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OPTIMAL MAINTENANCE TIMES OF CORRODED BRIDGES INCLUDING CLIMATIC CHANGE AND KERNEL IMPROVEMENT TO THE SIMULATION PROCESS

David De León(1), Julio César Rolón Aguilar(2),Salvador Ibarra Martínez(3)

(1) Profesor, Universidad Autónoma del Estado de México, México, dleon@uaemex.mx
(2) Profesor, Universidad Autónoma de Tamaulipas, México, jrolon@docentes.uat.edu.mx
(3) Profesor, Universidad Autónoma de Tamaulipas, México, sibarram@docentes@uat.edu.mx

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ABSTRACT

The corrosion degrades the bridge capacity in such a way that its vulnerability is exacerbated and its maintenance rises serious concerns. By considering the effect of climatic change, the corrosion process accelerates and the prediction of the time when a maintenance work is required should be a careful exercise. Uncertainties are also of the utmost importance and, in particular, the corrosion hazard requires a probabilistic model. This work deals with a procedure to assess the optimal maintenance times of prestressed concrete bridges, and the focus the corrosion rate, which is random, and several climatic change scenarios make variable its mean value and the standard deviation. By recognizing that, in a bridge network, the most important bridges require a more detailed follow-up, the bridge importance impacts the maintenance times in terms of the size of the potential losses. The reliability reduction and the rate of reliability reduction characterize the bridge degradation and infer the priority of the maintenance needs. The calculation of the bridge failure probability uses Monte Carlo simulations. As crude Monte Carlo is very time-consuming, Kernel tools help to improve the calculations efficiency. This is performed for 3 climatic change scenarios and recommendations are obtained for these scenarios and for two levels of failure consequences (bridge importance). As expected, the worst scenarios of climatic change anticipate the maintenance time. In addition, the more important bridges require also an anticipation on the required maintenance times.

Keywords: bridge maintenance, bridge importance, climatic change, corrosion hazard, failure probability, live load.

TIEMPOS ÓPTIMOS DE MANTENIMIENTO DE PUENTES CORRÍDOS INCLUYENDO CAMBIO CLIMÁTICO Y MEJORAMIENTO KERNEL DEL PROCESO DE SIMULACIÓN

RESUMEN

La corrosión degrada la capacidad de puentes de modo que se acelera su vulnerabilidad y su mantenimiento levanta serias preocupaciones. Si a esto se agrega el efecto del cambio climático, el proceso de corrosión se acelera y la predicción del tiempo requerido para hacer un trabajo de mantenimiento debe ser planeado de manera cuidadosa. Las incertidumbres son también de la máxima importancia y, en particular, el peligro de corrosión requiere un modelado probabilístico, En este trabajo, se propone un procedimiento para evaluar los tiempos óptimos de mantenimiento en puentes de concreto preesforzado y se pone énfasis en el modelo de la tasa de corrosión, que se considera aleatoria. Se proponen varios escenarios de cambio climático y se reconociendo que en una red de puentes el nivel de importancia del puente impacta también los tiempos de mantenimiento. La reducción, tanto de la confiabilidad como de su tasa, son indicadores para identificar la prioridad de las necesidades de mantenimiento. El cálculo de probabilidad de falla del puente hace uso de técnicas de simulación de Monte Carlo y, dado que el proceso crudo Monte

Carlo es muy lento, se aplican técnicas Kernel para mejorar su eficiencia. Esto se ejecuta para 3 escenarios de cambio climático y se generan recomendaciones para estos escenarios y para 2 niveles de importancia del puente. Como se espera, a medida que el efecto de cambio climático es más severo, el tiempo de mantenimiento debe anticiparse más. Los puentes más importantes requieren una mayor anticipación del tiempo de mantenimiento.

Palabras clave: Cambio climático, carga viva, importancia del puente, mantenimiento del puente, peligro de corrosión, probabilidad de falla.

1. INTRODUCTION

Bridges are essential works that require a detailed care to protect them and maintain them within adequate service conditions. Climatic change is adding now a special challenge to all infrastructure works but, in particular, the global warming accelerates some degrading processes like the corrosion on bridges (IPCC, 2018). The bridge vulnerability considered the impact of the climate change (Balomenos et al., 2018). In addition, the uncertainties are different due to the climatic change and their influence on the bridges evaluations have been recognized (Mondoro, Frangopol, and Liu, 2018). Huge annual losses as high as 5 billion euros due to the impact of windstorms on structures, including bridges, have been reported (Spinoni, 2020). However, the effect of a random corrosion rate on the corrosion progress and on the expected damage costs have not been analyzed. Technology from Computer Engineering helps to improve the data handling, like fuzzy logic, genetic algorithms, parallel computing, among many other algorithms. Gaussian Kernel optimization is a tool to enhance the numerical efficiency of the simulations (Sydeman et al., 2011). Kernel methods are efficient tools to design or evaluate the structural behavior of wind turbine power structures. These procedures contribute to improve the efficiency of the wind turbines. (Skrimpas et al., 2015). Machine learning and vision-based embedded systems are being used to monitor bridges networks and provide information for a permanently follow up bridges with an autonomous and remote control (Teng and Mosalam, 2020).

Multi-criteria decision analysis and risk concepts assessed the impact of the climate change effects on bridges (Nasr et al., 2022). The impact of global climate on the resiliency of critical infrastructure has been evaluated (Argyroudis et al., 2022).

The transference of prior knowledge for infrastructure condition assessment, with emphasis on surrogate methods, allowed for the generation of meta-learning techniques (Cheng et al., 2022). Tsunami hazard assessment, through time-variant stochastic renewal processes, derived on the nonstationary effects of the elevation on the sea level, due to climate change (Alhamid et al., 2022). Machine learning techniques and probabilistic models are powerful tools to assess the seismic performance of bridges (Soleiman and Hajializadeh, 2022). Vibration –based monitoring and machine-learning methods helped to execute intelligent damage diagnosis of bridges (Niyirora, 2022). Experimental studies, complemented with machine learning techniques, allowed for the assessment of bridges with corroded rebars (Srivaranun et al., 2023). The combined effect of live load on bridges have been analyzed under the hazards of corrosion and earthquake (Han and Frangopol, 2023), but the impacts of the uncertainty on the corrosion rate under climatic change, and the effect of the bridge importance on the bridge maintenance times, have been less studied.

In this paper, the uncertainty on the corrosion rate shows how the scenarios of climatic change and the probability distribution of the bridge capacity have an impact on the decision-making on the maintenance times; the climatic change reduces the maintenance times. In addition, the procedure shows that higher failure consequences of the bridge types produces an anticipation on the maintenance times within a bridge network. The funds priorization is an important issue to optimize the management of scarce resources to attend the maintenance needs of bridges through risk-informed criteria.

2. PROPOSED FORMULATION

A probabilistic framework is appropriate for the uncertainties involved in the determination of maintenance times of bridges (the random nature of the corrosion rate is emphasized because of the impact of climatic change). The numerical work required is extensive so, therefore, the use of kernel techniques are proposed in the formulation to add efficiency to the simulation process.

The core of the proposed procedure is the identification of the adequate time to perform maintenance work, and this is achieved through the following steps:

1) The bridge failure probability calculated on a year-by-year basis and, due to the corrosion progress, these probability increases with time.
2) The target failure probability is calculated by minimizing the present value of the expected life-cycle cost.
3) The bridge failure probability is compared to the target value and, when the bridge failure probability exceeds its target value, this is the adequate time to perform maintenance works.

The exercise is repeated for three climatic change scenarios and for two levels of bridge importance. Figure 1 shows a simplified flowchart with the proposed procedure.

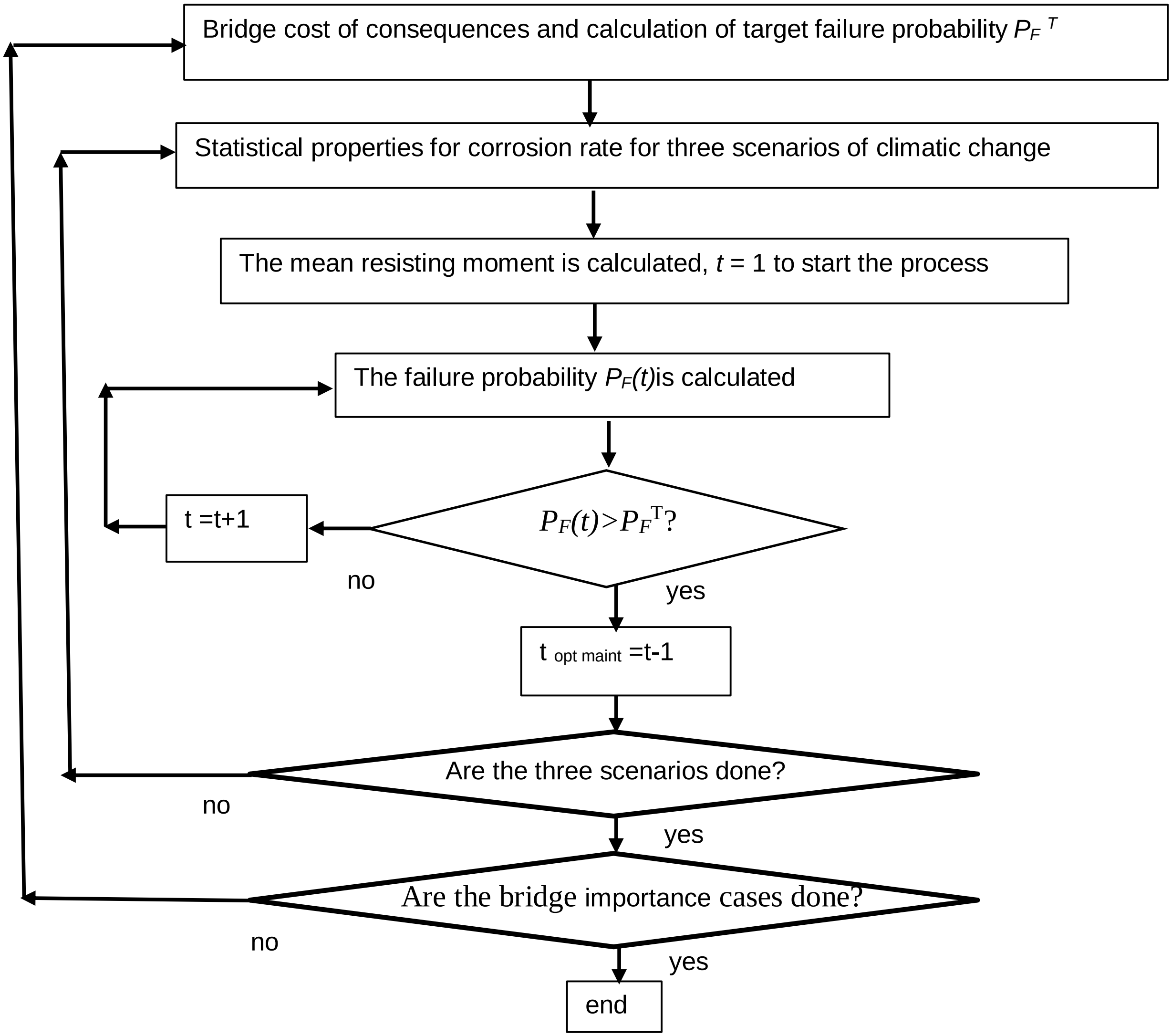

Figure 1 Simplified flowchart of proposed procedure

The concrete resistance f´c and the bridge live load are lognormal random variables, as in some previous works (De León-Escobedo et al., 2014); their statistical properties appear in Table 1.

Table 1. Distribution, mean value and coefficient of variation for concrete resistance and live load

Random variable	Distribution	Mean value	Coefficient of variation
Concrete resistance f´c	Lognormal	34 Mpa	0.18
Live load (T3-S2-R4)	Lognormal	761 kN	0.3

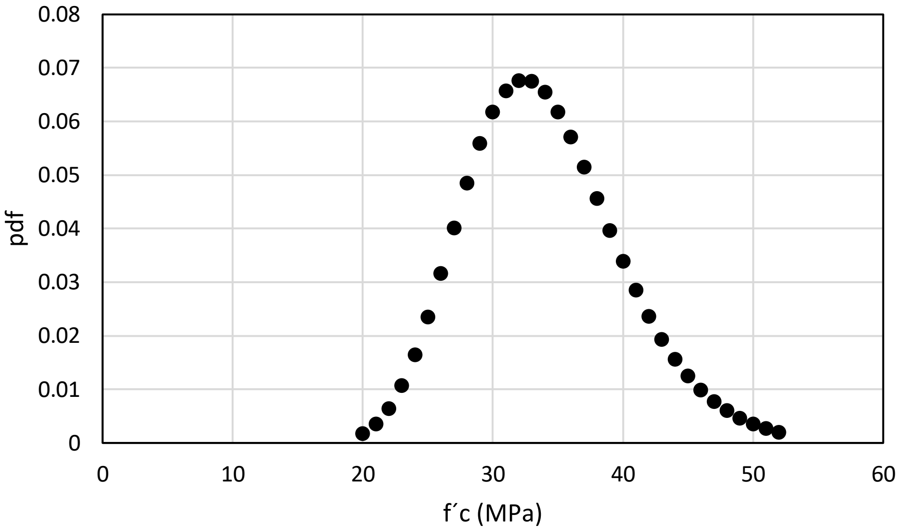

Figure 2 Distribution of concrete resistance

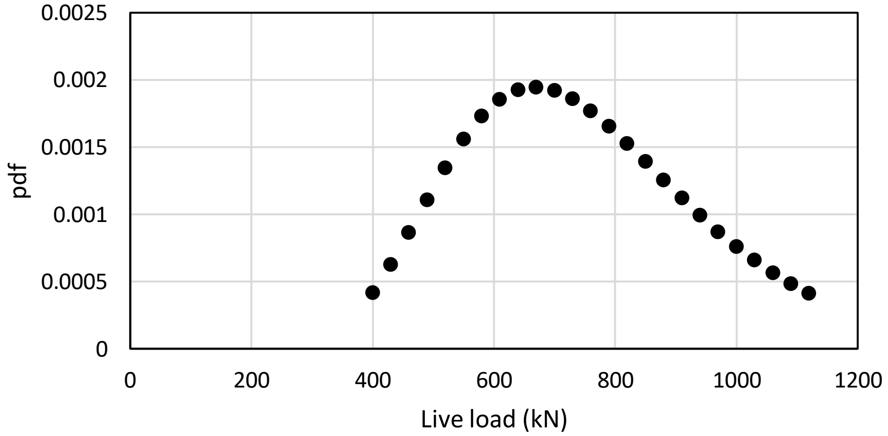

Figure 3 Distribution of live load

As far as the corrosion process is concerned, the types of distribution and the values of the pertinent parameters appear in Table 2 (De León-Escobedo, et al., 2014).

Table 2. Corrosion random variables, distribution type and parameters

Variable	Type of distribution	Parameters
T_1, corrosion initiation time	Weibull	c = 1.81, μ = 63.67
$corr_{rate}$, corrosion rate (mA/cm^2)	Uniform	LL =lower limit, UL = upper limit

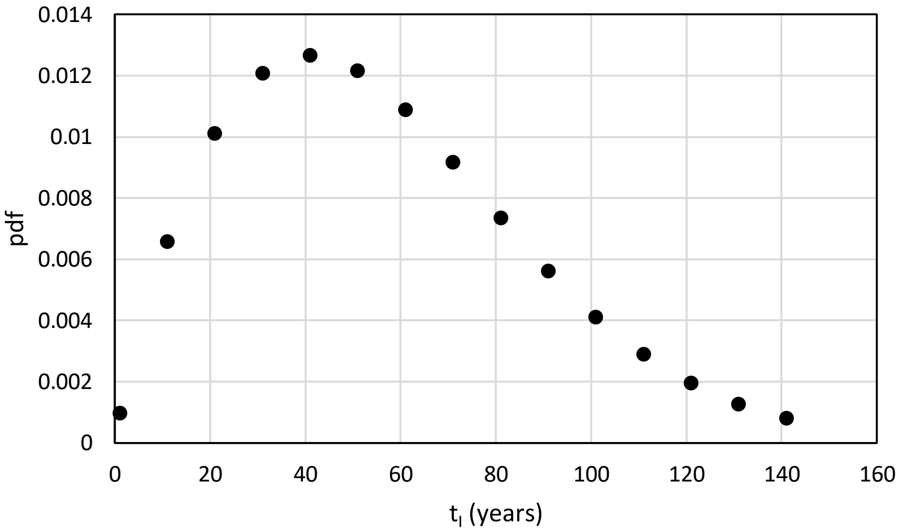

Figure 4 Distribution of corrosion initiation time

The lower and upper limits [LL, UL] for the corrosion rate, due to the climatic change, move on the rise according to the climatic change scenario; three cases are proposed and shown in Table 3.

Table 3. Lower and upper limits for uniform distribution of $corr_{rate}$ for three scenarios

Scenarios	LL	UL
1	2.1	3.1
2	2.3	3.3
3	3	4

The time-variant diameter, for a typical steel prestressed wire, produced by the corrosion progress is (De León-Escobedo et al., 2014):

$$D(t) = DI\text{-}0.0203 corr_{rate} t \tag{1}$$

Where DI is the initial diameter of the wire, $corr_{rate}$ is the corrosion rate and t the time. The corrosion rate has the uniform distributions with the limits shown in Table 3 and, from classical probability theory has the variance:

$$\sigma^2 = (UL - LL)^2/12 \tag{2}$$

Where UL and LL are the upper and lower limits, respectively.

The evolution of chloride concentration has been modeled in terms of the corrosion depth x, the chloride concentration at the surface level (x=0) CC_0 and the error function *erf* (Costa and Appleton, 1999^a; Costa and Appleton, 1999b).

$$CC(x,t) = C_{C0}\left\{1 - erf\left[\frac{x}{2\sqrt{(Dt)}}\right]\right\} \quad (3)$$

The time-variant of the resisting moment *RM (t)* is calculated for the time *t* and, with the maximum acting moment *AM* obtained from conventional bridge analysis for the dead and live load (De León-Escobedo et al, 2014), the bridge failure probability is calculated:

$$FP(t) = P(AM > RM(t)) \quad (4)$$

The expected losses *EL*, which depend on the bridge importance level, are a critical component to assess the target failure probability $P_F{}^T$ (De León-Escobedo et al., 2013):

$$P_F{}^T = CE/[(PVF)(EL)] \quad (5)$$

Where *CE* is the cost for enhancing the bridge safety and *PVF* the present value factor.

$$PVF = (1 - \exp[(-\delta)(LT)])/\delta \quad (6)$$

Where δ is the net annual interest rate and LT the bridge lifetime; the target value results from the minimization of the present value of the expected life-cycle cost.

3. CASE STUDY

The bridge used to illustrate the case study to apply the proposed procedure is the one located at the intersection of Pino Suarez and Tollocan the city of Toluca, Mexico State (De León-Escobedo et al., 2013. This is a prestressed concrete bridge with six hollow-box longitudinal beams, which constitute the support of the slab. The critical members where the bending capacity governs the bridge failure model. The corrosion attacks the prestressed steel wires located at the bottom of each beam and the place where the pitting corrosion is located. As ahead explained, the bending resistance varies with time according to the corrosion progress.

4. RESULTS

Given that neither the seismic forces nor the Eolic ones are significant, for the bridge location, the only governing actions are the live load and the corrosion deterioration process.

4.1 Variation on resisting moment due to corrosion without including climatic change

The reduction on the resisting moment capacity, as the time goes on, can not be avoided; even before the climatic change is included. The probability density function of the resisting moment is calculated and, as a sample, these functions are showed in Fig. 5, for *t* = 0 and 20 years.

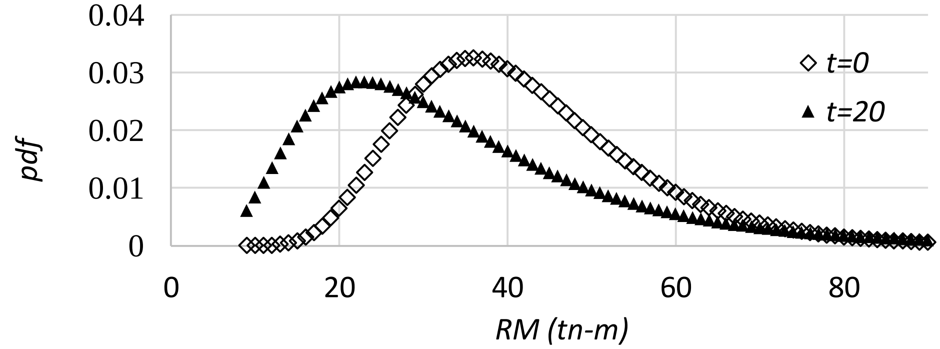

Figure 5 Resisting moment for *t* = 0 and 20 years without climatic change

As observed, the resisting moment has a clear reduction after 20 years, due to the corrosion progress; in particular, the mean value reduces from 38 to a value close to 22 tn-m. This occurs before the climatic change is considered.

If a cost of failure consequences of 400 USD million, δ = 0.1 and *LT* = 100 years are considered for the bridge, a target failure probability PF^T = 0.004 is obtained (De León-Escobedo et al., 2014).

Then, the failure probabilities for the considered bridge are calculated for several times from *t* = 0 to 80 years and by following the procedure above described. In order to reduce and make more efficient the simulations, a Kernel method helps to minimize the time spent on the calculations:

$$\hat{y} = sgn \sum_{i=1}^{n} w_i y_i k(x_i, x') \tag{7}$$

The selection of an appropriate similarity function *k,* together with the weights w_i, allows for the reduction from the thousands of simulations required in a crude MCS to a few trials needed to achieve the required precision. The number of trials depends approximately on what is the order of the failure probability to achieve.

4.2 Bridge failure probability with climatic change effects

The statistical properties of the corrosion rate $corr_{rate}$, are shown in Table 4 for the three assumed scenarios due to climatic change.

Table 4. Statistical properties of the corrosion rate

Scenario	Mean (mA/cm^2)	Standard deviation (mA/cm^2)
1	2.5	0.287
2	2.6	0.287
3	2.8	0.287

The resulting failure probabilities, for times from 0 to 80 years, and the target failure probability 0.004, appear in Fig. 6.

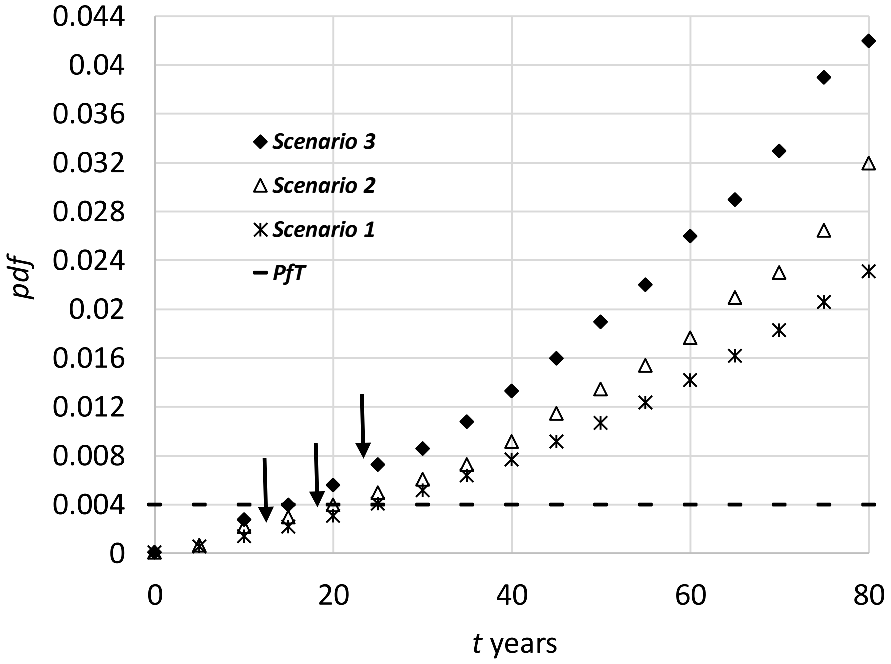

Figure 6 Failure probabilities for 3 scenarios of climatic change and target failure probability

As observed, the failure probability curves shifted to the left for the scenarios 1 to 3; this has the meaning that there is a reduction on the required maintenance times. Therefore, the optimal inspection/maintenance time (indicated by arrows) anticipate from 25 (scenario 1) to 20 (scenario 2) and to 15 years (scenario 3). In addition, because of the positive curvature of the three curves, the slope of the tangent grows as the times grows. Besides, for a specific time, the slope of the tangent is higher as the scenario gets worst. That means that the growth speed of the failure probability, for any specific time, is higher as the climatic change scenario is more adverse.

4.3 Bridge importance effect

The effect of the bridge importance on the determination of the maintenance times is significant because, as the bridge importance grows, the target failure probability is lower and an anticipation is required for bridge maintenance. In addition, the climatic change accelerates these effects, because the anticipation is larger for scenarios with stronger climatic change. Fig. 7 shows how the optimal maintenance time depends on the target failure probabilities PFT1 and PFT2 (the cost of failure consequences) and on the climatic change scenario. These optimal times anticipate as the bridge importance grows and as the scenario becomes worst.

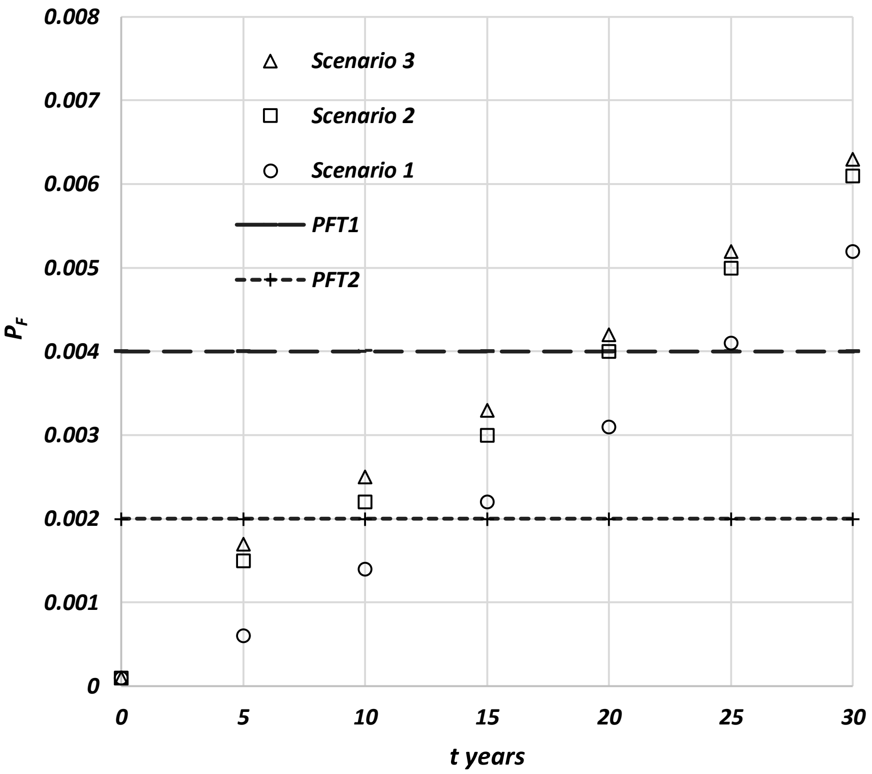

Figure 7 Maintenance time for three levels of bridge importance

For the purpose of a better budget management at a regional or national level, is important to prioritize and identify the specific needs of each bridge, in order to save time and money to maintain a bridge network.

5. ANALYSIS OF RESULTS

Given that the target failure probability was calculated on the basis of the minimum expected life-cycle cost, the optimal of all the derived maintenance times is based on the same minimum. Therefore, if the maintenance works are performed after the recommended time, the expected life-cycle cost will have higher values than the optimal.

If the climatic change is included into the bridge maintenance schedule, the maintenance time become shorter than in the case that the climatic change is not included. In addition, the harder the scenario is, the shorter the maintenance time becomes. By ignoring the climatic change, the provided maintenance time will be after the one that involves the minimum cost.

Important bridges require a more anticipated maintenance times than the ones not so important. An overall bridge priorization strategy helps to optimize the costs for the whole bridge inventory of the country. Risk-informed preventive maintenance policies and life-cycle planning should be integrated and implemented not just for bridges but for the types of infrastructure in México.

The use of Kernel methods probed the benefit of having a substantial reduction on the employed computational time. The use of these and other AI techniques should be emphasized to dedicate more time and efforts to the study of computationally complex problems, to perform more detailed procedures and to target key trends for multi-hazard or multi-objective challenging situations with many interactions among the variables.

6. CONCLUSIONS

1.- In general, the maintenance times for bridges degraded by corrosion, become shorter for the worst climatic change scenarios than for the ones less drastic. In particular, for the example illustrated here, the maintenance time reduces from 20 to 8 years, for the scenario 3.

2.- The bridge maintenance time is further reduced as the bridge importance grows, for bridges where the corrosion process is significant. For the case considered here, if the costs of failure consequences are of 400 and 800 million USD, the corresponding maintenance times are of 45 and 10 years.

3.- The use of a Kernel method, makes more efficient the Monte Carlo simulations, with the consequent saving on computational time.

4.- The bridge maintenance times obtained here, after they are combined with other maintenance needs, may be used for a planning of the maintenance programs to optimize the use of limited resources and advance towards an effective life-cycle cost-benefit criteria.

5.- Some of the limitations of the present study are: a) only the failure mode of bending on beams was considered, other failure modes may be critical for other bridges types; b) a simplified model of pitting corrosion was considered; c) natural hazards like scour, wind or earthquake have not been considered.

6.- Caution should be exercised before trying to apply the proposed formulation to other cases with assumptions that were not considered here.

7. RECOMMENDATIONS

1.- It is recommended to further expand the study to incorporate other bridge types, other bridge materials like steel, other corrosion environments and other bridge hazards like scour. Once a whole set of cases with the proper hazard(s) is included, the findings are useful to build a rational planning to keep bridges under safe operating conditions in Mexico.

2.- With additional studies, the formulation proposed here may be adapted to other types of infrastructure, for maintenance objectives, like electrical, port and maritime facilities, as they can be exposed to corrosion hazard and also prone to suffer the climatic change effects.

3.-Also, technical guidelines oriented to balance cost and safety may be generated to develop public policies on bridges and to complement the body of knowledge required to design the standards and codes required to advance the best practices towards risk-informed and longterm and sustainable infrastructure maintenance.

4.- It is recommended to work on the formation of high-level specialists in particular for bridge maintenance but and, in general, for infrastructure exposed to any kind of hazards.

5.- It is recommended to pursue on the purpose of gaining advantage of computational engineering techniques in order to develop efficient methods to face the challenges that involve complex numerical problems in engineering.

6.- It is advisable to further apply the proposed formulation to consider other structural types of bridges and other hazards that may occur at different sites of the country.

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REFERENCES

Alhamid A. K., Akiyama M., Aoki K., Koshimura S. and Frangopol D. (2022) Stochastic Renewal Process Model of Time-variant Tsunami Hazard Assessment under Nonstationary Effects of Sea-level Rise due to Climate Change, Structural Safety, Elsevier, Vol. 99, 2022, 1022763, 1-17, doi.org/10.1016/j.strusafe.2022.102263

Argyroudis S. A., Mitoulis. A., Chatzi E., Baker J. W., Brilakis I., Gkoumas K., Vousdoukas M., Hynes W., Carluccio S., Keou O., Frangopol D. and Linkov I. (2022) Digital Technologies Can Enhance Global Climate Resilience of Critical Infrastructure, Climate Risk Management, Elsevier, Vol. 35,100387, 1-9, doi.org/10.1016/j.crm.2021.100387

Balomenos G. P., Kameshwar S., Bass B., Padgett J. E. and Bedient P. (2018) Vulnerability of bridges exposed to coastal hazards and climate change. Book chapter from Maintenance, Safety, Risk, Management and Life-Cycle Performance of Bridges. 1st. Edition, CRC Press, 7 pages, eBook ISBN 9781315189390

Cheng M., Dang C., Frangopol D., Beer M. and Yuan X. X. (2022) Transfer Prior Knowledge from Surrogate Modelling: A Meta-learning Approach, Computers & Structures, Elsevier, Vol. 260, 106719, 1-16, doi.org/10.1016/j.compstruc.2021.106719

Costa, A., and Appleton, J. (1999a). “Chloride penetration into concrete in marine environment—Part I: Main parameters affecting chloride penetration.” Mater. Struct. 32(4), 252–259.

Costa, A., and Appleton, J. (1999b). “Chloride penetration into concrete in marine environment—Part II: Prediction of long-term chloride penetration.” Mater. Struct. 32(5), 354–359.

De León-Escobedo D., Camacho S. and González-Pérez. C. A. (2013) Reliability-based optimal next inspection time of prestressed concrete bridges including the effect of corrosion deterioration. Rev. Téc. Ing. Univ. Zulia. Vol. 36, Nº 2, 114 – 121.

De León-Escobedo D., Delgado-Hernández D. J., Martinez-Martinez L., Rangel-Ramírez J. G. and Arteaga-Arcos J. C. (2014) Corrosion initiation time updating by epistemic uncertainty as an alternative to schedule the first inspection time of pre-stressed concrete vehicular bridge beams, Structure and Infrastructure Engineering, 10:8, 998-1010, DOI: 10.1080/15732479.2013.780084.

Han X. and Frangopol D. M. (2023) Life-Cycle Risk-Based Optimal Maintenance Strategy for Bridge Networks Subjected to Corrosion and Seismic Hazards. Journal of Bridge Engineering, 28(1), https://doi.org/10.1061/JBENF2.BEENG-5799.

IPCC (Intergovernmental Panel on Climate Change). Masson-Delmotte V., Zhai P., Pörtner H. O., Roberts D., Skea J., Shukla P. R., PiraniA., Moufouma-Okia W., Péan C., Pidcock R., ConnorsS., Matthews J. B. R., Chen Y., Zhou X., Gomis M. I., Lonnoy E., Maycock, T. Tignor M. and Waterfield T. (eds.). (2018). Summary for Policymakers. In: Global warming of 1.5°C. An IPCC special report on the impacts of global warming of 1.5°C above pre-industrial levels and related global green- house gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty. World Meteorological Organization, Geneva, Switzerland, 32 pp.

Mondoro, A., Frangopol, D. M. and Liu, L. (2018). Bridge adaptation and management under climate change uncertainties: A review. Natural Hazards Review, 19(1), 04017023

Nasr A., Johansson J., Larsson Ivanov O., Björnsson I. and Honfi D. (2022) Risk-based multi-criteria decision analysis method for considering the effects of climate change on bridges, Structure and Infrastructure Engineering, DOI: 10.1080/15732479.2022.2033278

Niyirora R., Ji W., Masengesho E., Munyaneza J., Niyonyungu F. and Nyirandayisabye R., (2022) Inteligent damage diagnosis in bridges using vibration-based monitoring approaches and machine learning: A systematic review. Results in Engineering, Volume 16, https://doi.org/10.1016/j.rineng.2022.100761.

Skrimpas G. A., Sweeney Ch. W., Marhadi K., Jensen B.-B., Mijatovic N. and Holbll J., (2015) Employment of Kernel Methods on Wind Turbine Power Performance Assessment. IEEE Transactions on Sustainable Energy 6(3), pp. 1-9, DOI:10.1109/TSTE.2015.2405971.

Soleiman F.; Hajializadeh, D. State-of-the-Art Review on Probabilistic Seismic Demand Models of Bridges: Machine-Learning Application (2022). Infrastructures, 7, 64. https://doi.org/10.3390/ infrastructures7050064.

Spinoni J. (2020), Joint Research Comission. Disaster Risk Management Unit. PESETA IV publications - https://ec.europa.eu/jrc/en/peseta-iv

Srivaranun S., Akiyama M., Yamada T., Frangopol D. and Xin J. (2023) A Novel Combined Experimental-Machine Learning Approach to Estimate the Probabilistic Capacity of RC Beams with Spatially Correlated Rebar Corrosion in Transverse and Longitudinal Directions, Engineering Structures, Elsevier, Vol. 279, 2023, 115588, 1-17, doi.org/10.1016/j.engstruct.2023.115588

Sydeman W. J., García-Reyes M., Schoeman D. S., Rykaczewski R. R., Thompson S. A.,
Yin J.-B., Li T. and Shen H.-B. (2011) Gaussian Kernel optimization: Complex problem and a simple solution. Neurocomputing, 74(18), pp. 3816-3822, doi.org/10.1016/j.neucom.2011.07.017

Teng, H. L., & Mosalam, K. (2020). Long-Term Monitoring of Bridge Settlements using Vision-Based Embedded Systems (Report No. 2020/25). Pacific Earthquake Engineering Research Center (PEER).
https://apps.peer.berkeley.edu/publications/peer_reports/reports_2020/2020_26_Teng_Final.pdf