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Research Article

Predicting Future Deterioration of Hydraulic Steel Structures with Markov Chain and Multivariate Samples of Statistical Distributions

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Combined effects of several complex phenomena cause the deterioration of elements of steel hydraulic structures on the nation's lock systems: loss of protective systems, corrosion, cracking and fatigue, impacts, and overloads. This paper presents examples of deterioration of steel hydraulic structures. A method for predicting future deterioration based on current conditions is also presented. This paper also includes a procedure for developing deterioration curves when condition state data is available.

1. Introduction

In the absence of a mechanistic-based deterioration model that requires quantitative contribution of these complex phenomena based on environmental effects and maintenance constraints, steel hydraulic structure's (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 [1–4].

Information on current and future conditions of navigation or flood-control SHS is essential for maintenance and rehabilitation of navigation infrastructure. Current conditions of navigation infrastructure are measured by periodic and detailed inspections following recommendations from [5–7].

The accuracy of these conditions depends on the type of inspection performed. On occasions, detailed inspections are conducted when the operators perceive a problem. 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 costs. These emergency repairs are avoidable with a proactive approach (e.g., a deterioration model) and 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 on a safe and reliable level of performance.

Methods for predicting infrastructure deterioration can be categorized into deterministic- and probabilistic-based models. Deterministic-based 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 [8]. Probabilistic-based models judge the deterioration states of the system as random variables and they are modeled by underlying probability distributions [9].

2. Deterioration Examples of Steel Hydraulic Structures

The following examples illustrate the potential results of casual inspections combined with inattention to deterioration of different components of SHS.

Figure 1: Corrosion on a miter gate.

Figure 2: Corrosion inside a lock miter gate compartment.

Figure 3: Quoin block failure.

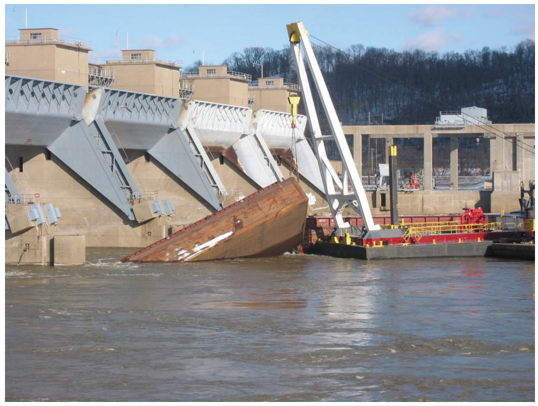

Figure 4: Barge impact at Belleville Locks and Dam.

Figures 1 and 2 show some particularly bad corrosion occurring in miter gate compartments that are normally above the water line. In Figure 1 the coating has not been kept in good condition, thus, allowing general corrosion to occur.

Figure 2 illustrates the adverse effects 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 a significant amount of section loss due to corrosion that may require an emergency closure for repairs and maintenance.

Quoin block deterioration analysis conducted by [10] demonstrated that deterioration in the quoin block (Figure 3) could 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. 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 some elements such 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.

Barge impact is one of the main concerns regarding navigation infrastructures (Figure 4) since they occur without prior warning.

Figure 5 shows a Tainter gate with strut arm damage from barge impact, before and after repairs.

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 [6].

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 affecting the towing industry. If the impact generates a long closure of the lock, the industry may have to find alternative routes or sources of

(a) (b)

Figure 5: Tainter gate with strut arm damage from barge impact before and after repairs.

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

Figure 7: Fatigue crack in girder flanges of miter gate.

transportation, decreasing production and causing lost sales and loss in revenue, in addition to the extra cost for extra labor hours for the 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 indicated that a significant number of stop logs and bulkheads had deficient welds that required repairs to bring them up to standards and proper operating conditions.

Many of these deficiencies were the result of ineffective quality control during the original fabrication welding of the structures (Figures 6 and 7).

3. Condition States for Steel Hydraulic Structures

Infrastructure conditions represent discrete condition states [2]. Condition states expressly define the condition of individual components of bridges and sewer pipes [9, 11–13]. New York State Department of Transportation uses a rating system (condition states) from 1 to 7, where 7 represents near-perfect conditions and 1 represents a state of failure [2]. Reference [12] recommends a rating system from 1 to 5, where 1 is near-perfect condition and 5 represents a state of failure.

Reference [14] developed a condition rating system similar to that in [12] 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 systems, corrosion, fatigue and fracture, and impacts 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, and pintle.

The following stages describe corrosion and section loss.

(1) A protective coating protects the member or other means or it 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 affect function. This state is bounded minimally by the onset of corrosion and maximally by section loss that is not measurable, for example, 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 necessary, or if its use should be restricted. The upper bound is a function of member strength, member load, and member use, but it could be capped at 10 percent of the 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 it affects the safety. An evaluation may be necessary to determine if the structure can continue to function safely.

The five general condition states are listed in Table 1 [14].

4. Markov Chain Prediction Model Applied to Steel Hydraulic Structures

The literature reveals that Markov models are extensively used to predict infrastructure deterioration [2, 15, 16] with bridges being a frequent candidate [9], followed by pavements [8] and sewer pipes [15, 17]. 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. First, 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 SHS, these periods correspond to periodic and detailed inspections. Second, the condition of a structure can have an infinite number of states, but in reality the condition of a SHS is defined by a finite set of numbers [14] such as 1, 2, 3, 4, and 5, where 1 represents the structure in its best possible condition and 5 represents imminent failure of the structure. Finally, the future condition of a SHS depends only on its present condition and not on its past conditions.

Markov chain is defined as follows:

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

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 $i_0, i_1, \dots, i_{t-1}, i_t, i_{t+1}$ and all $t \geq 0$.

Markov chain is considered to be homogeneous if the probability p_{ij} of going from state i, at time t, to state j, at time $(t+1)$, is independent of t.

For all states i and j and all t,

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

The expressed transition probabilities are an $m \times m$ matrix called the transition probability matrix. The transition probability matrix, P, 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,

$$Q_0=\left[q_1, q_2, \dots, q_m\right]. \tag{5}$$

And q_i represents the probability of being in state i at time 0; then the state vector Q_t, representing the state at time t, can be expressed as

$$Q_t = Q_0 \cdot P^t. \tag{6}$$

If the system is in the first state at time zero, Q_0 can be expressed as

$$Q_0=[1,0,0,0,0], \tag{7}$$

indicating that the probability of the system being in the first state is equal to 1 (or 100%) and the probability of any other state is 0.

Similarly, if the system is in the second state Q_0 can be expressed as

$$Q_0=[0,1,0,0,0], \tag{8}$$

indicating that the probability of the system being in the second state is equal to 1 (or 100%) and the probability of any other state is 0.

The time when the available data changes from state 1 to state 2, state 2 to state 3, state 3 to state 4, and so forth is obtained from the linear regression equation of the condition state data shown in Figure 8 and Table 2.

Defining a normalized vector of time when the measured condition states change as follows:

$$R=\begin{bmatrix}0 & 0.25 & 0.50 & 0.75 & 1.00\end{bmatrix}, \tag{9}$$

the time when the condition rating changes state after t periods is calculated as

$$R_{P,t} = Q_t \cdot R', \tag{10}$$

Table 1: Five condition states.

Number	Condition	Description
1	Protected	Member is sound, functioning properly, and lacking in deficiency.
2	Exposed	Members show beginning signs of deficiency but are still sound and functioning as intended. There is no impact on performance or reliability.
3	Attacked	Deficiency has advanced and the member still functions as intended, but if continued, unabated deterioration will lead to the next condition state.
4	Damaged	Deficiency has advanced to the point that function may be impaired.
5	Failed	Deficiency has advanced to the point that the member no longer serves its intended function and safety is impacted.

Table 2: Time at which condition states change (from Figure 8).

State	Time of change (years)
1	0
2	63.11
3	72.61
4	109.11
5	145.61

where

$$R' = R^T. \tag{11}$$

When using the process to simulate deterioration, the following condition applies:

$$p_{ij} = 0 \quad \text{for } i > j. \tag{12}$$

This is because the condition of a deteriorating element cannot return to a previous state (a better condition) without external intervention. That is, the probability of an element returning to a previous condition is always zero.

When an element reaches its worst state (failure state), the following condition applies:

$$p_{m,m} = 1. \tag{13}$$

This indicates the element has deteriorated to the point of failure and will remain in that state. Consequently, the general form of the transition probability matrix defined for a deteriorating element is

$$P = \begin{bmatrix} p_{1,1} & p_{1,2} & p_{1,3} & \cdots & p_{1,m} \\ 0 & p_{2,2} & p_{2,3} & \cdots & p_{2,m} \\ 0 & 0 & p_{3,3} & \cdots & p_{3,m} \\ \vdots & \vdots & \vdots & & \vdots \\ 0 & 0 & 0 & \cdots & 1 \end{bmatrix}. \tag{14}$$

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 indicated as

$$P = \begin{bmatrix} p_{1,1} & p_{1,2} & 0 & \cdots & 0 \\ 0 & p_{2,2} & p_{2,3} & \cdots & 0 \\ 0 & 0 & p_{3,3} & \cdots & 0 \\ \vdots & \vdots & \vdots & & \vdots \\ 0 & 0 & 0 & \cdots & 1 \end{bmatrix}. \tag{15}$$

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 (11) may better fit actual inspection data.

5. Derivation of Transition Probabilities

There are several methods for deriving a transition probability matrix. The methods include expert opinion, linear regression, and Poisson regression [2]. Since the available data containing condition states are limited for navigation structures, the development of a probabilistic method is proposed that can be updated, as data will become available. The main goal is to develop a method, and verifying this method as actual data becomes available. This allows confidence in the use of the method to predict future deterioration of hydraulic steel structures. The New York State Department of Transportation provided the data used in the development of this method. This data was applicable not only because it was accessible but also because it represents condition state data for thousands of steel bridge elements over a period of eighty years of inspections. Additionally, the same effects that cause the deterioration of navigation structures (loss of a protective system, corrosion, cracking and fatigue, impact, and overloads) cause steel bridge element deterioration. Figure 8 shows the data used.

Fluctuations in the data, as can be seen between 30 and 40 years, occur because the data represent the average condition state of many elements. To eliminate the fluctuations and make the data more manageable a linear regression equation was calculated as follows:

$$y = 0.0274x + 1.0104, \tag{16}$$

where x is the age in years and y is the condition state.

The authors calculated condition state values at ten-year intervals by using (13). The calculated values were used as the average condition state at each interval. Using Weibull distribution and a Latin hypercube simulation (LHS), synthetic random condition state values were generated to represent a range of condition states at each ten-year interval. The authors used Weibull distribution parameters for each interval to yield approximately the same average values represented in Figure 8.

Figure 9 shows the synthetic values (vertical points) generated to simulate a range of condition states at each ten-year interval. The authors generated one-thousand random

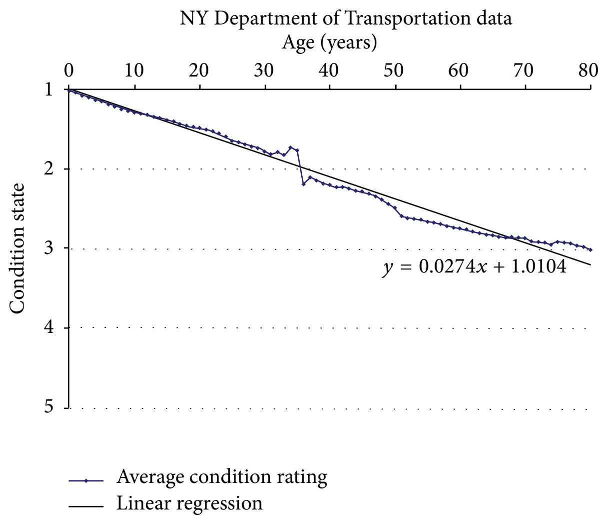

FIGURE 8: New York Department of Transportation condition state data.

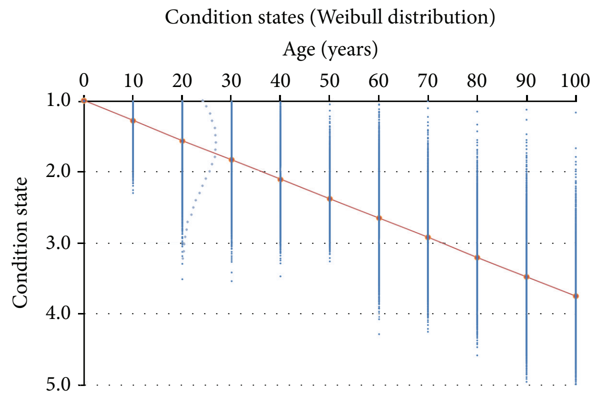

FIGURE 9: Synthetic condition state values.

values at each interval. The diagonal line crosses through the average value of each ten-year interval.

Figure 10 shows the distribution of values generated for the 20-year interval. These superimposed values are in Figure 9. In addition, similar distributions of values were generated for each of the other intervals.

Using the generated condition state values for each interval, the transition probabilities were calculated as

$$p_{i,j} = \frac{N_{i,j}}{N_i}, \tag{17}$$

where $N_{i,j}$ is the number of elements that change from condition i to condition j after one interval and N_i is the number of elements that were in condition i in the previous interval.

Table 3 shows the transition probability values.

Applying Markov chain,

$$P = \begin{bmatrix} 0.973 & 0.027 & 0 & 0 & 0 \\ 0 & 0.972 & 0.028 & 0 & 0 \\ 0 & 0 & 0.972 & 0.028 & 0 \\ 0 & 0 & 0 & 0.973 & 0.027 \\ 0 & 0 & 0 & 0 & 1.000 \end{bmatrix}. \tag{18}$$

Express the initial state of a new element as

$$Q_0 = [1, 0, 0, 0, 0]. \tag{19}$$

The normalized vector of time when the measured condition states change is as follows:

$$R = [0 \quad 0.25 \quad 0.50 \quad 0.75 \quad 1.00]. \tag{20}$$

Now to calculate the time for the next rating cycle ($t = 2$), applying Markov chain, we obtain

$$P_2 = P^2$$

$$P^2 = \begin{bmatrix} 0.9469 & 0.0524 & 0.0007 & 0 & 0 \\ 0 & 0.9456 & 0.0536 & 0.0008 & 0 \\ 0 & 0 & 0.9447 & 0.0545 & 0.0008 \\ 0 & 0 & 0 & 0.9460 & 0.0540 \\ 0 & 0 & 0 & 0 & 1.0000 \end{bmatrix}. \tag{21}$$

Applying (6), vector Q_t representing the condition state after two periods is calculated as

$$Q_2 = Q_0 \cdot P^2 = [0.9469 \quad 0.0524 \quad 0.0007 \quad 0 \quad 0]. \tag{22}$$

And the normalized time, using (10), is calculated as

$$R_{P,2} = Q_2 \cdot R' = 0.0135. \tag{23}$$

Continuing in a similar fashion, the time at which the states change (Table 4) is set. In addition, plotting this information, we obtain the stepwise graph shown in Figure 11. Figure 11 also shows the upper and lower bounds for the deterioration of navigation steel structures.

6. Conclusions

The aim of this study was to present deterioration examples of navigation steel structures and to develop a results-based model of current inspections. Because of this study, a deterioration model was developed with the assistance of real inspection data provided by the New York Department of Transportation. The results presented in Figure 11 indicate that there is a marked correlation between the proposed deterioration model and the actual data presented in Figure 8. For example, the model indicates that the condition state reaches level 2 at 35.71 years and state 3 at 74.79 years. Compared with Figure 8, it indicates that the condition state reaches state 2 at 36.12 years and state 3 at 72.61 years. The difference between the model and the actual data was about 1%.

These results suggest that, using the method presented in this paper, you may develop a deterioration model that

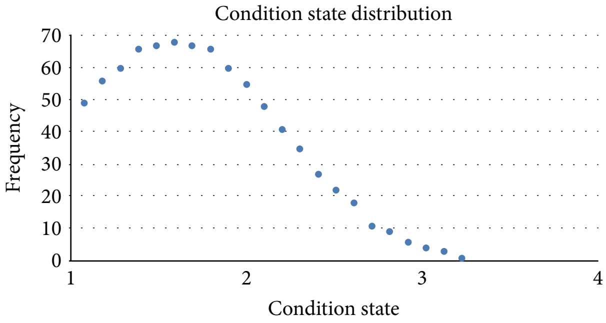

Figure 10: Distribution of condition state values generated for 20-year interval.

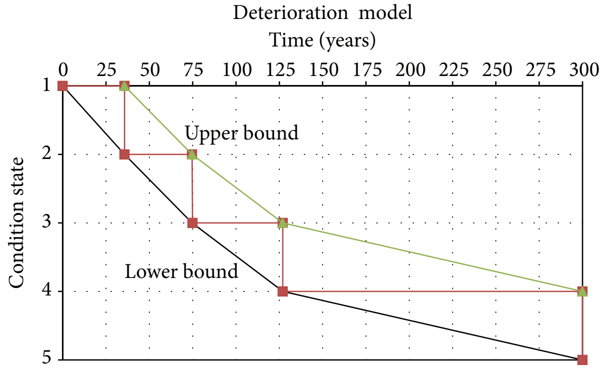

Figure 11: Markov chain deterioration model.

Table 3: Transition probabilities.

Condition state	1	2	3	4	5
1	0.973	0.027			
2		0.972	0.028		
3			0.972	0.028	
4				0.973	0.027
5					1.000

Table 4: Time at which the states change.

State	Time (years)
1	0
2	36.69
3	74.69
4	127.04
5	300.00

reflects actual results. Therefore, predicting future deterioration of these structures is possible by using this model. The model represents a vital starting point in predicting deterioration, which can continue updating and recalibrating as more data becomes available.

For this study, the authors used the Weibull distribution to generate synthetic data for condition states. However, if the current data curve has different morphology, they could use other (normal, lognormal) distributions.

In addition to predicting the deterioration, the model can be useful in scheduling inspections. Currently, inspections are programmed without any consideration of anticipated deterioration. If a deterioration model is used as a reference, these inspections can be programmed by the model suggesting better anticipation of when the structure must be maintained to avoid emergency repairs.

The deterioration model is applicable in combination with a life cycle analysis on the prediction and optimal repair costs. Additionally, you can determine the optimum point when inspections are necessary to maintain the structural system in a reliable condition.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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