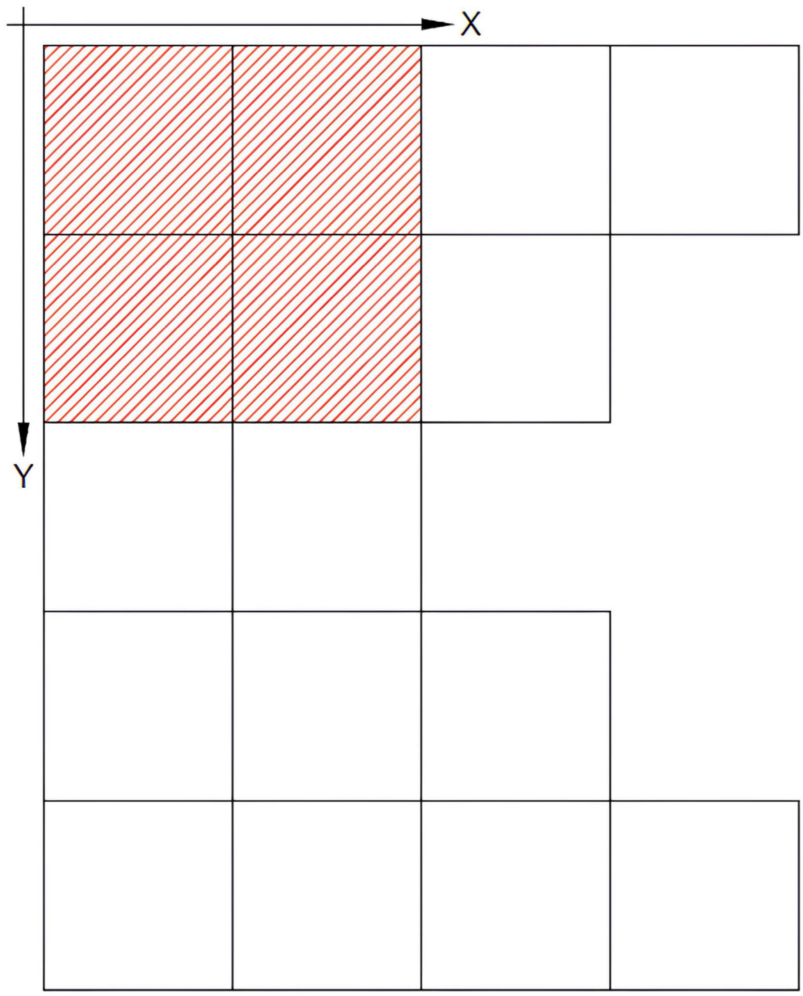

Figure 8: Stretch of slab used for the study. Source: the authors.

obtained in the studied slab, a region of the slab was chosen, based on the place that presented the highest corrosion potential in the same area (Figure 8). From this premise, it was decided to perform a Geostatistical Analysis of Corrosion in this stretch of the slab in reinforced concrete, considering the Potentials as Z variable.

5. RESULTS AND DISCUSSIONS

Adopting the section of slab indicated previously as the basis for this analysis, information was extracted regarding the electrochemical potentials and the spacing between the measurement points, for the X axis (horizontal) and for the Y axis (vertical). Figure 9 shows the values of the reinforcement/concrete potentials used in the calculations for Geostatistical Analysis of Corrosion.

It is important to emphasize that the data were analyzed in both directions, X (horizontal) and Y (vertical), in order to understand the impact of corrosive activity in both directions of the selected slab.

Understanding that, during the field procedures, all points of measurement of potentials were equidistant and the methodology for identifying the predominant values of electrochemical potentials was similar in all cases.

The semivariance $\gamma(\tau)$ is calculated according to Equation 8, presented earlier in this work.

Tables 2 and 3 show the values calculated for the semivariance of the horizontal and vertical directions, respectively, where:

- τ, means the distance between the measuring points;
- n, means the number of correlated pairs at such a distance;
- The values of the Z potentials, treated and applied to Equation 8, are shown in Figure 9.

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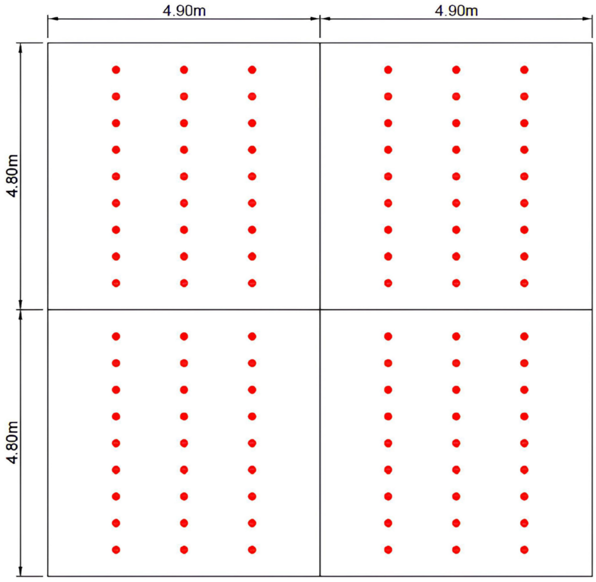

-583	-695	-505	-417	-423	-400
-630	-512	-511	-344	-380	-368
-695	-476	-519	-326	-411	-386
-493	-620	-637	-627	-598	-593
-540	-638	-439	-649	-566	-539
-553	-628	-490	-613	-601	-535
-464	-799	-619	-626	-495	-630
-698	-649	-634	-511	-505	-604
-548	-562	-864	-533	-457	-512
-767	-778	-815	-717	-409	-532
-804	-797	-725	-507	-425	-527
-852	-893	-855	-425	-515	-453
-605	-659	-812	-444	-506	-624
-571	-671	-805	-456	-798	-432
-787	-921	-967	-507	-456	-398
-615	-755	-570	-472	-444	-453
-709	-569	-638	-507	-461	-531
-613	-624	-633	-576	-480	-474

Figure 9: Reinforcement/concrete potentials of the selected slab section. Source: the authors.

Table 2: Semivariance for horizontal direction.

τ	*n*	γ(τ)
0,00	108,00	–
1,63	90,00	**11.719,12**
3,26	72,00	**16.519,68**
4,89	54,00	**26.293,64**
6,52	36,00	**25.501,61**
8,15	18,00	**21.806,50**

Source: the authors.

Table 3: Semivariance for vertical direction.

τ	*n*	γ(τ)
0,00	108,00	–
0,53	102,00	**8.164,21**
1,06	96,00	**11.262,11**
1,59	90,00	**12.047,45**
2,12	84,00	**13.108,47**
2,65	78,00	**12.504,76**
3,18	72,00	**14.817,80**
3,71	66,00	**16.535,58**
4,24	60,00	**16.427,66**
4,77	54,00	**15.753,03**
5,30	48,00	**15.973,24**
5,83	42,00	**16.224,96**
6,36	36,00	**16.047,49**
6,89	30,00	**15.451,98**
7,42	24,00	**11.045,81**
7,95	18,00	**6.029,75**
8,48	12,00	**7.455,13**
9,01	6,00	**4.694,25**

Source: the authors.

The calculated values for the semivariance γ(τ) are expressed in mV^2/m^2, since the values established for the potentials are in millivolts (mV) and the distances between the measurement points are in meters (m).

Graphs (called Variogram) in both directions of the slab were elaborated from the data of Tables 2 and 3 to identify the correlation between semivariance and spacing. Then, a variogram was generated for the Horizontal axis and another for the Vertical axis in order to analyze them clearly and separately.

Figures 10 and 11 show the variograms for the Horizontal axis and the Vertical axis, respectively, based on the data shown in Tables 2 and 3.

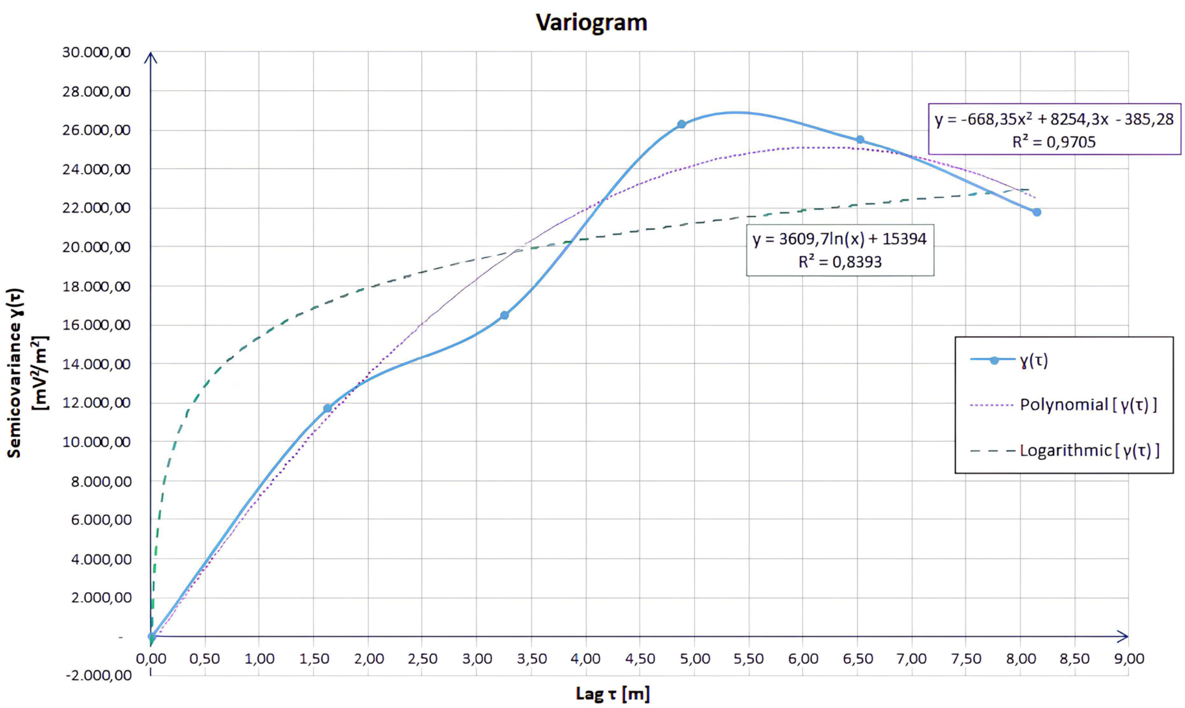

Figure 10: Variogram for horizontal axis. Source: the authors.

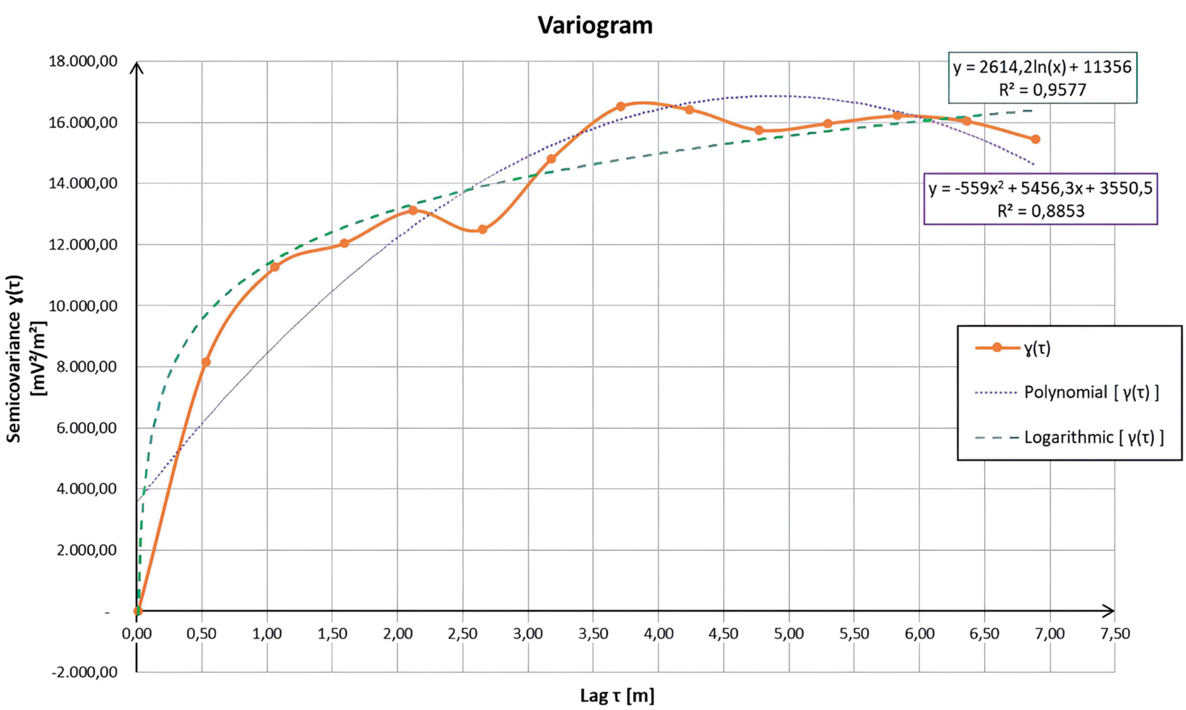

Figure 11: Variogram for the vertical axis. Source: the authors.

It is essential to explain some important points regarding the plotted graphs (Figures 10 and 11), which are:

- Both variogram graphs were generated using an Excel tool, by Microsoft.
- During the preparation of the graphs, it was decided to display only the trend lines for the polynomial equations and logarithmic equations.
- For the variogram referring to the horizontal axis (Figure 10), all the spacings (τ) resented in Table 2 were maintained, in order to consider up to the farthest point for later analysis.
- On the other hand, for the variogram referring to the vertical axis (Figure 11), the spacings (τ) greater than 7.00 m was disregarded, without causing a negative impact in the subsequent analysis. This decision was made after concluding that, for the vertical axis, points from this distance are irrelevant and make the curve immediately decreasing.
- Briefly, both graphs started at the 0.00 m distance mark. However, the variogram graph for the horizontal axis has its last point at 8.15 m spacing, while the variogram graph for the vertical axis ends at 6.89 m spacing.

After the construction of the mentioned graphs some data were extracted, such data are the polynomial, logarithmic, power and exponential equations, in addition to their respective R^2 values. These data can be seen in Table 4 below, which shows the data extracted from the variogram for the horizontal and vertical axis.

It can be seen that the polynomial and logarithmic equations were the ones that best adjusted to the measured values, this is clear when analyzing the graphs together with the table of extracted data and verifying R^2 values, which are closer to one.

In addition, a histogram was generated considering the general values concerning the electrochemical potentials obtained during the reinforcement/concrete potential measurement procedures in the studied slab. This histogram is shown in Figure 12.

Table 4: Data extracted from the graphs.

	HORIZONTAL		VERTICAL	
	EQUATION	**R^2**	**EQUATION**	**R^2**
POLYNOMIAL	y = –668,35x2 + 8254,3x – 385,28	0,9705	y = –559x2 + 5456,3x + 3550,5	0,8853
LOGARITHMIC	y = 3609,7ln(x) + 15394	0,8393	y = 2614,2ln(x) + 11356	0,9577
POWER	y = 1888,8 x 1,5742	0,5655	y = 2662,4 x 1,4051	0,4990
EXPONENTIAL	y = 86,825 e 0,9244x	0,1321	y = 956,29 e 0,5795x	0,2469

Source: the authors.

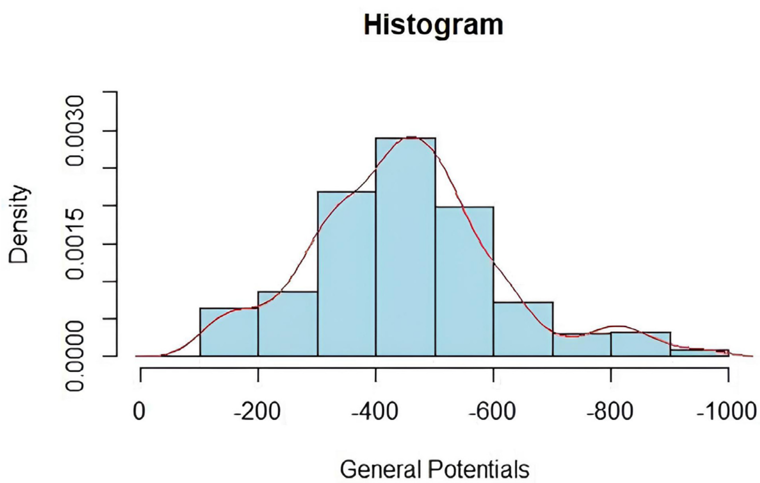

Figure 12: Histogram considering the electrochemical potentials of the slab studied. Source: the authors.

As mentioned by in some articles, cathodic protection is a safe and efficient technique for combating and controlling corrosion in the reinforcement of a concrete structure, preventing premature deterioration and extending the useful life of a given structural element [24–26]. Cathodic protection becomes an efficient method for attenuating and stabilizing the electrochemical potentials identified along this slab, making it possible to act against the corrosive process at different points and with adequate spacing, according to the needs of each region. It is understood that cathodic protection could be applied to the slab studied in order to adjust the electrochemical potentials to acceptable parameters and eliminate the corrosive activity present in this structure.

6. CONCLUSIONS

The mapping of the reinforcement/concrete potentials allowed a preliminary critical analysis of the corrosive state of the slab studied, allowing the choice of a more suitable region for the application of the proposed study. The fragmentation of the structure into several smaller sections and the determination of the number of equidistant measurement points in each section of slab turn possible to understand the behavior of the corrosive activity throughout the structure.

According to the data presented in the histogram, it can be seen that most of the points of measurement of electrochemical potentials verified in the slab have values between –300 mV and –600 mV, with an accentuation for the values obtained between –400 mV and –500 mV. According to the classification of corrosion potentials prescribed in the ASTM C876 standard [10], these results indicate that the regions are migrating from an intermediate range (corrosion uncertainty) to an active corrosion range, presumably due to environmental conditions, chloride contamination index and consequent depassivation of the reinforcements.

It was observed through the variogram graphs, generated for the horizontal axis and for the vertical axis, that after approximately 7.00 m of distance the graph curve changes significantly, demonstrating that from this distance there is no influence for the electrochemical potentials of a certain point verified in this slab. In addition, by generating the variograms on different charts, it became easier to perceive the trend lines that were closest to the expected value for the chart.

Analyzing the variogram of the horizontal axis, as well as the data extracted from it, it can be seen that the trend line referring to the polynomial equation has the major value of R^2, indicating a better inference curve. On the other hand, when checking the variogram of the vertical axis and its extracted data, it is understood that the trend line referring to the logarithmic equation and this is the best approximation.

The study of the Geostatistical Analysis of the Corrosion of a given structure in reinforced concrete has several advantages, among them: the complete understanding of the spatial extent of the problem that is corrosion; knowledge of the severity and evolution of corrosion from the existing corrosive process; and a possible prognosis of the surface area of concrete in deterioration/contamination. However, the main advantages of this type of study are the obtaining of information that will allow the adjustment of the area to be worked during repair or structural reinforcement procedures and the feasibility of technical strategies, which include the combat or mitigation of existing corrosion, applied at more precise distances in both directions, since such analysis provides two-dimensional information.

This work can be considered studies to choose a technique to combat corrosion and simulate its application. as well as its benefits, for a previously determined region.

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