USING CONDITION INDEX INSPECTION RESULTS TO UPDATE THE RELIABILITY OF MITER GATES FOR NAVIGATION LOCKS

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Abstract

In an effort to ensure public safety, many civil engineering structures undergo various inspections to assess their condition or performance. Comprehensive procedures for using routine inspection data to update reliability assessments have not been developed. This paper illustrates how the Condition Index inspection data from a specific miter gate on a Corps of Engineers navigation lock can be modified and used for this purpose.

Introduction

The U.S. Army Corps of Engineers (USACE) maintains 238 chambers at 198 lock sites. Miter gates are an important operating component of a lock and dam facility. In many situations, only one lock is available at a site and if the miter gate does not function, navigation along the entire river is delayed. USACE has developed a Condition Index inspection and rating system that uniformly and consistently describes the current condition of miter gate lock structures. Similarly, the Corps has completed reliability analyses on specific miter gates to justify funding major repairs. Because the development of reliability assessments and Condition Index inspection procedures have progressed independently, no comprehensive effort has been made to use the two in combination. This paper uses the Condition Index inspection information regarding corrosion deterioration to update the reliability of an existing miter gate, highlights the benefits and limitations of the approach and identifies where more research is needed in this area.

Reliability Analysis

The Rock Island District of the U.S. Army Corps of Engineers prepared a time-dependent reliability analysis on Lock and Dam #12 on the Mississippi River near Dubuque, Iowa to predict how this structure will perform over its useful life (USACE 1997). The reliability analysis is critical for maintenance planning and is a mandatory step in justifying a major rehabilitation project (USACE 1996). The reliability analysis on Lock and Dam #12 miter gates was based on the moment failure limit state on a typical vertical girder which was determined to be the most critical component. The random variables considered in the analysis were the yield stress of the steel, the amount of material loss due to corrosion, a modeling uncertainty factor, and the head differential which constituted the load on the structure. Corrosion deterioration was considered in both the splash zone and atmospheric zone of the miter gate. Based on results from corrosion tests of bare steel under simulated splash zone conditions conducted in Memphis, the following deterioration models were derived for the respective zones (Padula 1994)

Atmospheric zone: $\log C = \log 23.4 + 0.65 \log t + \varepsilon_c$

Splash zone: $\log C = \log 148.5 + 0.903 \log t + \varepsilon_c$

where C is the thickness loss due to corrosion in micrometers, t is time in years and ε_c is an uncertainty factor with a mean of 0 and a standard deviation of 0.219 and 0.099 for the atmospheric and splash zones, respectively. With this information, the future performance of the miter gate was estimated using time-dependent reliability, hazard functions, and an event tree to compute the expected costs of disruptions.

Condition Index Inspections

The reliability analysis on Lock and Dam #12 extended from 1938 when the miter gate was placed in service to the year 2030. The analysis needs to be updated over time based on inspection results to verify or modify the deterioration model on which it was based. Ideally a specific non-destructive evaluation (NDE) would provide the basis for updating the parameters of the random variable that accounts for thickness loss due to corrosion. NDE tests are often expensive and are not conducted often. A Condition Index (CI) inspection is conducted periodically as part of a program of visual inspections to assess the general condition of a miter gate. The condition index ratings which range from 0 (failed) to 100 (excellent) are used to help prioritize maintenance (Greimann 1990). While these inspections were not specifically designed for updating the reliability of a structure, they can be used conservatively for this purpose in some cases with some minor modification. The CI inspection conducted on the miter gates on Lock and Dam #12 (USACE 1998) provided a sub-rating specifically for corrosion deterioration as shown in Table 1.

Table 1. Inspection Results from Auxiliary Miter Gate on Lock and Dam Number 12

Structural Element	Left Leaf		Right Leaf	
	Upstream	Downstream	Upstream	Downstream
Girder	2	2	1	2
Intercoastal	2	2	1	2
Skin Plate	2	2	1	2

The inspection results translate to a Condition Index rating for corrosion of CI=54 which is described as "Fair: moderate deterioration; function is still adequate". The ratings of 0 through 5 are condition levels assigned by an inspector who relates the level of corrosion that he or she observed on the components of the miter gate to one of five photographs with word descriptions that show differing degrees of corrosion. By itself, this information is not sufficient to update the reliability analysis. The limitations of the CI inspection data are:

- The amount of corrosion loss has not been numerically quantified and cannot be used to update a random variable in its current form
- The CI inspection was only conducted for the splash-zone area while reliability was assessed in both the splash zone and atmospheric zone
- The CI rating was based on the worst condition observed anywhere on the gate. The analyst does not know on which member or where on the member the corrosion occurs. It is also unknown whether the rating is representative of the entire gate or one isolated section.
- There is no knowledge of condition state transition or how long the miter gate has been and will be in that condition state

Some conservative assumptions and slight modifications are proposed to the CI inspection procedure and data to account for these limitations. The six levels of corrosion are conservatively quantified within a range of values as shown in Table 2. The distributions are defined such that the mean value is based on how far the member is assumed to have transitioned through its condition state and the standard deviation is based on the capability and credibility of the inspector as shown in Estes (1997). A segment-based inspection is introduced where each girder, skin plate, and intercoastal section is given its own rating in the same manner as suggested by Renn (1995) for highway bridges. With the segment-based inspection, it is possible to update system reliability analyses and to consider other failure modes where the location of the damage is important.

Table 2. Assigned Corrosion Levels from a Condition Index Inspection

Levels of Corrosion			
Level	**Description**	**Thickness loss per side***	
		mils	μm
0	New condition	0	0
1	Minor surface scale or widely scattered small pits	0-8	0-200
2	Considerable surface scale and/or moderate pitting	0-20	0-500
3	Severe pitting in dense pattern, thickness reduction in local areas	0-40	0-1000
4	Obvious uniform thickness reduction	40-120	1000-3000
5	Holes due to thickness reduction and general thickness reduction	>120	>3000
*** Not currently in CI manual – created to quantify corrosion distress**			

Updating Methods

Four separate methods are considered for using this CI inspection data to update the reliability analysis for a miter gate. Method A is the easiest and does not require the segment-based inspection. Method D is the most complex and requires both a segment-based and Bayesian updating. Method D is also the most versatile and has the broadest capabilities. Table 3 outlines the requirements and capabilities of the four methods. All four methods were used on the auxiliary miter gate on Lock and Dam #12. For methods A and C, the actual inspection data (USACE 1998) was used while for methods B and D, the data was created from a hypothetical segment-based inspection by filling in the gaps based on the actual inspection data.

Table 3. Characteristics of the Four Updating Methods A through D

Characteristic of Update Method	Update Method			
	A	B	C	D
Requires quantification of corrosion loss (Table 2)	x	x	x	x
Segment-based inspection required		x		x
Bayesian updating – considers prior information			x	x
Can update reliability of structure at point in time	x	x	x	x
Can update deterioration model and reliability over time		x		x
Can track progress through a condition state		x		x
Applicable to system reliability analysis		x		x

Table 4 shows the thickness loss predicted by the reliability analysis deterioration models in both the splash zone and the atmospheric zone as well as the updated thickness loss using all four methods based on 1998 inspection data. The results indicate that the model used for the atmospheric zone offers a good representation of what is actually happening in the splash-zone. The splash-zone model greatly overestimates the severity of the corrosion.

Table 4. Corrosion Loss Estimate Based on Original Models and Inspection Results

Corrosion Loss (μm)	Atmospheric Zone Model	Splash-zone Model	Update Method			
			A	B	C	C
Mean	298	5080	250	285	314	349
Standard Dev.	197	1301	151	151	150	150

Model Updating

Methods B and D allow the deterioration model and thus the time dependent reliability to be updated. Using Method D which requires both a segment-based inspection and Bayesian updating, the deterioration model was updated based on a hypothetical segment-based inspection in the year 2008. Figure 1 shows the distribution of the thickness loss for condition state 2 (from Table 2) based on the results of the segment-based inspections. The graphs show the computed distribution when the structure first enters the condition state 2 (it is conservatively assumed that the condition state is entered at the half-way point), at the year 1998, and at the year 2008. After the inspections in 1998 and 2008, the deterioration model was updated based on the prior and new information. The new models as shown in Figure 2 are:

After 1998 inspection: $C = 10.23t^{0.903}$

After 2008 inspection: $C = 4.22t^{1.13}$

With the parameters of the thickness loss due to corrosion estimated at any point in time, it is a straight forward process to update the reliability, the hazard functions, and the economic analysis for the miter gate. The original model greatly overestimated the effect of the corrosion. While the new analysis is based on visual inspection data and conservative assumptions, the results are much better than if the information had not been used at all.

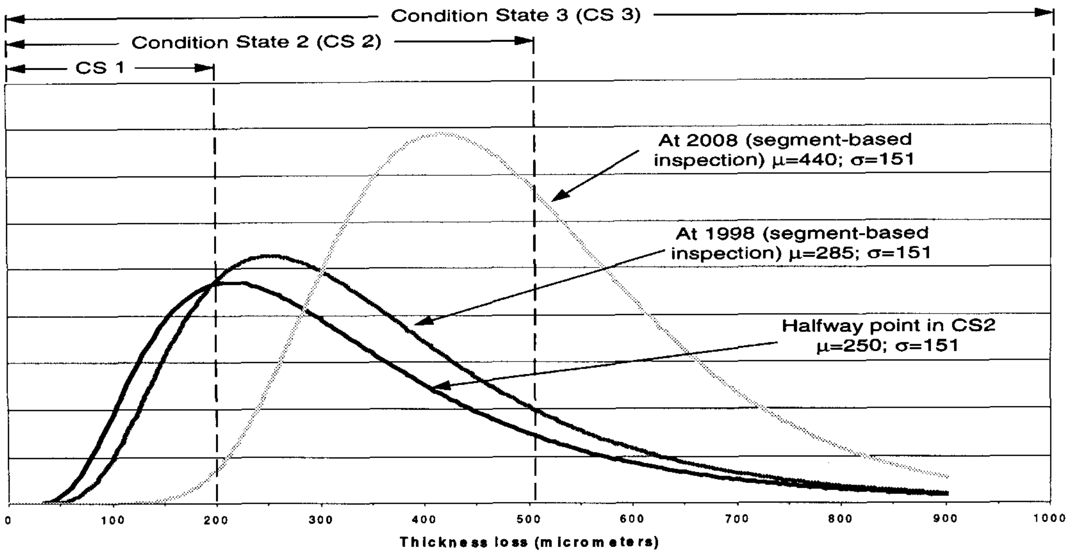

Figure 1. Distributions for Condition State 2 at the halfway point and after inspections in 1998 and 2008

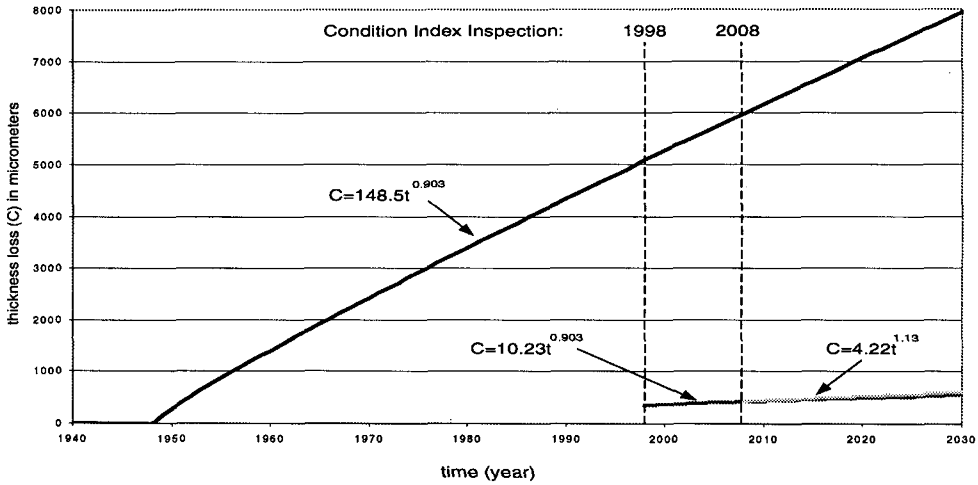

Figure 2. Deterioration Model for Miter Gate based on Original Model and after Inspection Results

Conclusion

When visual inspection data is available, it should be used whenever possible to update the reliability of a structure. It is not a substitute for a specific NDE inspection, but it is far better that blindly relying on an untested deterioration model. With conservative assumptions and slight modifications, much of the visual information can be useful. Visual data will produce higher uncertainties than NDE results. This will produce lower and more conservative estimates of reliability. As a minimum, these techniques will help identify which structures are the best candidates for the more expensive and rigorous NDE inspections.

Applying reliability-based methods to real structures in a useful and productive manner is still in its infancy. While a lot of work has been done, there remain many areas worthy of future research. In miter gates alone, the reliability analysis was based on a single failure mode for a single component. Considering multiple failure modes that treat the miter gate as a system is worthy of investigation. The Condition Index inspection looks at many other critical areas such as downstream movement, noise jump vibration, gaps, dents, cracks, leaks, boils, and the anchorage system. These represent potential failure modes that could be considered where there is opportunity to use inspection results to update reliability. A critical deterioration mechanism on miter gates is fatigue. Since the CI inspections investigate cracks, a similar study which uses CI results to update fatigue models would be valuable. As reliability methods become more widely implemented, all available information should be used. It is also important that the individuals who design routine inspection procedures and those who perform reliability analyses communicate so that both their needs can be met.

Acknowledgements

The financial support of the U.S. Army Construction Engineering Research Laboratory is gratefully acknowledged. The opinions and conclusions presented is this paper are those of the writers and do not necessarily reflect the view of the sponsoring organizations.

References

Estes, A.C. (1997). *A System Reliability Approach to the Lifetime Optimization of Inspection and Repair of Highway Bridges*. Ph.D. Thesis, Department of Civil, Environmental, and Architectural Engineering, University of Colorado, Boulder, Colorado.

Greimann, L.F., Stecker, J.H., & Rens, K., 1990. *Management System for Miter Gate Locks*, Technical Report REMR-OM-08, U.S. Army Construction Engineer Research Laboratory, Champaign, IL.

Padula, J., Chasten, C., Mosher, R., Mlaker, P., Brokaw, J., Stough, W. (1994). *Reliability Analysis of Hydraulic Steel Structures with Fatigue and Corrosion Degradation*, Technical Report ITL-94-3, U.S. Army Corps of Engineers, Washington D.C.

Renn, D.P. 1995. *Segment-based inspection for load rating within bridge management systems*. Masters Thesis, Department of Civil, Environmental, and Architectural Engineering, University of Colorado, Boulder, Colorado.

USACE: U.S. Army Corps of Engineers, 1996. *Project Operations: Partners and Support (Work Management Guidance and Procedures)*, Engineer Pamphlet EP 1130-2-500, Washington D.C.

USACE: U.S. Army Corps of Engineers, 1997. *Reliability Analysis of Miter Gates Lock and Dam #12*, Rock Island District, Rock Island, IL

USACE: U.S. Army Corps of Engineers, 1998. *Condition Inspection Summary Report, Mississippi River Lock and Dam #12*, Inspected by LDI and MVR, 24 Nov 1998, Dubuque, Iowa