Predicting Deterioration of Navigation Steel Hydraulic Structures with Markov Chain and Latin Hypercube Simulation

by Guillermo A. Riveros and Elias Arredondo

PURPOSE: The deterioration of elements of steel hydraulic structures (SHS) on our nation's lock system is caused by combined effects of several complex phenomena: corrosion, cracking and fatigue, impact, and overloads. This Coastal and Hydraulics Engineering Technical Note presents examples of deterioration and a method for predicting future deterioration based on current conditions. In a companion Technical Note (Riveros and Arredondo 2010), the procedure for generating the deterioration rate curves are presented and explained with practical examples.

BACKGROUND: In the absence of a mechanistic-based deterioration model that requires quantitative contribution of these complex phenomena based on environmental effects and maintenance constraints, SHS inspection data can be used to determine the need for rehabilitation or replacement and prioritize the order of work and funding. This can be accomplished by the use of deterioration models (Bulusu and Sinha 1997; Madanat et al. 1995; Madanat et al. 1997; Morcous et al. 2002).

Information on current and future conditions of navigation or flood-control SHS is essential for maintenance and rehabilitation of our navigation infrastructure. Current conditions of our navigation infrastructure are measured by periodic and detailed inspections following recommendations from Engineer Regulation (ER) 1110-2-100, Periodic Inspection and Continuing Evaluation of Completed Civil Works Structures, (Headquarters, U.S. Army Corps of Engineers (HQUSACE) 1995); ER 1110-2-8157, Responsibility for Hydraulic Steel Structures (HQUSACE 2009); and EM 1110-2-6054, Inspection, Evaluation, and Repair of Hydraulic Steel Structures (HQUSACE 2001). The accuracy of these conditions depends on the type of inspection performed. On occasions, detailed inspections are conducted when a problem is perceived by the operators. In some cases the deterioration of the SHS has been found to be critical and emergency repairs and contingencies have been conducted. This reactive approach will usually incur more cost. These emergency repairs could be avoided if a proactive approach (e.g., a deterioration model) is used to predict the future condition of the structure. The prediction will indicate when the structure will fall below a satisfactory performance level and when its condition may become severe if the structure is not maintained properly. Accurate predictions of the condition of the structure in the future are essential to maintain the inventory at a safe and reliable level of performance.

Methods for predicting infrastructure deterioration can be categorized into deterministic- and probabilistic-based models. Deterministic models are those in which no randomness is involved in the development of future deterioration states of the system. These models calculate the condition of the system as a precise value based on mathematical formulations of the actual deterioration (Ortiz-Garcia et al. 2006). Probabilistic-based models consider the deterioration states of

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the system as random variables and are modeled by underlying probability distributions (Agrawal et al. 2008).

This Technical Note presents deterioration examples, describes deterioration states that have been developed for SHS, and presents a method for predicting future deterioration states based on current conditions.

DETERIORATION EXAMPLES OF STEEL HYDRAULIC STRUCTURES: The following examples illustrate the potential results of casual inspection combined with inattention to deterioration of different components of SHS.

Figures 1 and 2 show some particularly bad corrosion occurring in miter gate compartments that are normally above the waterline. In Figure 2 the coating has not been kept in good condition, thus allowing general corrosion to occur. Figure 2 illustrates the adverse affects of corrosion inside a lock miter gate compartment. This figure shows that this particular miter gate has not had an impressed current cathodic protection system for many years. If the protective system is not preserved and repairs are not performed periodically, it will lead to significant amounts of section loss caused by corrosion, damage that may require an emergency closure for repairs and maintenance.

Figure 1. Corrosion on miter gate.

Figure 2. Corrosion inside a lock miter gate compartment.

Quoin block deterioration analysis conducted by Riveros et al. (2009) demonstrated that deterioration in the quoin block (Figure 3) can drastically affect the state of stresses on the element transferring loads to the pintle and the pintle connection. If the deterioration is severe, the stresses can reach undesirable levels. The location of the stress concentrations depends on the quoin deterioration area: if the deterioration occurs in the pintle area (bottom section of quoin block), the maximum stresses will be generated in the pintle zone; and if the deterioration is in the upper region of the quoin block, the maximum stress will be generated in the elements near the quoin block effective area end. This deterioration will cause such elements as the thrust diaphragm, thrust diaphragm stiffeners, end diaphragms, and the pintle connection to be overloaded from the redistribution of the forces not being transmitted to the wall when the gate is in the miter position. In some cases some of these elements have shown buckling failures when severe deterioration of the quoin block is present.

Figure 3. Quoin block failure.

Barge impact is one of the main concerns regarding the nation’s navigation infrastructures (Figure 4). Figure 5 shows a tainter gate with strut arm damage from barge impact before and after repairs. Loss of navigation pool can have serious effects. Failure of the project operating systems can render lock and flow control gates inoperable, causing delays to river traffic or possible overtopping of the project. Structural failure of a lock gate could severely impede or stop river traffic. Catastrophic failure of a spillway gate, dewatering bulkhead, or a lock gate could cause uncontrolled release and/or loss of pool resulting in loss of life (ER 1110-2-8157 (HQUSACE 2009)).

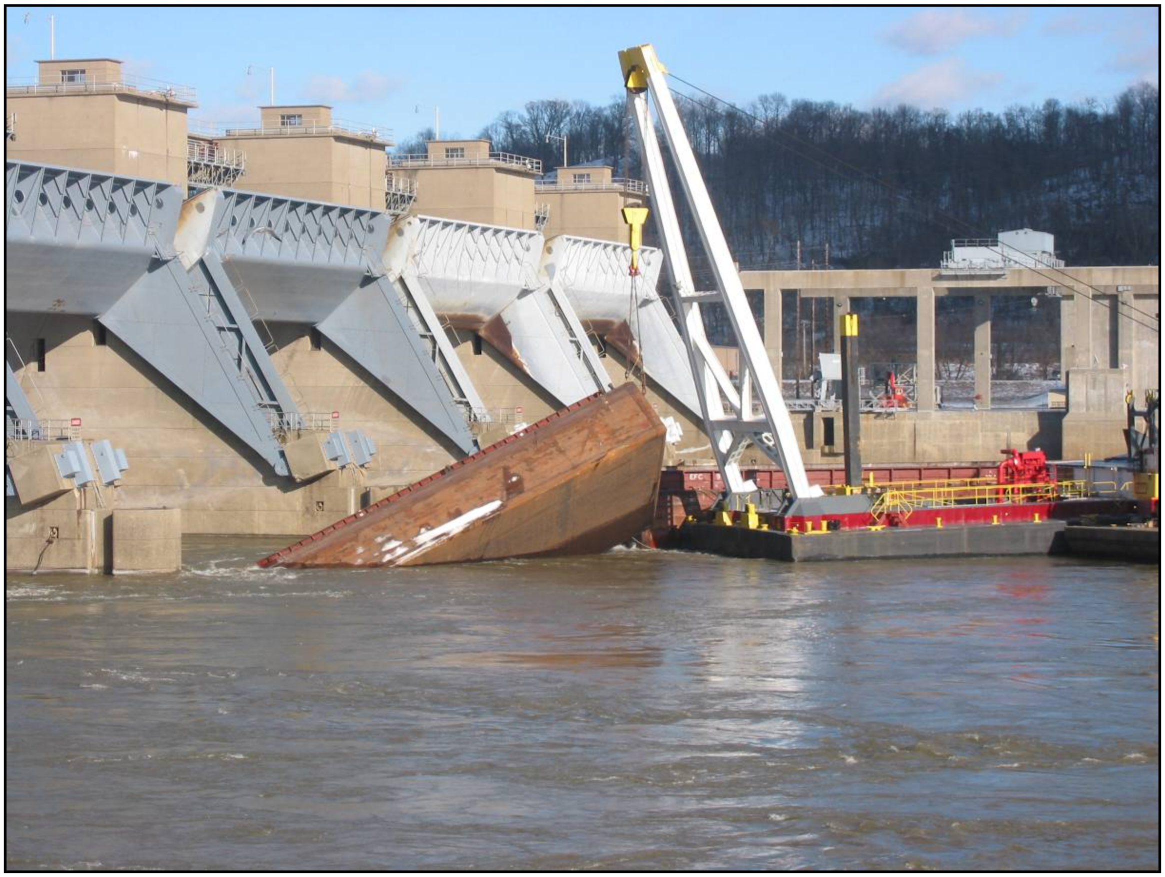

Figure 4. Barge impact at Belleville Locks and Dam.

Additionally, it would be necessary to close that section of the river to navigation traffic, disrupting the movement of coal shipments to power companies and impacting the towing industry. If the impact causes a long closure of the lock, the industry may have to find alternative routes or sources of transportation, decreasing production and causing lost sales and loss in revenue in addition to the extra cost to the district office for extra labor hours for the repairs.

Figure 5. Tainter gate with strut arm damage from barge impact before (left) and after (right) repairs.

In many cases, the primary forms of distress have been fatigue damage and fracture. The most common causes of fatigue cracking have been a lack of proper detailing during design, poor weld quality during fabrication, and poor detailing and execution of repairs. Recent inspections by districts have indicated that a significant number of stop logs and bulkheads had deficient welds that required repairs.

Many of these deficiencies were the result of ineffective quality control during the original fabrication welding of the structures (Figure 6).

Figure 6. Fatigue crack in diaphragm flanges of miter gate.

CONDITION STATES FOR STEEL HYDRAULIC STRUCTURES: Infrastructure condition is often represented by discrete condition states (Madanat et al. 1995). Condition states have been used to define the condition of individual components of bridges and sewer pipes (Agrawal et al. 2008; Federal Highway Administration (FHWA) 1995; American Association of State Highway and Transportation Officials (AASHTO) 2002; Thomson and Shepard 2000). New York State Department of Transportation uses a rating system (condition states) from 1 to 7, where 7 represents near-perfect conditions (Agrawal et al. 2008). AASHTO (2002) recommends a rating system from 1 to 5 where 1 is near-perfect condition.

Sauser and Riveros (2009) developed a condition rating system similar to that in AASHTO (2002) for SHS that uses an ordinal, integer-value scale from 1 to 5. This system indicates relative health of the infrastructure elements for the four most common deteriorations encountered in SHS: protective system, corrosion, fatigue and fracture, and impact or overloads. The overall condition rating of the entire structure is computed by a weighted average of the individual element condition ratings and is a function of selected weights. The selection of appropriate weights is driven by sound engineering reasons, such as the importance of fracture-critical members, primary members, pintle, etc. The system is described in the following paragraphs.

Various condition states follow a natural progression of deterioration that typical members experience. Subjected to similar conditions, all members of similar materials should deteriorate at similar rates. Therefore, to track conditions and predict deterioration rates, the exact number and extent of condition states are not important. It is important to understand the mechanism for deterioration, recognize the various stages of deterioration, and understand the impact on performance and reliability. For example, behavior of steel members subjected to conditions that lead to corrosion and section loss can be described in the following stages:

1. The member is protected by a protective coating or other means or has not been subjected to corrosive action. The member is in like-new or as-built condition and has no deterioration.

2. The member has lost some of its protection or has been subjected to corrosive action and is beginning to deteriorate (corrode) but has no measurable section loss. Deterioration does not impact function. This state is bounded minimally by the onset of corrosion and maximally by section loss that is not measurable, e.g., pitting not measurable by simple hand tools.

3. The member continues to deteriorate and measurable section loss is present but not to the extent that it affects its function. The upper bound of this state is, for example, pitting to a depth less than 1.5875 mm (0.0625 in.) or total loss of section thickness less than 3.175 mm (0.125 in.).

4. The member continues to deteriorate, and section loss increases to the point where function may be affected. An evaluation may be necessary to determine if the structure can continue to function as intended, if repairs are needed, or if its use should be restricted. The upper bound is a function of member strength, member load, and member use, but could be capped at 10 percent of total section loss for ease of and consistency in reporting.

5. The member continues to deteriorate, and section loss increases to the point where the member no longer serves its intended function and safety is affected. An evaluation may be necessary to determine if the structure can continue to function safely.

MARKOV CHAIN PREDICTION MODEL APPLIED TO STEEL HYDRAULIC STRUCTURES: The literature reveals that Markov models are extensively used to predict infrastructure deterioration (Madanat et al. 1995; Micevski et al. 2002; DeStefano and Grivas 1998) with bridges being a frequent candidate (Agrawal et al., 2008) followed by pavements (Ortiz-Garcia et al. 2006), and sewer pipes (Micevski et al. 2002; Baik et al. 2006). The Markov chain prediction model is a stochastic process that is discrete in time, has a finite state space, and establishes that the future state of the deterioration process depends only on its present state.

Applying the Markov process to predict the deterioration of navigation structures involves the following observations and assumptions. The deterioration process of a structure is continuous in time. However, to render it discrete in time, the condition is usually analyzed at specific periods. For SHSs these periods correspond to periodic and detailed inspections. The condition of a structure can have an infinite number of states. But in reality the condition of an SHS is defined by a finite set of numbers (Sauser and Riveros 2009) such as 1, 2, 3, 4, and 5 where 1 represents the structure is in its best condition possible and 5 represents imminent failure of the structure. The future condition of an SHS is assumed to depend only on its present condition and not on its past conditions.

The Markov process can be expressed as follows:

$$P\left(X_{t+1}=i_{t+1} \mid X_t=i_t,\, X_{t-1}=i_{t-1},\ldots,\, X_1=i_1,\, X_0=i_0\right)=P\left(X_{t+1}=i_{t+1} \mid X_t=i_t\right) \tag{1}$$

where P is a function of X representing the probability to change from state i to state j at time t+1.

For all deterioration states $i_0, i_1, \ldots, i_{t-1}, i_t, i_{t+1}$ and all $t \geq 0$.

The Markov process assumes that the conditional probability does not change over time. Therefore, for all states i and j and all t,

$$P\left(X_{t+1}=j \mid X_t=i\right)=p_{i,j} \tag{2}$$

is independent of t where p_{ij} is the probability that given the system is in state i at time t, it will be in state j at time (t + 1).

The transition probabilities are expressed as an m x m matrix called the transition probability matrix. The transition probability matrix is defined as

$$P=\begin{bmatrix} p_{1,1} & p_{1,2} & \cdots & p_{1,m} \\ p_{2,1} & p_{2,2} & \cdots & p_{2,m} \\ \vdots & \vdots & \vdots & \vdots \\ p_{m,1} & p_{m,2} & \cdots & p_{m,m} \end{bmatrix} \tag{3}$$

The probability that the system goes from state i to state j after t periods can be obtained by multiplying the probability matrix P by itself t times. Thus:

$$P_t = P^t \tag{4}$$

If Q_0 is the initial state vector, then the state vector Q_t can be expressed as

$$Q_t = Q_0 \cdot P^t \tag{5}$$

where

$$Q_0 = [q_1, q_2, \ldots, q_m]$$

and q_i is the probability of being in state i at time 0.

When the process is used to simulate deterioration, the following condition applies:

$$p_{ij} = 0 \text{ for } i > j \tag{6}$$

This is because the condition of a deteriorating element will not improve by itself. When an element reaches its worst state, the following condition applies.

$$p_{m,m} = 1 \tag{7}$$

This is because the condition of a deteriorating element will not change after it reaches the worst state. Consequently, the general form of the transition probability matrix for a deteriorating element is defined as

$$P = \begin{bmatrix} p_{1,1} & p_{1,2} & p_{1,3} & \cdots & p_{1,m} \\ 0 & p_{2,2} & p_{2,3} & \cdots & p_{2,m} \\ 0 & 0 & p_{3,3} & \cdots & p_{3,m} \\ \vdots & \vdots & \vdots & & \vdots \\ 0 & 0 & 0 & \cdots & 1 \end{bmatrix} \tag{8}$$

A further restriction allowing the condition to deteriorate by no more than one state in one rating cycle is commonly used in deterioration modeling. The transition probability matrix is then denoted as

$$P = \begin{bmatrix} p_{1,1} & p_{1,2} & 0 & \cdots & 0 \\ 0 & p_{2,2} & p_{2,3} & \cdots & 0 \\ 0 & 0 & p_{3,3} & \cdots & 0 \\ \vdots & \vdots & \vdots & & \vdots \\ 0 & 0 & 0 & \cdots & 1 \end{bmatrix} \tag{9}$$

However, some SHS inspection reports have shown that the structure has changed by more than one state during the inspection period; therefore, the transition probability matrix defined in Equation 8 may better fit actual inspection data.

A procedure for generating a deterioration rate curve when condition state inspection data are available is presented in Riveros and Arredondo (2010).

Using this procedure with data obtained from the New York State Department of Transportation and Agrawal et al. (2008), shown in Figure 7, a deterioration rate curve was generated. The resulting deterioration rate curve is shown in Figure 8.

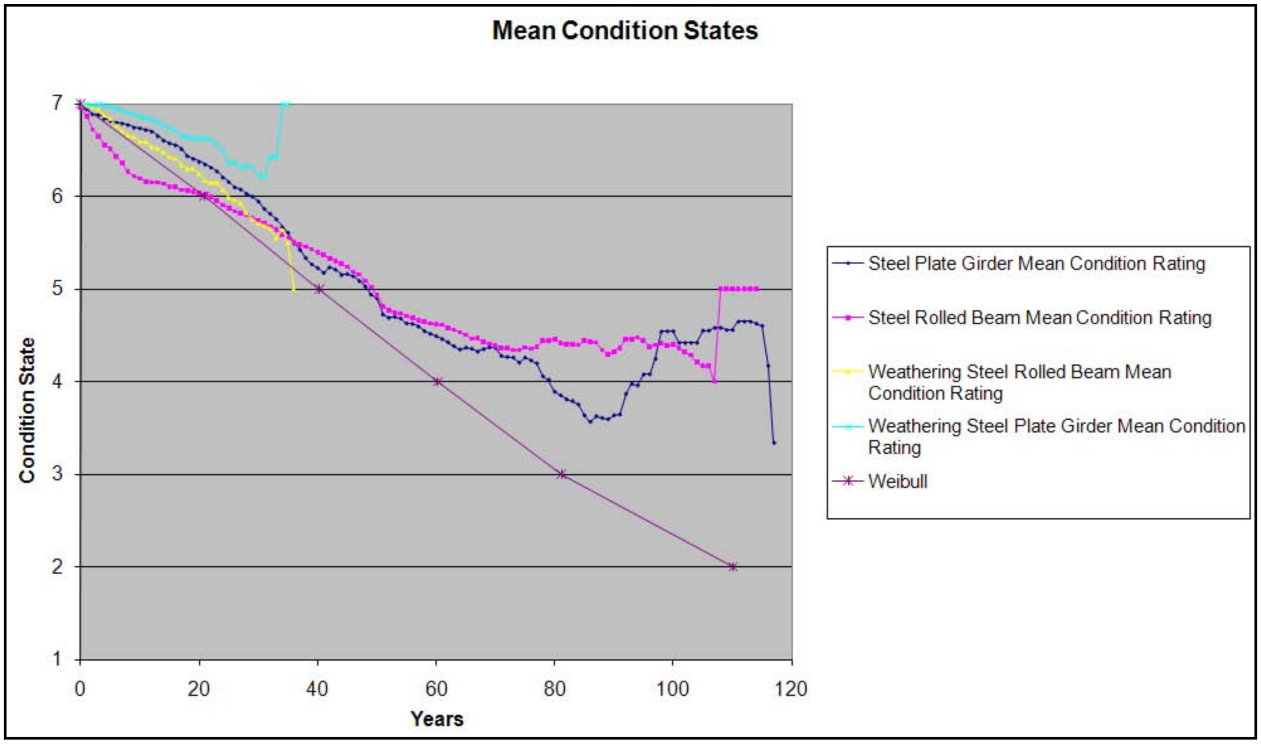

Figure 7. New York State Department of Transportation condition rating states.

CONCLUSIONS: The theory of the Markov chain is well developed and based on simple multiplications of matrices. The application of the Markov chain provides navigation structure managers a powerful and convenient tool for estimating structure service life. Service life prediction using the Markov chain has the advantage over the statistical regression approach in that it can be used to estimate not only the average service life of navigation structures but also the service life of any individual structural component. Furthermore, the Markov chain prediction is based on the current condition and age of the structure; therefore, it is simple and can be updated by new information on condition states and structure age. However, it should be noted that this study was based on synthetic data and assumed that limited numbers of inspection reports with conditions states are available. However, by utilizing the Latin hypercube analytical tools to generate random numbers based on a predefined distribution, it was possible to obtain realistic values to define the transition probability and therefore the deterioration curve.

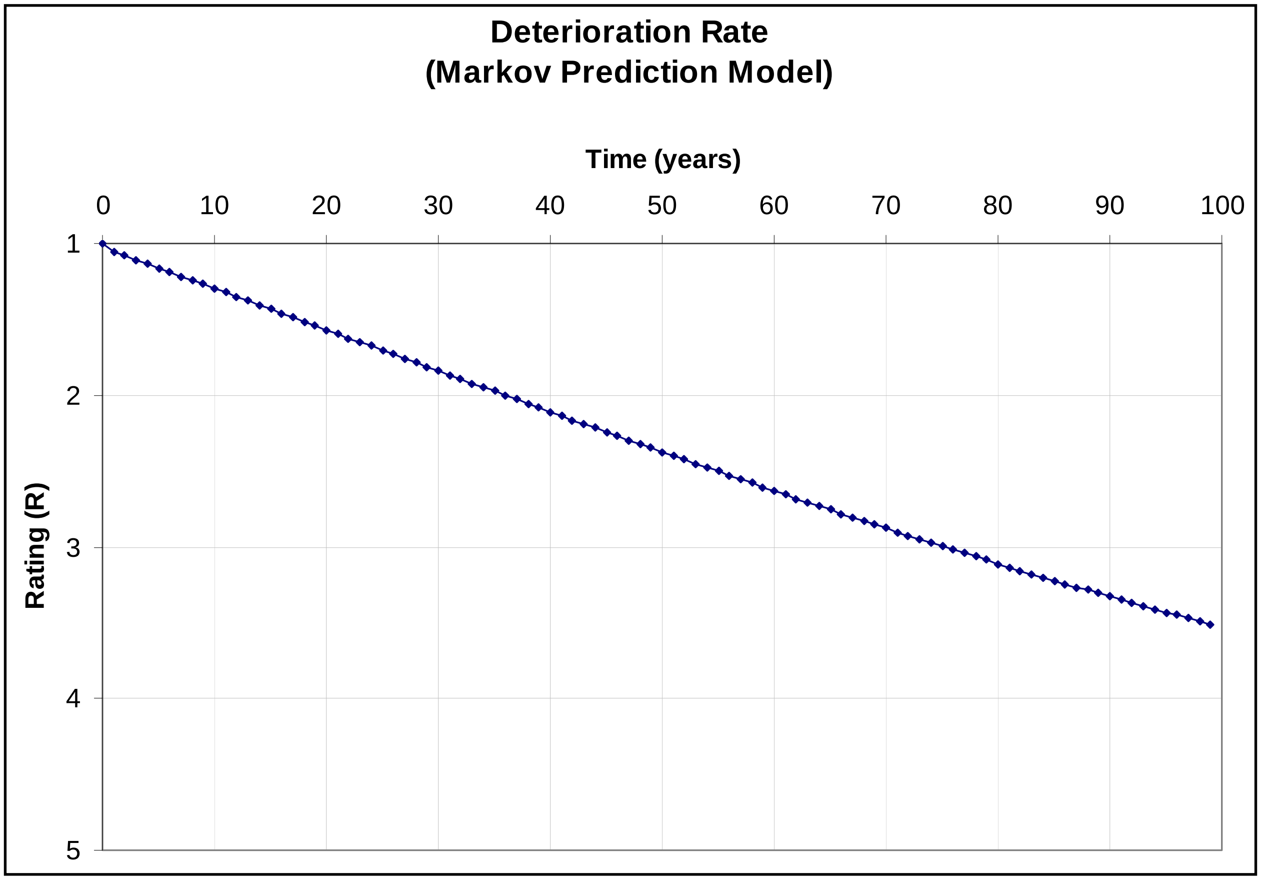

Figure 8. Deterioration rate.

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REFERENCES

Agrawal, A. K., A. Kawaguchi, and G. Qian. 2008. *Bridge deterioration rates*. Albany, NY: Transportation Infrastructure Research Consortium, New York State Department of Transportation.

American Association of State Highway and Transportation Officials. 2002. *Guide for commonly recognized structural elements and its 2002 interim revisions.* Washington, DC: American Association of State Highway and Transportation Officials.

Baik, H. S., H. S. Jeong, and D. M. Abraham. 2006. Estimating transition probabilities in Markov chain-based deterioration models for management of wastewater systems. *Journal of water resources planning and management* 132(1): 15-24.

Bulusu, S., and K. C. Sinha. 1997. Comparison of methodologies to predict bridge deterioration. *Transportation research record: Journal of the Transportation Research Board* 1597: 34-42.

DeStefano, P., and D. Grivas. 1998. Method for estimating transition probability in bridge deterioration models. *Journal of infrastructure systems* 4(2): 56-62.

Federal Highway Administration. 1995. *Recording and coding guide for the structure inventory and appraisal of the nation's bridges*. Report No. FHWA-PD-96-001. Washington, DC: Office of Engineering, Bridge Division, Bridge Management Branch.

Headquarters, U.S. Army Corps of Engineers. 1995. *Periodic inspection and continuing evaluation of completed civil works structures*. Engineer Regulation 1110-2-100. Washington, DC: Headquarters, U.S. Army Corps of Engineers.

Headquarters, U.S. Army Corps of Engineers. 2001. *Inspection, evaluation, and repair of hydraulic steel structures*. Engineer Manual 1110-2-6054. Washington, DC: Headquarters, U.S. Army Corps of Engineers.

Headquarters, U.S. Army Corps of Engineers. 2009. *Responsibility for hydraulic steel structures*. Engineer Regulation 1110-2-8157. Washington, DC: Headquarters, U.S. Army Corps of Engineers.

Madanat, S., M. G. Karlaftis, and P. S. McCarthy. 1997. Probabilistic infrastructure deterioration models with panel data. *Journal of infrastructure systems* 3(1): 4-9.

Madanat, S., R. Mishalani, and W. H. W. Ibrahim. 1995. Estimation of infrastructure transition probabilities from condition rating data. *Journal of infrastructure systems* 1(2): 120-125.

Micevski, T., G. Kuczera, and P. Coombes. 2002. Markov model for storm water pipe deterioration. *Journal of infrastructure systems* 8(2): 49-56.

Morcous, G., H. Rivard, and A. M. Hanna. 2002. Modeling bridge deterioration using case-based reasoning. *Journal of Infrastructure Systems* 8(3): 86-95.

Ortiz-Garcia, J. J., S. B. Costello, and M. S. Snaith. 2006. Derivation of transition probability matrices for pavement deterioration modeling. *Journal of Transportation Engineering* 132(2): 141-161.

Riveros, G. A., J. L. Ayala-Burgos, and J. Perez. 2009. *Numerical investigation of miter gates*. ERDC/ITL-TR-09-1. Vicksburg, MS: U.S. Army Engineer Research and Development Center.

Sauser, P., and G. Riveros. 2009. *A system for collecting and compiling condition data for hydraulic steel structures for use in the assessment of risk and reliability and prioritization of maintenance and repairs; Report 1, Miter gates.* ERDC/ITL TR-09-04. Vicksburg, MS: U.S. Army Engineer Research and Development Center.

Thomson, P. D., and R. W. Shepard. 2000. *AASHTO commonly-recognized bridge elements: Successful applications and lessons learned*. National Workshop on Commonly Recognized Measures for Maintenance, June 2000. Washington, DC: American Association of State Highway and Transportation Officials.

Riveros, G. A., and E. Arredondo. 2010. *Guide to the development of a deterioration rate curve using condition state inspection data.* Coastal and Hydraulics Engineering Technical Note, ERDC/CHL CHETN-IX-25. Vicksburg, MS: U.S. Army Engineer Research and Development Center.