Modelling the Deterioration of Infrastructures Using Network-Scale Visual Inspections

Zachary Hamida[1], James-A. Goulet[1]
[1]Department of Civil, Geologic and Mining Engineering, Polytechnique Montreal, Quebec, Canada, H3T 1J4
Email : zachary.hamida@polymtl.ca, james.goulet@polymtl.ca

ABSTRACT: Deterioration models represent one of the essential components in bridge management systems. This paper describes recent developments in methods for modelling the deterioration of infrastructures based on visual inspections. The performance of these methods is demonstrated through an application on visual inspection data from a real case, for bridges within the Quebec province, Canada. The results of the analyses illustrate the capacity of the deterioration framework to predict the deterioration behaviour on the element-level as well as on a network-scale for a subset of bridges.

KEY WORDS: Visual Inspections; Structural Health Monitoring; Bridge Deterioration; Inspectors Uncertainty.

1. INTRODUCTION

Infrastructures have to be monitored and maintained on a regular basis in order to sustain their levels of safety and serviceability. There exist different techniques for monitoring the health-state of bridges, however, visual inspections is by far the most common choice [2, 3].

Visual inspections on infrastructures are on-site evaluation techniques performed by teams of inspectors. One of the main limitations of visual inspections is the evaluation methods being subjective, as they depend on the experience and judgment of different inspectors [2]. In addition, the inspection data is limited due to the inspection interval ranging from 2 to 4 years. These aspects present challenges in interpreting and understanding the deterioration process of infrastructures.

This paper presents an overview of developments in modelling the deterioration and effect of interventions on infrastructures, followed by an application using inspection data from bridges within a municipality in the Quebec province. The deterioration analyses are demonstrated at the element-level for one bridge, and on network-scale for a subset of bridges.

2. MODELLING DETERIORATION AND EFFECT OF INTERVENTIONS

2.1. Element-Level Analyses

The deterioration of infrastructures is a monotonic process, which can be described by a kinematic model. Integrating information coming from visual inspection data with the estimates of the kinematic model is possible by using state-space models (SSM) [2]. The SSM-based deterioration model enables predicting the deterioration condition $x^j_{t,p}$, speed $\dot{x}^j_{t,p}$ and acceleration $\ddot{x}^j_{t,p}$, such that,

$$\underbrace{\begin{bmatrix} x^j_{t,p} \\ \dot{x}^j_{t,p} \\ \ddot{x}^j_{t,p} \end{bmatrix}}_{\boldsymbol{x}^j_{t,p}} = \underbrace{\begin{bmatrix} 1 & \Delta t & \frac{\Delta t^2}{2} \\ 0 & 1 & \Delta t \\ 0 & 0 & 1 \end{bmatrix}}_{\boldsymbol{A}^{ki}} \cdot \underbrace{\begin{bmatrix} x^j_{t-1,p} \\ \dot{x}^j_{t-1,p} \\ \ddot{x}^j_{t-1,p} \end{bmatrix}}_{\boldsymbol{x}^j_{t-1,p}} + \underbrace{\begin{bmatrix} w_t \\ \dot{w}_t \\ \ddot{w}_t \end{bmatrix}}_{\boldsymbol{w}^{ki}_t}, \tag{1}$$

where $\boldsymbol{x}^j_{t,p}$ is the deterioration state at time t for structural element e^j_p in bridge b_j, $\boldsymbol{A}$ is the transition matrix and $\boldsymbol{w}_t : \boldsymbol{W} \sim \mathcal{N}(\boldsymbol{w}; \boldsymbol{0}, \boldsymbol{Q}_t)$ represents the model process error. In order to take into account the information from inspection data, an observation model is employed,

$$y^j_{t,p} = \overbrace{\boldsymbol{C}}^{\boldsymbol{C}=[1\,0\,0]} \boldsymbol{x}^j_{t,p} + v^j_{t,p}, \tag{2}$$

where $y^j_{t,p}$ represents the observation (i.e., inspection data), $\boldsymbol{C}$ is the observation matrix, and $v^j_{t,p} : V \sim \mathcal{N}(v; \mu_V(I_i), \sigma^2_V(I_i))$ is the observation error described by the expected value $\mu_V(I_i)$, and the variance $\sigma^2_V(I_i)$ associated with inspector I_i. The inspectors parameters $\mu_V(I_i)$, and $\sigma_V(I_i)$ are considered as model parameters, that are estimated along with other model parameters. The estimation of the deterioration states $\boldsymbol{x}^j_{t,k}$ is performed using the Kalman Filter (KF) and Kalman Smoother (KS) algorithms [2].

In order to account for the effect of repairs on bridges, the state vector is augmented to include the changes in the deterioration state $\boldsymbol{\delta}$, which consists in, the change in the condition δ, speed $\dot{\delta}$ and acceleration $\ddot{\delta}$. Similarly, the transition matrix is modified to allow the addition of the effect of intervention $\boldsymbol{\delta}$ with,

$$\boldsymbol{A}_{t=\tau} = \begin{bmatrix} \boldsymbol{A}^{\text{ki}} & \boldsymbol{I}_{3\times3} \\ \boldsymbol{0}_{3\times3} & \boldsymbol{I}_{3\times3} \end{bmatrix}, \; \boldsymbol{A}_{t\neq\tau} = \begin{bmatrix} \boldsymbol{A}^{\text{ki}} & \boldsymbol{0}_{3\times3} \\ \boldsymbol{0}_{3\times3} & \boldsymbol{I}_{3\times3} \end{bmatrix},$$

where $\boldsymbol{I}$ is the identity matrix and τ represents the time of intervention. Further details about the estimation of model parameters and the prior estimate for the effect of interventions $\boldsymbol{\delta}$ are available in the work of Hamida and Goulet [1].

2.2. Network-Scale Analyses

SSM-based deterioration models have the capacity to scale and extend the deterioration analyses beyond structural elements for representing the overall deterioration state of a bridge as well as an entire network of bridges. This is possible by using a Gaussian mixture reduction approach, which allows estimating the probability density (PDF) for a weighted sum of E Gaussian densities [4]. In the context of analyzing the deterioration of a system composed of multiple elements, the expected value $\hat{\boldsymbol{\mu}}_{t|t}$ and covariance $\hat{\boldsymbol{\Sigma}}_{t|t}$ of the system are,

$$\begin{aligned}\hat{\boldsymbol{\mu}}_{t|\mathtt{T}} &= \sum_{p=1}^{\mathtt{E}} \lambda^{p} \boldsymbol{\mu}^{j}_{t|\mathtt{T},p},\\ \hat{\boldsymbol{\Sigma}}_{t|\mathtt{T}} &= \sum_{p=1}^{\mathtt{E}} \lambda^{p} \boldsymbol{\Sigma}^{j}_{t|\mathtt{T},p} + \sum_{p=1}^{\mathtt{E}} \lambda^{p} (\boldsymbol{\mu}^{j}_{t|\mathtt{T},p} - \hat{\boldsymbol{\mu}}_{t|\mathtt{T}})(\boldsymbol{\mu}^{j}_{t|\mathtt{T},p} - \hat{\boldsymbol{\mu}}_{t|\mathtt{T}})^{\intercal},\end{aligned}$$

where λ^{j} is the mixture weight, $\mathtt{E}$ is the number of components, $\boldsymbol{\mu}^{j}_{t|\mathtt{T}}$ and $\boldsymbol{\Sigma}^{j}_{t|\mathtt{T}}$ are the expected condition and covariance of the components.

3. CASE STUDY

This section presents a case study for the deterioration analyses of visual inspection from $\mathtt{B} = 3$ bridges $\mathcal{Q}_1 = \{b_1, b_2, b_3\}$ within a municipality in the province of Quebec. The visual inspections in this study are considered on a scale $\tilde{y} \in [25, 100]$, where $\tilde{y} = 100$, represents a perfect condition, and $\tilde{y} = 25$ represents the worst possible condition for a structural element. According to the inspections and interventions databases, the bridge $b_1 \in \mathcal{Q}_1$ has underwent major repairs in the year $\tau = 2015$. Figure 1 shows the effect of repairs on the condition of a *slab* structural element e^1_{31} in bridge b_1.

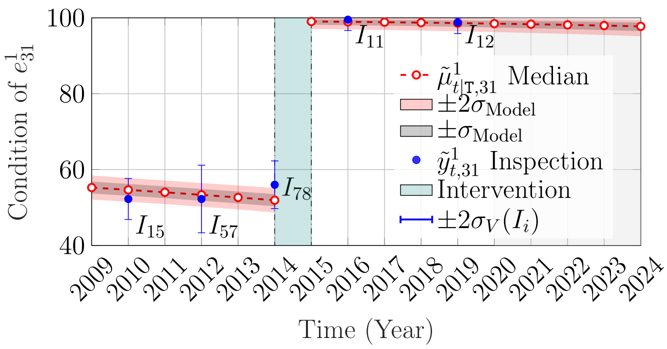

Figure 1: Deterioration state analysis for the condition based on the inspections $\tilde{\boldsymbol{y}}^1_{t,31} \in [25, 100]$ of the slab *structural element with repairs at time $\tau = 2015$, and error bars representing the inspectors' uncertainty estimates.*

The analyses on the structural element level can be aggregated on a network-scale according to Equations 3 based on the concepts defined in the work of Hamida and Goulet [2]. The overall deterioration condition for the bridges in $\mathcal{Q}_1 = \{b_1, b_2, b_3\}$ is shown in Figure 2. From Figure 2, it is noticeable that the overall expected condition has changed slightly after year $t = 2015$, due to the repair works on bridge b_1. The aforementioned change is accompanied by a significant change in the confidence interval of the condition estimates. This is mainly attributed to the variability in the deterioration condition among bridges $\{b_1, b_2, b_3\}$ prior to year $t = 2015$; since bridge b_1 had a lower condition than $\{b_2, b_3\}$ before the repairs. By examining the changes in the expected condition and the variability, it is possible to conclude that even for a small sample

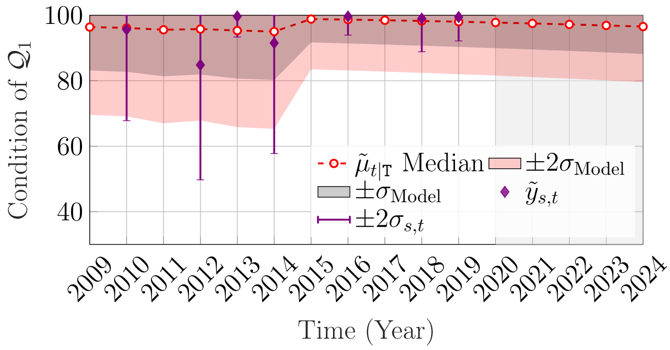

Figure 2: Deterioration state analysis for the network's condition based on the average state of the principal structural elements from $\mathtt{B} = 3$, *bridges, with the aggregated observations $\tilde{\boldsymbol{y}}_{s,t} \in [25, 100]$, with their corresponding uncertainty estimates represented by the error bars and the shaded area representing the prediction period.*

size ($\mathtt{B} = 3$ bridges), the overall expected deterioration condition does not provide a sufficient representation for the deterioration state of the network, and it is required to consider the variability associated with it. Such aspects are essential for building and designing decision making systems.

4. CONCLUSIONS

In this paper, an overview is presented about the main theoretical aspects for modelling the deterioration and effect of intervention based on network-scale visual inspections. The overview is followed by an example case study using visual inspection data from bridges within the Quebec province. The case study has highlighted some of the advantages of the SSM-based deterioration model, such as the capacity to scale from element-level deterioration analyses to network-scale. Furthermore, the case study has demonstrated that even for a small sample of bridges, relying on the expected condition of the network for decision making is insufficient. Therefore, it is required to include the variability associated with the expected value to alleviating the information loss due to upscaling.

ACKNOWLEDGEMENTS

This project is funded by the Transportation Ministry of Quebec Province (MTQ), Canada.

REFERENCES

[1] Hamida, Z. and Goulet, J.-A. (2021). "Quantifying the effects of interventions based on visual inspections of bridges network." *Structure and Infrastructure Engineering*, 1–12.

[2] Hamida, Z., Laurent, B., and Goulet, J.-A. (2022). "Openipdm: A probabilistic framework for estimating the deterioration and effect of interventions on bridges." *SoftwareX*, 18, 101077.

[3] Moore, M., Phares, B. M., Graybeal, B., Rolander, D., and Washer, G. (2001). "Reliability of visual inspection for highway bridges, volume i." *Report no.*, Turner-Fairbank Highway Research Center, 6300 Georgetown Pike.

[4] Runnalls, A. R. (2007). "Kullback-leibler approach to gaussian mixture reduction." *IEEE Transactions on Aerospace and Electronic Systems*, 43(3), 989–999 0018–9251.