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Multivariate Analysis of the Variables Influencing the Form of the Chloride Profile in Reinforced Concrete Structures Exposed to a Tropical Marine Climate

Análisis Multivariado de las Variables que Influyen en la Forma de los Perfiles de Concentración de Cloruro en Estructuras de Hormigón Armado Expuestas a un Clima Tropical Marino

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Abstract

Chlorides coming from the marine breeze are the main cause of corrosion and deterioration of the structures in marine environment. On the other hand, the interpretation of their concentration profile is an important tool to predict future behavior of the structure and to take preventive/corrective actions. Such profiles are commonly interpreted through mathematical tools and the exposure environment is one of the heaviest variables in the resulting predictions. Because of the complexity of the species transport phenomena associated to the predictions, there is no enough consensus when explaining results obtained under different circumstances and materials.

The multivariate analysis is applied in this work as a tool to validate the interpretation of the form of the chloride concentration profile of concrete as well as to show its dependency with several parameters such as the direction and incidence of dominant winds, the blocking to the marine breeze and the wet and dry process in the substructure of the Turigüanó.Cayo Coco viaduct bridges.

An association of the different variables in groups allowed obtaining a dendogram that confirmed: more influence of chloride penetration in the elements located to the East side, and in coincidence with the dominant winds; the existence of a peak in the concentration profile of the closest external beams¨ parts that would be associated to the wet and dry process of the elements; the existence of a blocking to the marine breeze that promotes lesser affection by the chlorides in the central beams and North sides from the bridges than on other parts.

Keywords: Chloride, corrosion, concrete, marine environment, multivariate analysis.

Resumen

Los cloruros provenientes de la brisa marina son la principal causa de corrosión y deterioro de las estructuras en ambientes marino. El estudio e interpretación de sus perfiles de penetración son valiosas herramientas para predecir el comportamiento futuro de la estructura y tomar medidas preventivas/correctivas. Dichos perfiles son comúnmente interpretados a través de herramientas matemáticas, siendo el ambiente de exposición una de las variables con mayor peso en las predicciones Dada la complejidad de los fenómenos de transporte asociados a la predicción no existe aún consenso al momento de explicar los resultados obtenidos bajo circunstancias y materiales diferentes.

Este trabajo aplica el análisis multivariado como una herramienta para validar la interpretación de la forma del perfil de concentración de cloruros del hormigón y demostrar la dependencia de la dirección e incidencia de los vientos, del apantallamiento y del proceso de mojado y secado en la estructura de los puentes del Pedraplén Turiguanó – Cayo Coco.

Se obtuvo un dendograma, en el que se asocian las diferentes variables en grupos, que permitió confirmar: que los elementos ubicados al lado Este, coincidentes con la dirección de los vientos predominantes, se encuentran mas afectados por la penetración del ion cloruro; la existencia de un pico en los porcentajes de cloruros cercanos a la cara exterior de las vigas, que pudiera estar asociado al efecto de mojado y secado en los elementos; la existencia de un efecto de apantallamiento que provoca que las vigas centrales y el lado norte de estos puentes estén menos afectados por el ion cloruro.

Palabras-clave: Cloruros, corrosión, hormigón, ambiente marino, análisis multivariado.

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1 Introduction

Better prediction models can be obtained through the correct interpretation of the form of the concentration profile in a concrete structure (Castro et al [1]). There are several authors from the literature that are giving importance to this matter (Berke y Hicks [2], Weyers [2]), although some of them recognize that found results apply to specific circumstances (Pérez-García et al [4]).

The effect of variables like height, wetting and drying zones and concrete quality in the form and interpretation of the chloride profile have been widely discussed (Castro et al [1], Pérez-García et al [4] Roy et al [5]) and the observed tendencies came from data of samples, buildings and a bridge exposed to marine environments. The quantity of results as well as the characteristics of the analyzed samples make out the influence of parameters like the blocking to the marine wind, the geographic position and the microclimate (Castro et al [6]).

A descriptive analysis is almost always presented in the reviewed literature but a need to explain the influence of the environmental factors on the structures through a statistical method is evident. A multivariate analysis is a tool that allows the combination of parametric and non-parametric variables as well as the interrelation among them.

The objective of this work is to demonstrate that a multivariate analysis can show effects like blocking to the marine breeze, predominant winds and geographical position on the form of the concentration profile, as well as to ratify the existence of wetting and drying processes under different materials and conditions to those reported in the literature.

2 Experimental

2.1 Characteristic of the viaduct and its bridges

The Turiguanó-Coco Key viaduct is in service since 1989. The surrounding atmosphere as well as the construction characteristics promoted severe corrosion damage in several of its bridges after only twelve years of exposure. The chloride profiles presented and discussed here come from the bridges 4, 5 and 6 and are representative of the observed damage. The corrosion inspection and results of these bridges have been published elsewhere (Pérez-García et al [7]). A total of 14 bridges is irregularly distributed along the viaduct. One of them is metallic and the others were constructed according to the traditional Cuban standards. This is, using prefabricated and postensioned concrete beams with the same materials, construction source

Table 1 – Percentage of total chloride by weight of cement in bridges 4, 5 and 6

Element	Parameters	Depth, cm.				
		1.0	2.0	3.0	4.0	5.0
Bridge 4	# of Measurements	18	18	18	18	18
	Average	0.57	0.68	0.78	0.61	0.49
	Std. Dev.	0.25	0.30	0.40	0.30	0.30
	Maximum	0.98	1.12	1.80	1.28	1.12
	Minimum	0.23	0.26	0.23	0.12	0.05
Bridge 5	# of Measurements	18	18	18	18	18
	Average	0.64	0.86	0.70	0.62	0.54
	Std. Dev.	0.41	0.51	0.41	0.44	0.41
	Maximum	1.48	1.88	1.36	1.68	1.43
	Minimum	0.26	0.36	0.19	0.08	0.01
Bridge 6	# of Measurements	18	18	18	18	18
	Average	0.63	0.74	0.87	0.72	0.55
	Std. Dev.	0.35	0.32	0.43	0.37	0.31
	Maximum	1.40	1.50	1.80	1.60	1.12
	Minimum	0.24	0.20	0.15	0.12	0.05

Table 2 – List of Variables

Nº	Name	Description	Type of Variable
1	P4	Bridge 4	Non-Parametric
2	P5	Bridge 5	Non-Parametric
3	P6	Bridge 6	Non-Parametric
4	V13	Beam 13	Non-Parametric
5	V 7	Beam 7	Non-Parametric
6	V 1	Beam 1	Non-Parametric
7	LN	North face	Non-Parametric
8	L S	South face	Non-Parametric
9	CO	West face	Non-Parametric
10	CE	East face	Non-Parametric
11	C A	Bottom face	Non-Parametric
12	PROF 1	Depth 1 cm.	Parametric
13	PROF 2	Depth 2 cm.	Parametric
14	PROF 3	Depth 3 cm.	Parametric
15	PROF 4	Depth 4 cm.	Parametric
16	PROF 5	Depth 5 cm.	Parametric
17	CADM	Chlorides < 0.20%	Parametric
18	CNA	Chlorides ≥ 0.20%	Parametric

and projected compressive strength at 28 days after setting. The projected compressive strength was reached in all the cases.

2.2 Materials and experimental program

Samples were obtained from the West beam 1, East beam 13 and Central Beam 7 at each of the bridges 4, 5 and 6. The North and South bearings of any beam, as well as their East, West and inferior parts were sampled.
Powder samples at 1.0 cm, 2.0 cm, 3.0 cm, 4.0 cm and 5.0 cm from the external face were obtained through a mechanical drill and a 2.5 cm diameter bit. It was used a guide to make sure the samples were taken at the right depth. The powder was collected in plastic bags and the rest of powders were cleaned from the drill bit through an air gun after each sampling to avoid any contamination. A total of 90 samples were taken and the total chloride content was determined through the ASTM C 1152 method (ASTM C-1152 [8]) in % by weight of cement.
The percentages of total chloride are showed in Table [1]. Series of variables with parametric and non-parametric values for the analyzed structures were proposed with the results of Table [1] and they are showed in Table [2].
The parametric variable is a variable form in function of defined parameters. The non-parametric variable is the one that data are not reported as continuous but in an ordinal scale that assigns a range to the data. The assumed parametric variables were the depth regarding the beam external part, in cm (PROF) and the total chloride percentages, in % by weight of cement (CNA for values equal or higher than a corrosion chloride threshold of 0.20 %, and CADM for values lower than 0.20 %). The value of 0.20 was taken from the DURAR Manual (Troconis et al [9]) although there is a wide availability of data about chloride thresholds to produce corrosion that would apply also to our circumstances once the transformation from free to total chloride is performed (Alonso et al [10]). On the other hand, the non-parametric variables identify position, place or element as is the case of the bridge with the letter P and the number of bridge (4, 5 or 6), the beam with the letter V and its corresponding number, the lateral side of the beam with the letter L and the geographic position (North or South), and the face with the letter C and a letter that identifies the position where the sample was taken.

Table 3 – Characteristics of the groups from figure 1

Group	Correlation
1	PROF 1 with CADM
2	PROF 2 with Group 1
3	PROF 5 with Group 2
4	V7 with Group 3
5	PROF4 with Group 4
6	P5 with Group 5
7	PROF3 ,V1,CE, with Group 6
8	P4 with Group 7
9	CO, V13, CA, P6 with Group 8
10	LS with Group 9
11	CNA , LN with Group 10

3 Results

The values were analyzed according to the statistical package S. P. S. S. 11 from the Microsoft family (SPSS 11 [11]). A group analysis or cluster was used as a multivariate exploratory technique that allows the classification of groups of variables. The cluster minimizes the internal variation inside the group and maximizes the variation among the groups. The hierarchical method (Martín-Guzmán [12]) was used to group the variables in successively long clusters, until the last step when all the variables stayed together in one cluster only. In order to avoid the disadvantage of the scale difference among the variables, they were standardized to Z according to the program (SPSS 11 [11]). In this way, all the variables were expressed with a mean = 0 and a variance = 1. The results of applying the program are showed in Figure [1]. This Figure shows the best graphic representation of a cluster analysis. The analysis among groups is presented as a list of cases or variables with reference in the Y axis, as observed in Table [2], and grouped in 11 groups with a scalar distance in the X axis. The shorter the scalar distance the higher is the interrelation among the groups of variables. Table [3] shows the groups numbered from 1 to 11 being the group 1 that with better interrelation.

4 Discussion

Figures [2], [3] and [4] correspond to the chloride profiles of the bridges 4, 5 and 6 (Pérez-García et al [4]) and they help to understand Figure [2]. Once having the result of the program and plotted the data in Figure [2], it is evident that shorter scalar distances correspond to better correlations. This means that 50% of the first groups offer very good interrelation but the others have to be carefully observed.

Figure 1 – Diagram of groups interrelations

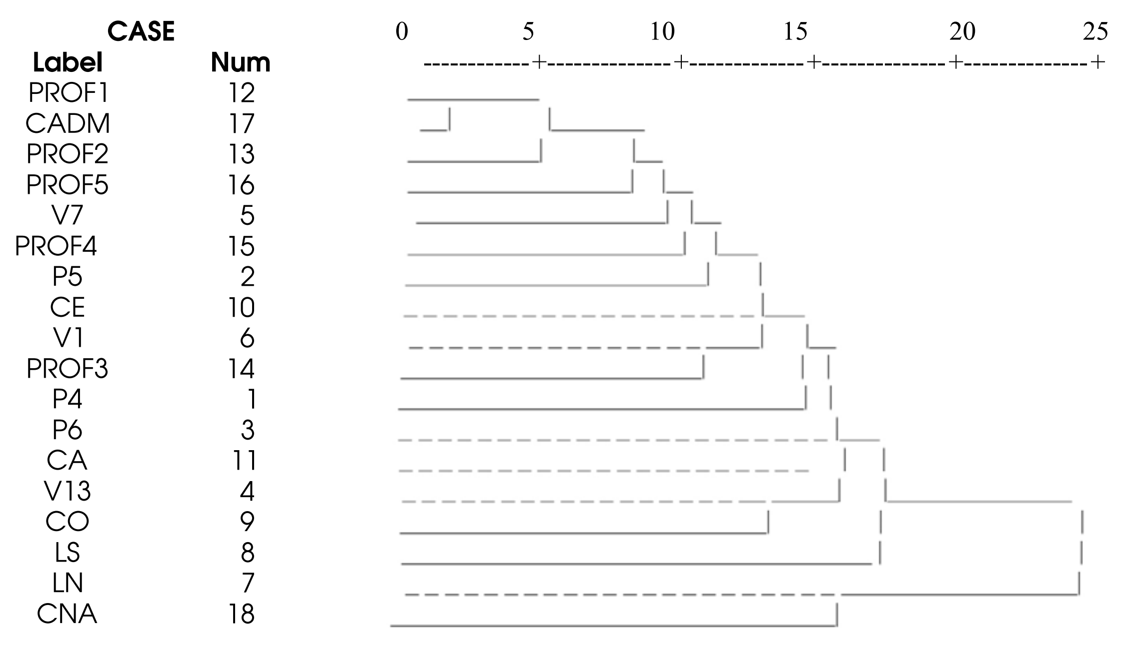
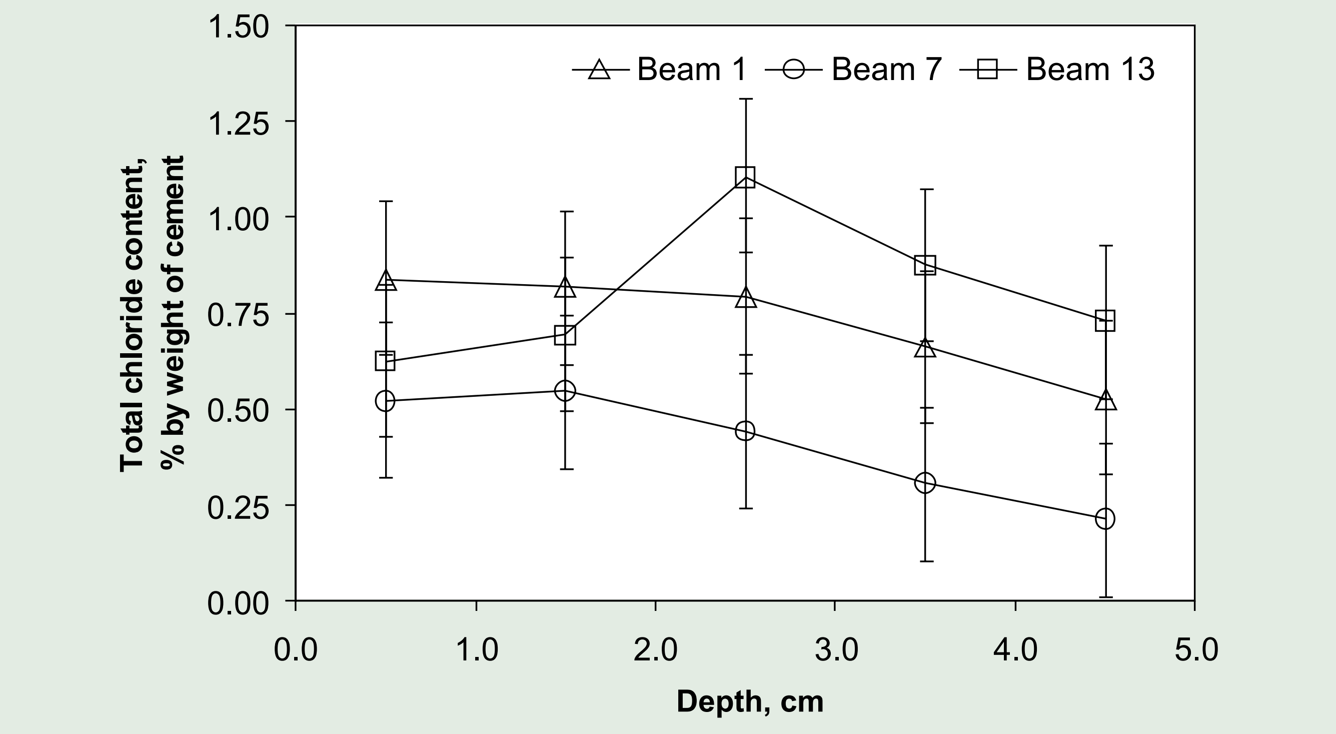


Figure 2 – Comparison among chloride profiles of beams 1, 7 and 13 in bridge 4



The groups 1 and 2 are validating the drying and wetting effects when the chloride threshold has not been reached (less than 0.20 (CADM)). It is clearly observed the close interrelation of this effect with the depths 1 and 2 (PROF1, PROF2) although depth 5 (PROF 5) is also showing good correlation. On the contrary, the central depths 3 and 4 (PROF 3 and PROF 4) are in the middle of the diagram and related with chlorides higher than the threshold (CNA). These depths and results are in coincidence with the chloride peaks observed in Figures [2], [3] and [4]. In this way, the form of the concentration profiles described in previous works (Pérez-García et al [4]) is validated statistically. Several authors (Castro et al [1, 6], Meira et al [13]) have reported or confirmed that, the detected peaks in the chloride concentration profiles of specimens exposed to different environments can be due to the skin effect (Meira et al [13]), the interface between carbonated and non-carbonated concrete (Castro et al [1,6]), the chloride washing by the rain (Meira et al [13]) or the interface between two zones: a) the zone that is permanently humid and b) that that wets and dries continuously (Castro et al [1,6]). Because of the characteristics of Coco Key bridges (concrete quality, geographical position, height regarding the sea level) it can be thought that the peaks are due to the existence of these two zones. This contribution is useful to understand the importance of the concrete cover quality and thickness.

The group 7 in Table 2 is validating the influence of the winds direction. The East face (CE) corresponds to the stronger wind action and is that with the higher chloride concentration at depths 3 and 4. The literature reports studies focused on the chloride analysis of real structures (Castro et al [14]). The contribution of the elevation, distance to the sea and geographic orientation are some of the effects reported in such a literature (Troconis et al [9], Petterson [15], Castro et al [1,6], Roy et al [5]). The effect of the predominant winds in the chloride concentration is anticipated but no discussed in these works. One of them (Castro et al [14]) discusses the wind effect for the case of structures where carbonation increases from West to east because the East side shows more time of wetting and drying. Taking into account that Yucatán and Coco Key have Northeast predominant winds, then it is understood why the wetting and drying process induces a higher and faster chloride ingress. For this reason, the East chloride profiles are higher than those of the West (Figures [2], [3] and [4]. This is very useful for the construction industry because the designers could take that into account and propose coatings, external covers and others to decrease the wind effect on the structures durability.

Some of the analyzed works (Troconis et al [9], Castro et al [14]) discuss the effect of the blocking as a barrier to avoid the ingress of deleterious agents to concrete. There are two types of blocking in the Case of Coco Key: the first comes from North to South because the South side (LS) receives directly the action of tides and winds and it is the most deteriorated and with the highest chloride profile; the second is due to the protection of beam 7 (V7) that

Figure 3 – Comparison among profiles of beams 1, 7 and 13 in bridge 5

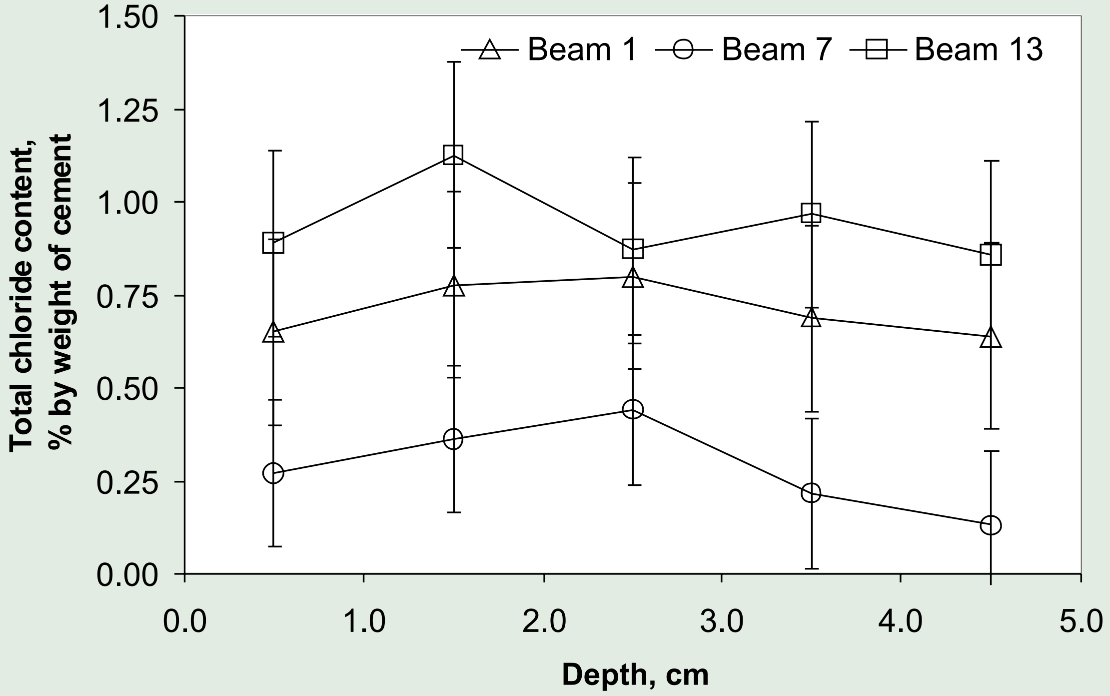
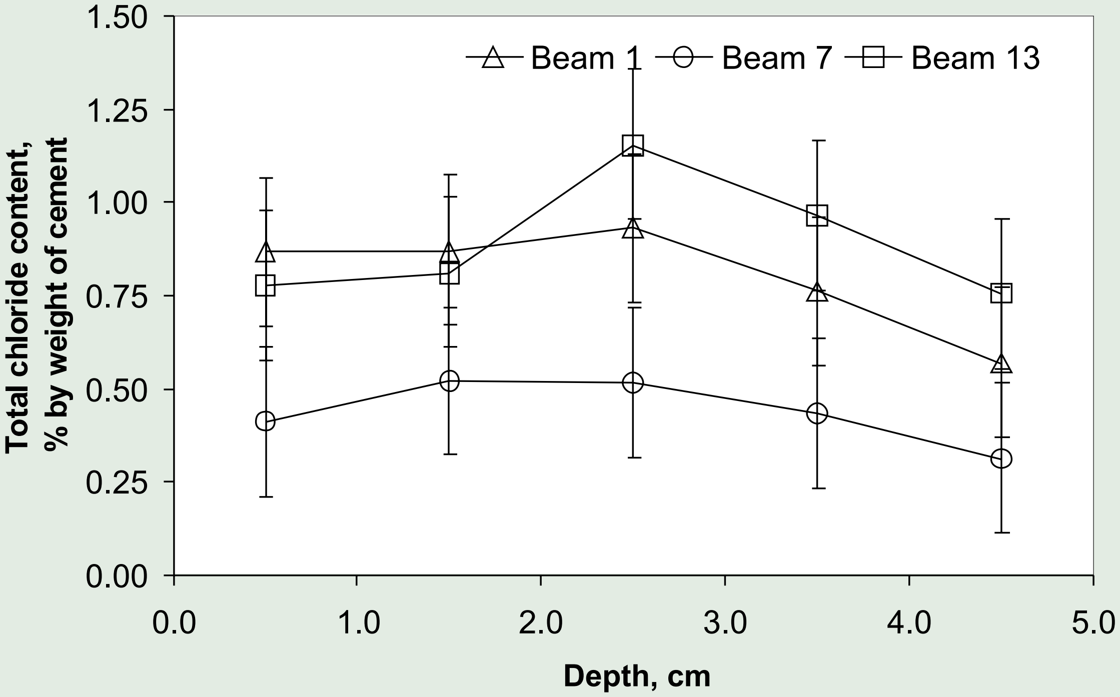


Figure 4 – Comparison among chloride profiles of beams 1, 7, and 13 in bridge 6



has no direct influence of the marine spray. It is inferred in the literature (Sand [16]) that the blocking is well known when the wind direction is analyzed in mountains zones or when the incidence of the microlimate and topography of the specific site. According to our own analysis the group 4 from Table 2 is related with beam 7 (V7), which is located in the middle of the bridges with chlorides contents that are lower than the threshold to produce corrosion (CADM). On the contrary, beam 13 (V13) of the group 11 is related with the South side (LS) with chlorides content higher than the threshold of 0.20 % (CNA). This effect is motivated by the position of the elements on the bridge. In the case of the construction industry, this allows the designers the establishment of a more demanding request of quality for the elements positioned in the non blocked zone in order to avoid the direct incidence of the sea and the salt spray in those parts of the structure.

5 Conclusions

The following conclusions apply for the tested environment and structures. Even when data of these structures were validated with those of other authors, a careful extrapolation with other constructions must be made because of the action of other possible non contemplated variables.

The multivariate analysis with variables associated in groups helped to validate relations from previous works, as follows:

a. The existence of a peak of chloride content very close to the external face of the beams that could be associated to the wetting and drying process.
b. The elements of the East side, which coincide with the wind direction, are more affected by the chloride penetration than those of the West side.
c. The central beams and the North sides of the analyzed bridges are less affected by the chloride ion than those of the remaining elements and this is due to a blocking effect.

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