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CORROSION DAMAGE EVALUATION AND DIAGNOSIS OF BRIDGES IN THE MEXICAN HIGHWAY NETWORK

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Abstract

This work presents an innovative and original method to determine the degree of corrosion in bridges built in the Mexican Federal Road Network (MFRN), as a function of environmental factors. These factors include prevailing climate where the bridge is located, accurate bridge geographic positioning (e.g. coastal line, river distance) and its distance from industrial corridors. This information was obtained and analyzed using the last generation of Global Positioning Systems (GPS), incorporating the current structural data produced during the last bridge evaluation available by the national bridge administration management program (SIPUMEX). This work presents the results obtained so far of the corrosion damaged bridges in the Mexican Federal Bridge Inventory.

INTRODUCTION

Concrete cover usually protects reinforcing steel bars (also known as rebars). A sound concrete cover physically provides a direct barrier preventing chemicals (chloride ions, carbon dioxide, etc.) from approaching the surface of the steel rebar. In addition, high alkalinity in concrete chemically protects the embedded bar against corrosion. In typical concrete environments, the pH ranges between 12.5 and 13.5 (Sagües et al 1997). This produces a film of γ-Fe2O3 (gama-ferric oxide or lepidocrite) on the bar surface (Bedu 1993), which acts as a barrier against corrosion and the steel exists in a passive condition (Fontana 1986). In a marine environment, however, chloride ions from seawater accumulate on the surface of the concrete and slowly migrate through the concrete cover to the underlying bar. When the chloride ion concentration at the bar depth exceeds a critical threshold value, the protective passive layer on the bar surface breaks down and active steel corrosion begins.

Similarly happens when carbon dioxide gas is transported in the concrete cover pore network, reaching the rebar at some time after being the structure in service. Carbon dioxide gas from urban and industrial areas reacts with the hydration products of concrete, forming other chemical compounds which decrease the alkaline properties of concrete, diminishing thus the chemical protection of steel (Moreno 1999). The decrease of this chemical protection leads afterward to active corrosion when sufficient electrolyte (i.e. water) is available at the rebar/concrete interface.

The transformation from steel to corrosion products in concrete is only partially understood. Analytical techniques cannot be used in situ to determine the type of corrosion products generated at the embedded bar surface without exposing the bar to the exterior. But corrosion products may further oxidize upon exposing the bar to air. Therefore, the physical and chemical properties of these corrosion products at the steel/concrete interface remain uncertain. Previous investigations performed by Bedu (1993) and Sagoe-Crentsil and Glasser (1989a, 1989b, 1993) observed ferrous hydroxide Fe(OH)2, hydrated ferrous chloride FeCl2xH2O, and black oxide Fe3O4 as the typical solid corrosion products at the bar surface upon exposure. The exact product formed depended on the availability of oxygen and water, the chloride ion concentration, and the pH (Bedu 1993). Although there are still discrepancies on the corrosion product types formed at the steel/concrete interface, it is well established that these corrosion products have smaller mass densities than steel (Tuutti 1982), resulting in volume expansion and concrete cover cracking (Torres-Acosta and Sagüés 2004).

THE MEXICAN FEDERAL ROAD NETWORK (MFRN)

There are different managing offices in charge of the Mexican road system. The roads are divided regarding if they were constructed by the Federal or State Governments or other instances. From the MFRN, there are two offices which are in charge of the toll and the non-tolled roads (or free roads). The Federal office called CAPUFE (Spanish initials for Federal Roads and Bridges) is in charge of the toll roads and bridges management. The toll-free road bridges are managed directly by the Ministry of Transport and Communications (Spanish initials: SCT) on each of their 31 State offices in Mexico. SCT has a bridge asset system for the MFRN bridge infrastructure maintenance, which determines, in a general way, the bridge conditions. This system is called SIPUMEX (Spanish for Mexican Bridge Inventory Management System), and gives a bridge grading method depending on the level of damage quantified from visual inspections only. But, in this system there is not any corrosion related type of grading, thus it does not have an objective way to separate structural or corrosion related deterioration, and is common to have misleading results during the evaluations.

Considering that the infrastructure must follow certain rules (i.e. type of structure, static and dynamic performance, local material used), there is not a precise knowledge of the environment aggressiveness and its effect on the bridge location. Therefore, there are not certain rules to design and build any concrete infrastructure under the concept of durability.

The weather conditions in Mexico's coastal areas are quite different than those from central Mexico. Therefore, it was found out that the coasts of Baja California aren't that aggressive like the coasts of Sinaloa or those in the Gulf of Mexico, which have been called the most aggressive tropical environment in North America (Troconis et al. 2005). Even in this region, the northern part of the Gulf of Mexico (i.e. Tamaulipas, Texas, Louisiana) is less harmful than the Southern coast (i.e. Veracruz, Coatzacoalcos, and Campeche).

For this reason, it is a priority to determine valuable information on the environment aggressiveness in combination with the typical concrete materials used on each region, to generate durability design and construction standards that must be followed in those places where future concrete infrastructure will be built.

Starting point – Mexican FRS bridge inventory

In 1993, the DGCC (Spanish initials for Road Management General Office) of the SCT implanted a bridge management system used for the Free Federal Road System denominated SIPUMEX. This data base includes the most important bridge properties for the management of maintenance expenditures. Some of this information includes structural appearance, bridge geometry, geographic coordinates, material and type of the structure, date of the construction, etc. It also includes the information on the repairs performed to the bridges. With the information collected by the bridge engineers, the SIPUMEX system grades the bridge (0 to 5) and defines the condition of the

bridge. This grade informs if the bridge is in excellent conditions (grade = 0) or if it needs an urgent detailed inspection to give the bridge a major repair (grade = 5). The grades that the SIPUMEX inventory gives to the bridge do not reflect a possible damage caused by corrosion.

Table 1 presents a SIPUMEX inventory summary with the numbers of bridges and the total length, in kilometers for each of the 31 Mexican States. It can be observed, that the State with the highest number of bridges is the state of Michoacán with 463 bridges and the state with the least number is Quintana Roo with 19 bridges.

In year 2000, the sub secretary of SCT infrastructure authorized the implantation of a new project for bridge evaluation which includes the corrosion parameter into the grading equation. The project name was National Plan for Evaluation and Diagnosis of Bridges Damaged by Corrosion, in Federal Highway Network

NATIONAL PLAN FOR EVALUATION AND DIAGNOSIS OF BRIDGES DAMAGED BY CORROSION, IN FEDERAL HIGHWAY NETWORK

The main objective of this project was to evaluate the corrosion deterioration of the bridges managed by the DGCC, in all Mexico's territory, and propose a permanent program that permits the control and the monitoring of those bridges from the environment's aggressiveness standpoint.

The main objective of this project was to provide to both DCGG and DGST the complete methodology and standard procedures for a correct inspection, diagnosis and evaluation of the bridge infrastructure of all the federal roads, using new technologies of diagnosis and evaluations of infrastructures, and, in case of having them corrosion damage pathology, planning a way to control, prevent and/or correct the problems diagnosed.

Methodology followed in this Plan

General objective: Classification of the bridge structures in the MFHN according to the state of deterioration caused by corrosion and structural integrity and establishing the priority level for detailed inspection or rehabilitation.

Task 1: Generate an inventory, in an electronic format, of the bridge structures of the MFHN defining name, identification number, State, highway, length, year of construction, year of last inspection, number of spans, geographic coordinates and slope.

Task 2: Use the specialized GIS software of the IMT(SIGET) and the inventory from Goal 1, to generate a map showing groupings of bridges that can be potentially damaged by corrosion based on their geographical position and the environmental exposure.

Task 3: Coordinate the visual inspections of all the bridges of the MFHN of the 31 states of the Mexican Republic. If no deterioration caused by corrosion is found, project the time to future detailed inspections of the structure.

Task 4: Gather the information generated by the visual inspections from the bridges that exhibited damage due to corrosion.

Task 5: Analysis of the field inspection results with the databases generated by the SIGET.

Information Sites Utilized

The current bridge administration system (SIPUMEX) of the Mexican ministry of transportation (Secretaría de Comunicaciones y Transportes, SCT), was incorporated to the National Plan of Evaluation and Diagnosis of Bridges Damaged by Corrosion, belonging to the IMT. This SIPUMEX system does consider structural integrity and general information of each bridge, but it does not include any parameters regarding environmental degradation of the concrete structures.

The current data regarding the amount of bridges and locations are shown in table 1. Further information from government institutions such as: National Institute of Geography and Statistics (Instituto Nacional de Estadistica Geografia e Informatica, INEGI), National Institute of Ecology (Instituto Nacional de Ecologia, INE), and institute of Geography at the National University (Instituto de Geografia de la Universidad Autónoma de Mexico, UNAM), and the IMT, is also available.

State	No. of Bridges	Total Length (km)	State	No. of Bridges	Total Length (km)
Aguascalientes	70	2.5	Nayarit	124	4.8
Baja California	122	4.8	Nuevo León	241	8.4
Baja Calif. Sur	96	2.9	Oaxaca	382	17.2
Campeche	74	2.0	Puebla	140	4.0
Coahuila	305	9.0	Querétaro	63	2.2
Colima	58	3.1	Quintana Roo	19	0.8
Chiapas	266	11.3	San Luis Potosí	251	8.6
Chihuahua	352	9.9	Sinaloa	230	10.4
Durango	237	7.0	Sonora	457	9.0
Guanajuato	162	3.9	Tabasco	84	5.6
Guerrero	390	18.5	Tamaulipas	349	10.9
Hidalgo	197	7.0	Tlaxcala	152	3.9
Jalisco	298	11.1	Veracruz	415	18.7
México	208	8.2	Yucatán	23	1.1
Michoacán	463	15.8	Zacatecas	195	4.8
Morelos	77	1.9			

TABLE 1 – SIMPUMEX resume. Number of bridges, per state and individual length.

The SIPUMEX system reports an age average of more than 50 years for the 6065 bridges under its administration scope, and this would eventually lead to consider stage of deterioration that the bridges are currently standing at, as shown below.

Variables and Criteria For Analysis Of Information

Based exclusively on the age of each bridge that is reported by SIPUMEX, a fundamental prime concern has been taken into account: The durability model. The residual life of most of the Mexican bridges has yet to be determined in the short future and this work should be the initial steps to determine at what phase of deterioration each bridge is.

The actual state of any concrete structure exposed to a corrosive environment can be determined following a service model diagram (Fig. 1) as proposed by Torres Acosta. This model presents the structural load capacity (or nominal resistance) as a function of its lifetime. In this investigation, reinforced concrete structures durability is considered to be a three-phase process. The lifetime, T, of the structure, is defined as [Torres Acosta]: $T = T1 + T2 + TRL$ (1)

T1 is the first phase (or corrosion initiation stage) from the time of construction to the time of corrosion initiation. T2 is the second phase (or corrosion propagation stage) during which the steel corrodes until an unacceptable level of corrosion loss has occurred. The unacceptable level is defined when the first crack appearing on the concrete surface is less than 0.1 mm wide [2]. Critical spalling may occur much later. Service life is defined, therefore, as $TSL = T1 + T2$.

The third phase, TRL (or residual life stage), starts from the time of external visual. Degradation (cracks < 0.1 mm wide) until a degradation level is such that the design load factors (e.g., for ACI318 Standard, 1.2 and 1.6 for dead and live loads, respectively) equals unity, before structural collapse. As observed from Figure 1, the load capacity remains almost the same during the first two periods until reaching the TRL stage, where the capacity decrease rate is accelerated.

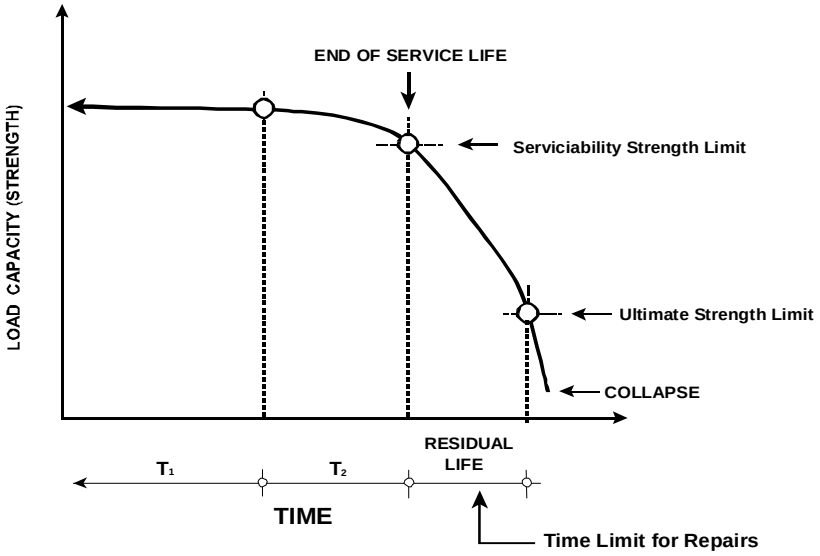

Figure 1. Service life model of Reinforced Concrete Structure (RCS) exposed to marine environment.

Taking into account the fact that each curve is to be produced per bridge, the complete Plan was put forward and according to the tasks mentioned earlier, a population of 6 065 bridges were identified for inclusion in the program. The bridges in this population were analyzed and grouped according the following variables and criteria:

1. Year of construction (select the bridges that were built in or before 1990 without considering the information about maintenance).
2. Bridges over rivers and canals.
3. Distance to the coastline: close to the coast line two buffer zones were identified about five kilometers from the coast; and another 20 km. If a river is present in this same area, the analysis sought to capture the combined effect of the humidity and the possible presence of high concentrations of chlorides.
4. Climate zone: In the case of corrosion by carbonization dry and semidry climates are considered, or places that have temperatures between 18° C and 22.9° C.
5. Counties or urban areas with industrial activities likely to increase probability of corrosion. Areas in where two or more industrial parks or cities are located, with a potential generation of air pollutants and waste that could lead to corrosion due to carbonization.
6. SIPUMEX current grade that actually qualifies and classifies the level of structural integrity of each bridge

PROCEDURES AND RESULTS OBTAINED

The routines followed to analyze the complete data handled are summarized in Figure 2.

1. Current available maps, sharp files, geographic referenced maps and NAD27 and WGS84 data al well as Clark´s 1866 spheroid were considered in the overpostioning and their spatial analysis.
2. The geographic referenced map of all the national bridges located in the MFHN is shown in Figure 3.
3. The year of construction variable, considered data available of all bridges built in year 2000 and before.
4. Bridges located over lakes or rivers and channels are cartographically shown in Figure 4.
5. The bridges located within a 5 km buffer zone at the coastal line, are shown in Figure 5.
6. Likewise, those bridges located within a buffer of 20km from the costal line are shown in Figure 6.
7. To establish the bridges under criterion 5, an analysis of SIPUMEX data was managed to identify the bridges located over urban areas, and counties in where more than two industrial parks, cities or industrial areas. The results can be seen in Figure 6.
8. After these assessments and data analysis was done, further fields were added, to assign a value, between 0 and 1 on each bridge that fulfilled any of above mentioned conditions.

9. At this stage of the assessment process, the SIMPUMEX grade was taken into account (as stated before, it assigns a value between 0 and 5) The values shown below correspond to the year 2000 evaluation. The assigned value in our analysis was 2 for SIPUMEX grade between 4 and 5; 1 for SIPUMEX grade between 2 and 3 and 0 for those with SIPUMEX grade of 0 and 1.

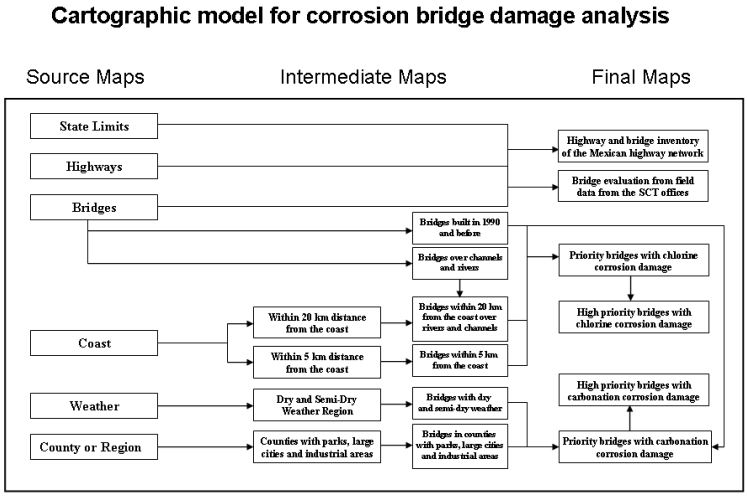

Figure 2. Method to create the maps of potentially corrosion- damaged bridges in the MFHN.

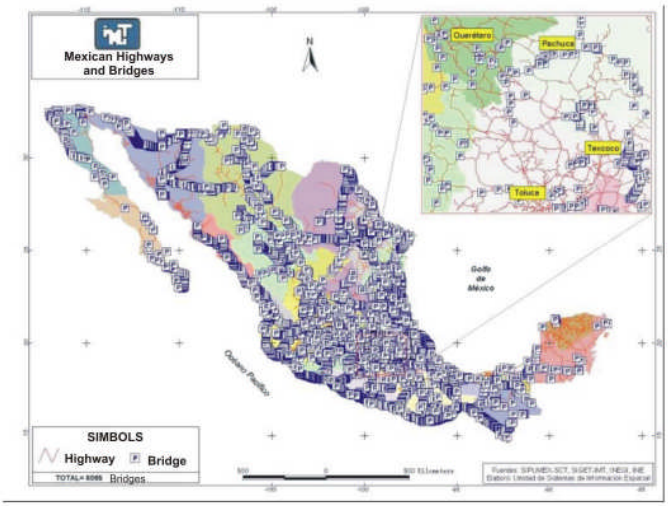

Figure 3. Inventory of all concrete bridges in the MFHN

Based on the preliminary results, to assess the potential damage of environmental variables, such a chloride and carbonation and the total numeric values were then processed into categories:

CHLORIDE CONTRIBUTION TO CORROSION DAMAGE	CARBONATION LIKENESS OF CORROSION DAMAGE
0 and 1 = low priority	0, 1 y 2 = low priority
2 y 3 = medium priority	3 y 4 = medium priority
4 y 5 = high priority	5 y 6 = high

Table 2. Categories of Damage

10. Alter analyzing these tables and all the produced data, priority maps were thus created, High, medium and low bridge inspection requirement was then processed as can be seen in figures 6, 7 and 8 This process led to establish the bridges in where a detailed inspection was to be planned for immediate attention, as shown in Figure 9.

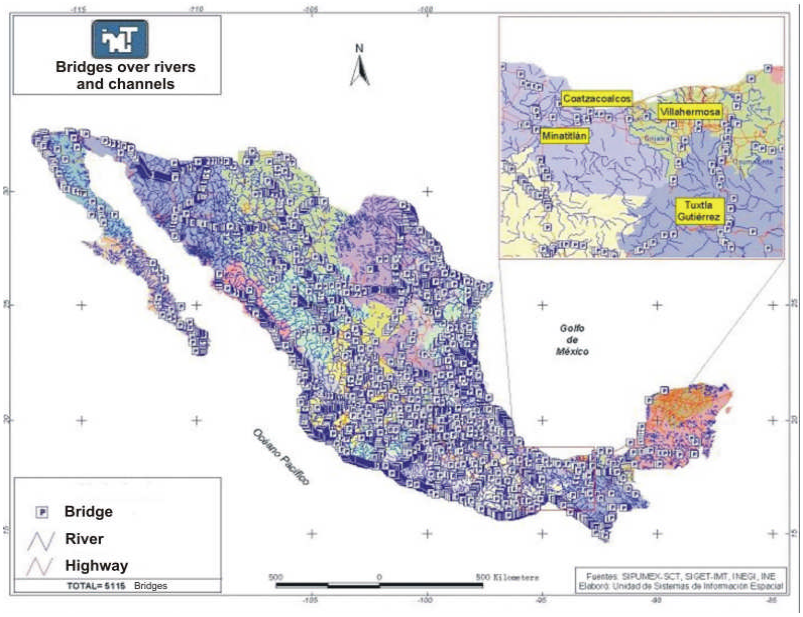

Figure 4. Map of location of concrete bridges over rivers and channels

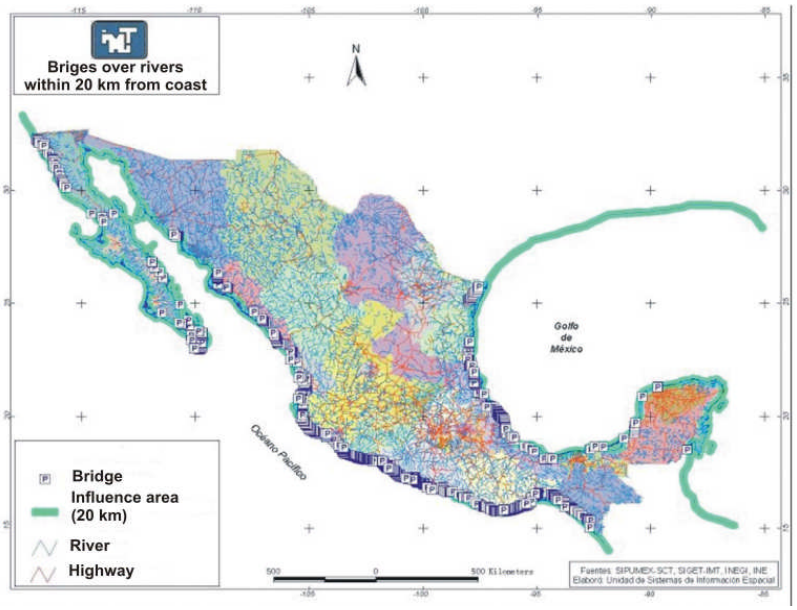

Figure 5. Map of concrete bridges over rivers and at 20km buffer on costal

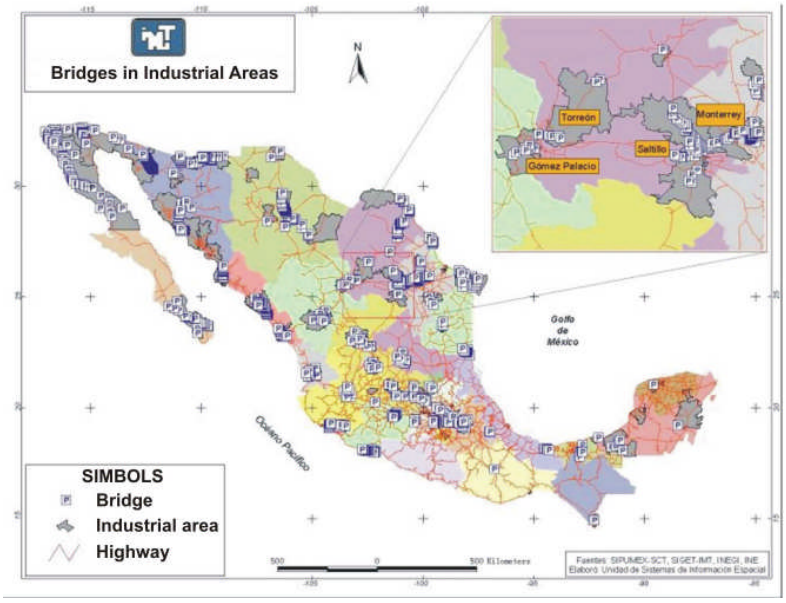

Figure 6. Map of Bridges located in Industrial corridors

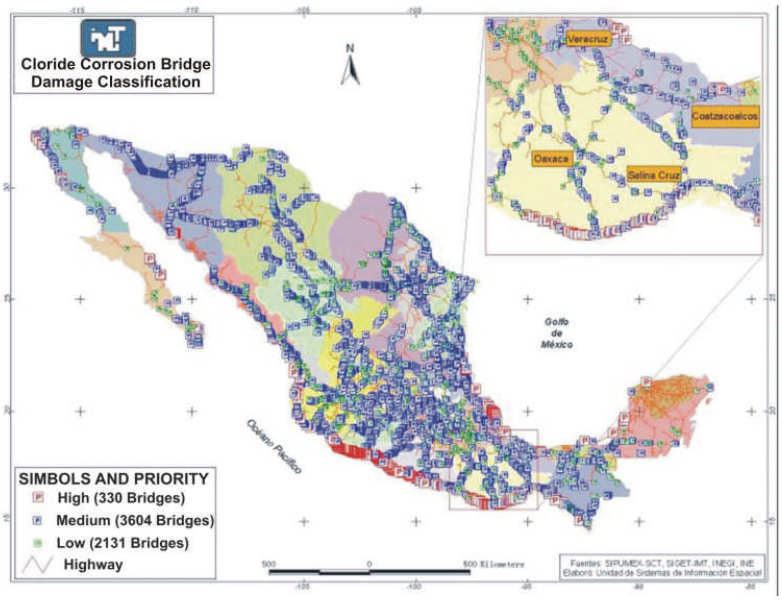

Figure 7. Map of concrete bridges potentially damaged by chloride damage

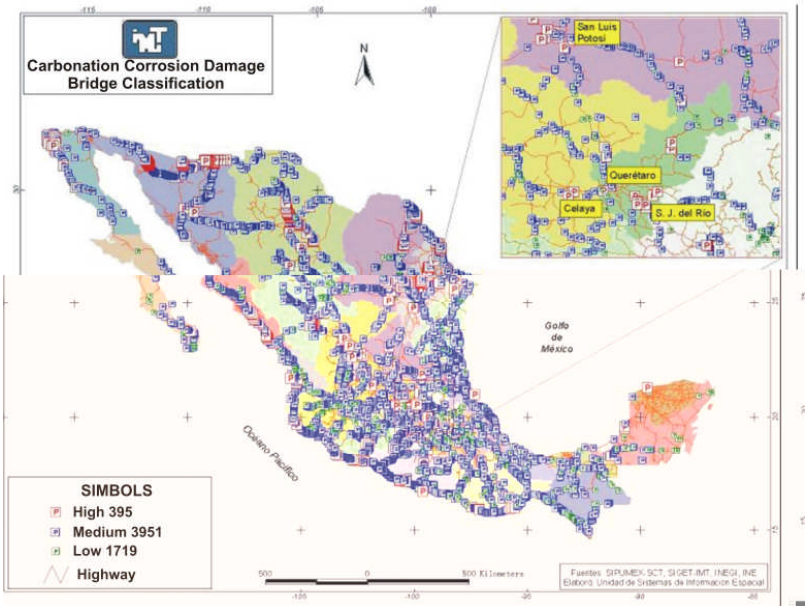

Figure 8. Map of concrete bridges potentially damaged by carbonation

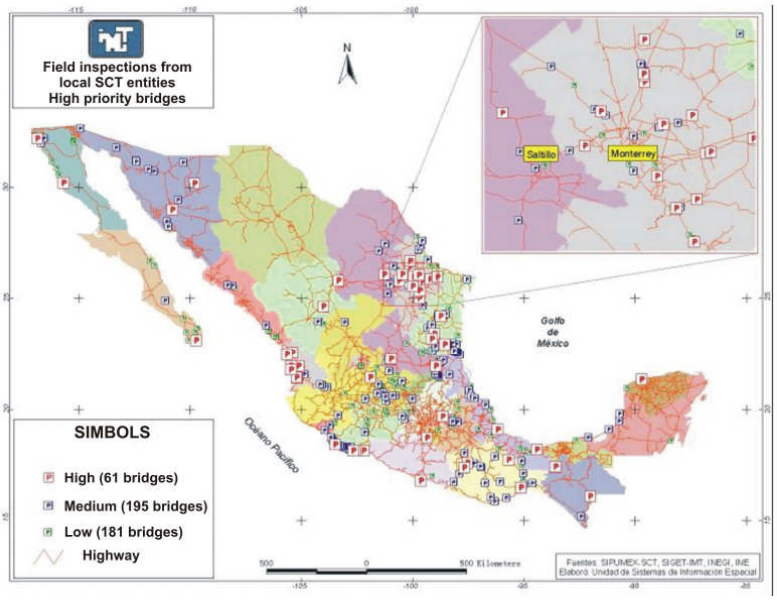

Figure 9 – Map of chosen bridges for immediate inspection. Field preliminary results

All MFHN bridges were then discriminated and prioritized based on potential for corrosion based on exposure to chlorides and based on carbonization, taking into account the current SIPUMEX rate or grade. The following represent numbers identified in each category and priority:

- Bridges with potential to corrode by chlorides: High Priority=330 bridges, Medium Priority=3604 bridges, Low Priority=2131 bridges.

- Bridges with potential to corrode by carbonization: High Priority=395 bridges, Medium Priority=3951 bridges, Low Priority=1719 bridges

CONCLUSIONS AND REMARKS

The results that have been obtained up to now demonstrate the use of GIS, SIMPUMEX incorporated into de National Plan, is a clue and deterministic tool to schedule detailed inspections of bridges that have a potential for deterioration, besides the typical degradation for common heavy load transit. At the same time, this work serves as a base for the authorities of conservation of bridges of the SCT of Mexico so that the rehabilitation on the bridges can include criteria design for extending residual life of the bridges. The differentiation of bridges by structural integrity and potential corrosion realized in this work is not definite and currently the databases are being improved. It is planned to merge other databases given by the INEGI to include more extensive parameters about the most important polluters in the urban areas of Mexico. By doing so, zones where there are high and critical concentrations of CO2 present for the generation of corrosion by the carbonation of the concrete will be accurately considered.

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