Paper 4 – Panama Canal Third Set of Locks Operations and Maintenance Strategy for the Civil Works

Rachael V. Bisnett[1]; Alessandro Zaffaroni[2]; and Joseph Bello[1]

[1]MWH Global, Chicago, IL USA; [2]Grupo Unidos Por el Canal (GUPC), Cocoli, Panama

Email (1st author): rachael.v.bisnett@mwhglobal.com

ABSTRACT: The new Third Set of Locks for the Panama Canal has been designed to optimize reliability, availability, maintainability, and safety (RAMS) of operation. To achieve this goal, operational requirements have been integrated with risk-based maintenance management techniques including fault tree analysis (FTA), failure mode effects and criticality analysis (FMECA), and application of reliability-centered maintenance (RCM) principles. Because the civil works components comprise the major water-retaining structures of the lock and canal system, it is a challenge to devise a comprehensive maintenance program – considering both planned and unplanned actions – that achieves the RAMS objectives without disrupting vessel transit operations or compromising personnel and vessel safety. This paper presents a unique approach to developing a comprehensive maintenance management program employing RAMS principles for the civil works components of the Third Set of Locks. The approach can serve as a template for other civil and structural systems where optimizing life-cycle performance is paramount.

1 INTRODUCTION

The new Third Set of Locks for the Panama Canal has been designed to optimize reliability, availability, maintainability, and safety (RAMS) of operation. To achieve this goal, operational requirements have been integrated with risk-based maintenance management techniques. These techniques include fault tree analysis (FTA), failure mode effects and criticality analysis (FMECA), and application of reliability-centered maintenance (RCM) principles. This integrated approach to performing required surveillance and maintenance practices while maximizing availability of the civil systems for lockages enables optimal management of the asset throughout its life cycle.

While these techniques are typically applied to critical electrical, mechanical, and process control systems, the same principles also apply to the civil works components – lock structures, embankment dams, water saving basins, and civil site features.

2 PROJECT OVERVIEW

The Panama Canal Third Set of Locks Project will add a third lane to the existing Panama Canal locks to allow Post-Panamax size ships to traverse the Canal, greatly expanding shipping through the isthmus. The Third Set of Locks Project consists of a new lock complex at both the Atlantic and Pacific entrances to the Canal, which will allow vessels to move between Lake Gatun and sea level, an elevation difference of about 27 m. Both the Atlantic and the Pacific locks complexes contain three lock chambers, which are 55 m wide and 427 m long, separated by lock heads (LH) with rolling gates.

Adjacent to each lock chamber is a water saving basin (WSB) designed to save and reuse approximately 60% of the water used in a lockage cycle.

The Borinquen Dams, comprised of four embankment dams, form the Lake Gatun approach channel to the Pacific set of locks and separate the waters of Lake Gatun from Miraflores Lake. Three of the dams, 2E, 1W, and 2W, are included in the scope of work for the Third Set of Locks Project.

Figure 1 presents a rendering of the Pacific Locks Complex features. The Atlantic Locks Complex layout mirrors the Pacific layout, however the Borinquen Dams are only present at the Pacific Locks Complex.

The existing Panama Canal locks feature two identical lanes which allow one lane to be taken out of operation to accommodate maintenance or repairs. The Third Set of Locks however, consists of a single lane. Although the Third Set of Locks includes redundancies in the filling and emptying systems (e.g. culverts and valves), and even the gates, reliability, availability, and ease of maintenance of the civil components is critical to successful operation.

3 AVAILABILITY REQUIREMENTS

Each lock complex is required to be operational at least 99.6% of the time each month. Therefore, the development of maintenance philosophy is driven not only by the charasteristics of the system, but also by the availability requirements. System control software has the greatest effect on availability, largely because unplanned software outages are likely to occur, and therefore need to be more carefully factored into availability computations.

The design of civil works utilizing international design standards and appropriate factors of safety, coupled with dedicated construction quality control, is a primary reason that unplanned outages due to civil components were considered to have a negligible influence on availability computations. Subjectively, unplanned outages due to civil works could be described as very unlikely to virtually impossible with corresponding probabilities of occurrence of 0.01 to 0.001 (USACE and USBR, 2012). Natural occurrences such as significant seismic events are categorized as force majeure events, so outages due to such events are similarly not incorporated into the availability computations.

Figure 1: Pacific Locks Complex Rendering

On the other hand, civil works components contribute substantially to the scheduled outage portion of availability computations. As discussed in more detail within this paper, scheduled outages for civil works arise from planned inspections of normally inaccessible (e.g. submerged) components and owing to the reliability-centered maintenance (RCM) philosophy that any maintenance designed to prevent an outage is condition based.

4 MAINTENANCE MANAGEMENT TECHNIQUES

Maintenance management techniques utilized in the development of the Third Set of Locks maintenance program include fault tree analyses (FTA); failure modes, effects, and criticality analyses (FMECA); and application of RCM principles. A system breakdown structure (SBS) was developed to organize each locks complex into systems, subsystems, and components for application of the maintenance management practices. The Third Set of Locks is comprised of eleven (11) major systems and eighteen (18) other systems.

Figure 2 presents an example SBS for lock system structures, one (1) of the eleven (11) major systems.

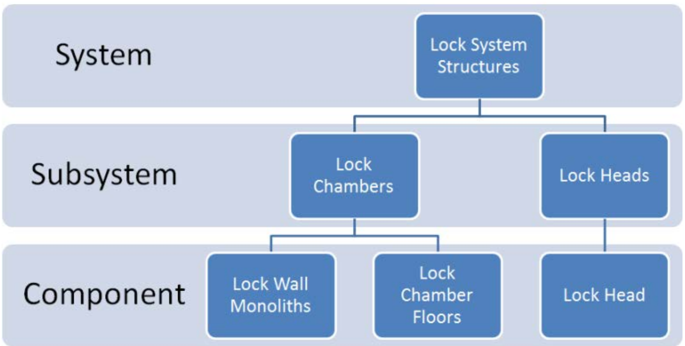

Figure 2: Example SBS for Lock System Structures

4.1 Fault tree analyses

The FTA is a "top-down" evaluation of a system or sub-system that begins with failure or malfunction of the system and ends with identification of root causes contributing to the system failure. Logic gates are used to define the path through the fault tree. Frequently, probability of failure of the system or subsystem will be computed using a fault tree that identifies the probability of occurrence and propagation of a root cause; the sum of probabilities in a FTA describes the probability of failure of the system or sub-system.

During the design process, fault trees are particularly beneficial to identify critical components of a system that may require additional analyses, redundancies, or special monitoring during operation.

A FTA was performed for each subsystem determined by the SBS. A conceptual example of the lock chambers subsystem fault tree is provided in Figure 3.

The top event in this fault tree describes the subsystem failure of "lock unavailable". The top event was determined by the basic function of the subsystem. The function of the lock chambers is to maintain a certain hydraulic geometry such that vessels can transit the canal.

The "or" gate below the top event indicates that the lock could become unavailable as a result of the occurrence of more than one series of events. The "or" gate leads to "geometry change" which is an intermediate event that describes the failure progression. Geometry change can be caused by lack of inspection coupled ("and" gate) with one of the following root causes: accumulation of sediment in the lock chambers; erosion or scour of the chamber floors or walls; differential movement of the lock chamber monoliths; or elevated water in the backfill. The condition-based maintenance program is designed to monitor the system for evidence of the potential root causes and perform early intervention to prevent a worsening that could lead to failure.

4.2 Failure modes, effects, and criticality analyses

The FMECA describes the effects, or indicators, and criticality of the root causes, or failure modes, identified in the FTA.

In the context of civil works, the indicators of a failure mode provide guidance for operations and maintenance (O&M) staff to identify the occurrence of a failure mode which is either in progress or has already occurred.

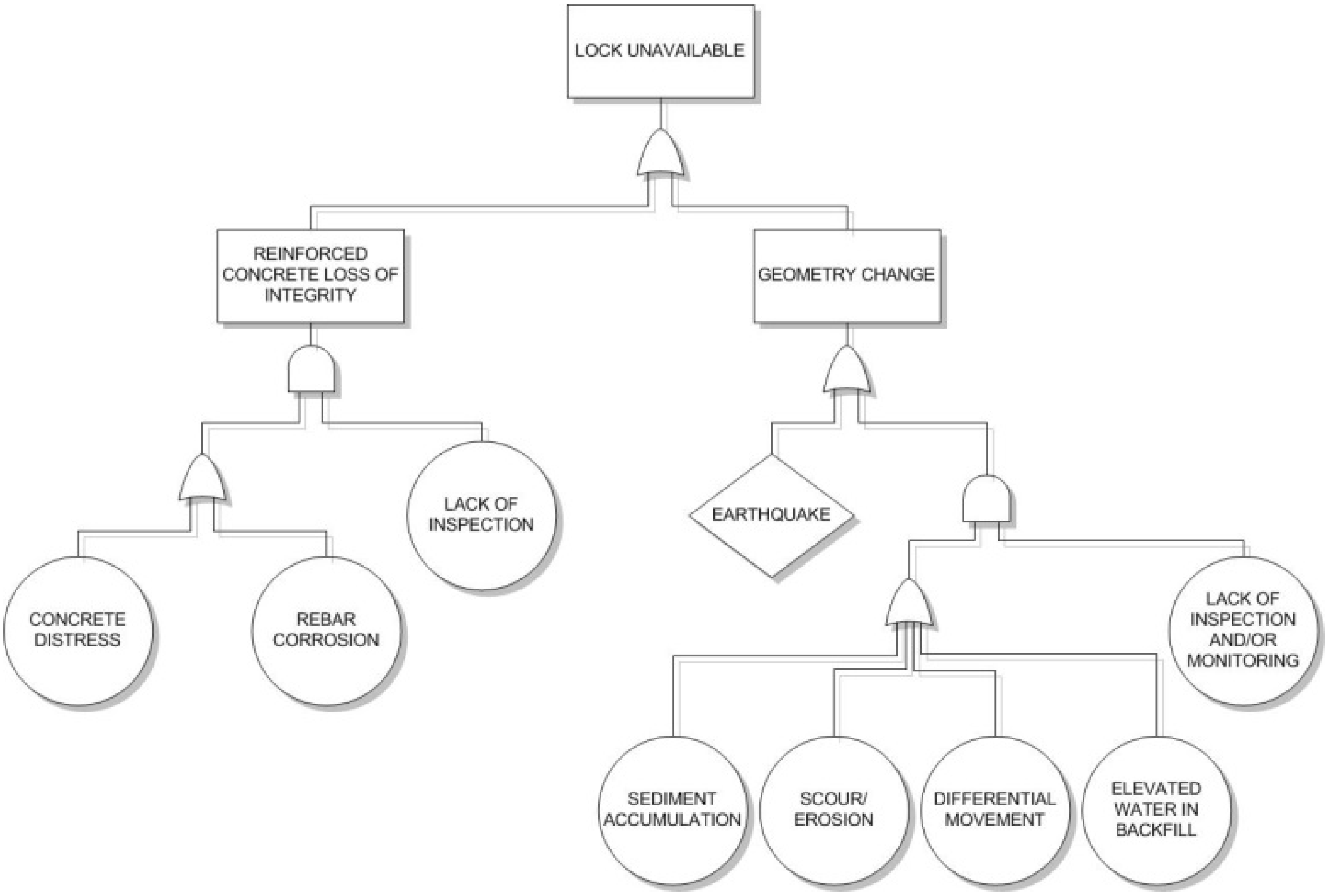

Figure 3: Lock Chambers Conceptual Fault Tree Analysis

Criticality can be defined in many ways, which may vary by project and stakeholder concerns. For the Third Set of Locks, criticality was ranked on a scale of I through IV in accordance with US Department of Defense MIL-STD-882D (2000) guidance which considers injury or death of employees or the public; economic loss; and environmental consequences. A Category I event has catastrophic consequences, while a Category IV event is negligible.

The assignment of criticality ranking varied by system or subsystem. For the lock chambers subsystem, the criticality ranking for each failure mode was assigned on the basis of potential to impact lock operations.

Taking the sediment build-up example event from Figure 3, there are actually two root causes that have to occur in order for the failure mode to propagate; sediment needs to accumulate and inspections fail to occur that would identify the accumulation. The effects identified from the occurrence of the root cause include notable debris or sediment buildup which could also manifest as insufficient draft for vessels. This root cause was assigned a criticality ranking of III, indicating that it is a marginal event with loss exceeding $10K but less than $200K.

Some subsystems will not cause a stop in lock operations therefore, the criteria to assign criticality considered impact at the subsystem level instead of potential to impact lock operations. For example, the Third Set of Locks are designed to function without the Water Saving Basins (WSB), however frequent or extended outages of the basins would be costly in terms of water usage.

Figure 4 is a simplified FTA for the WSB subsystem. It shows that the WSB could be rendered unavailable due to failure of one or more of the basin components: concrete elements; underdrainage system; or earthen berms. In this example, the criticality was assigned based on repair cost, which takes into account likely duration of the outage.

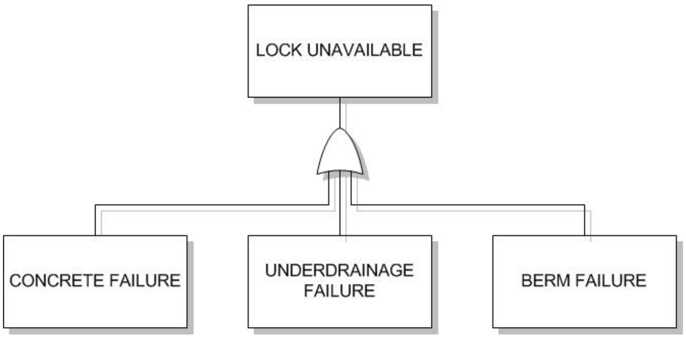

Figure 4: WSB Conceptual Fault Tree Analysis

4.3 Reliability-centered maintenance

The objective of RCM is to optimize the maintenance of an asset. RCM strategies include run to failure maintenance; fixed time maintenance; and condition based maintenance. The effects/indicators and criticality of the failure modes identifed from the FMECA are used to inform the selection of RCM strategy for each asset.

Run to failure maintenance is applicable to those components where early detection of a failure or deterioration is not possible; or failure of the component is not critical to overall system availability. Fixed time maintenance is applicable to those components that have known durations of effectiveness such that regular intervals of maintenance efforts can be scheduled to prevent deterioration or failure of the component. Condition based maintenance relies on inspections to determine the condition of components and requires maintenance efforts to be scheduled as necessary based on the observed condtions.

For both the Lock Chambers and WSB, condition based maintenance is most applicable. In the case of the accumulated sediment example from Figure 3, inspections will be used to evaluate accumulation of sediment. Based on the amount of sediment observed in the regular inspections, maintenance can be scheduled to prevent excessive sediment buildup and minimize interference with lock operations.

5 MAINTENANCE MASTER MANUAL

Maintenance requirements for Third Set of Locks systems and components are grouped into preventive or corrective maintenance programs (manuals) based on the results of the FTA, FMECA, and RCM determination.

Preventive maintenance for the Project's civil components includes inspections, periodic maintenance, predictive maintenance (through monitoring instrumentation), and documentation of the condition of system components. Corrective maintenance typically incorporates necessary maintenance identified through the inspections and monitoring.

Both preventive and corrective maintenance are opportunities for intervention to prevent a root cause from propagating up the fault tree toward a failure mode.

5.1 Preventive maintenance - inspections

Fixed-time inspections are part of the preventive maintenance program and consist of a program of routine and comprehensive inspections.

Routine inspections are performed daily by operations staff as a part of their normal duties. Routine inspections are considered the first-line of defense against potential development of failure modes. The success of the routine inspection program relies on the experience of operations personnel identifying something that looks different or out of place from what they are accustomed to seeing on a daily basis. If something out of the ordinary is noted, the staff member is required to document the observation for follow-up.

Comprehensive inspections are more detailed inspections performed by knowledgeable and trained engineers at standard time intervals.

During a comprehensive inspection for normally visible (i.e. not submerged) features, the inspector uses a checklist to walk through a standard series of observations for each feature. The checklists are constructed so that any positive ("yes") response requires additional comments, description, and follow-up. Additionally, care is taken to particularly observe any previous repairs or positive responses for a feature.

Comprehensive inspections for normally submerged features (e.g. most of the lock chambers) require specialized tools to avoid unwatering the locks. Side-scan sonar is ideally suited since it is a widely available technology that provides visibility of underwater features and can be deployed with only minor planned interruption to lock operations.

5.2 Preventive maintenance - monitoring

Preventive maintenance also includes necessary instrumentation monitoring to evaluate performance of the systems. Instrumentation for the civil works includes piezometers, survey monuments, water level measurement wells, and accelerometers. Certain instruments are connected to an automatic data acquisition system that will record readings at set intervals, while many instruments will require manual readings.

The instruments each have action levels and threshold values established to aid in the interpretation of readings following guidance from Chapter 14 of the US Federal Energy Regulatory Commission's (FERC) Engineering Guidelines for the Evaluation of Hydropower Projects (2005).

A reading that reaches an action level indicates a significant departure from the normal range of readings, and prompts an action. A reading that reaches a threshold value is indicative of the design threshold for the structures; and readings exceeding threshold values have the potential to impact the safety and stability of the structures. The data is evaluated to look for individual exceedance values as well as trends indicative of declining performance.

5.3 Corrective maintenance

Corrective maintenance tasks are contingent on the findings from preventive maintenance inspections and instrumentation monitoring.

In the accumulated sediment example from Figure 3, the appropriate corrective maintenance would be to perform dredging within the lock chambers to remove the accumulated sediment.

As stated above, corrective maintenance is triggered if an action level or a threshold value is reached. In most cases, the corrective maintenance is defined as performing a comprehensive inspection of the feature(s) in question.

6 MAINTENANCE MASTER SCHEDULE

The maintenance master schedule compiles the planned maintenance tasks for each system into a schedule that can be rolled-up to form an overall maintenance schedule for the lock complex. For additional functionality, the schedule could be resource loaded with preventive and corrective maintenance crew and equipment to ensure adequate resource and budget allocations.

Inspection cycles were developed in consideration of the standard of care and quality control employed during construction. Therefore, comprehensive inspections are typically performed annually for easy to inspect or access systems. A longer time between inspections, once every five or more years, is planned for systems that are more difficult to access and have monitoring installed to evaluate the structure performance in the interim.

Monitoring cycles were developed based on previous project experience and in general accordance with the recommendations presented in Chapter 9 of the FERC Engineering Guidelines (1991). The monitoring frequency considers the type of instrument, criticality of measurement, and length of project operations (since certain readings, such as settlements, should decrease over time as

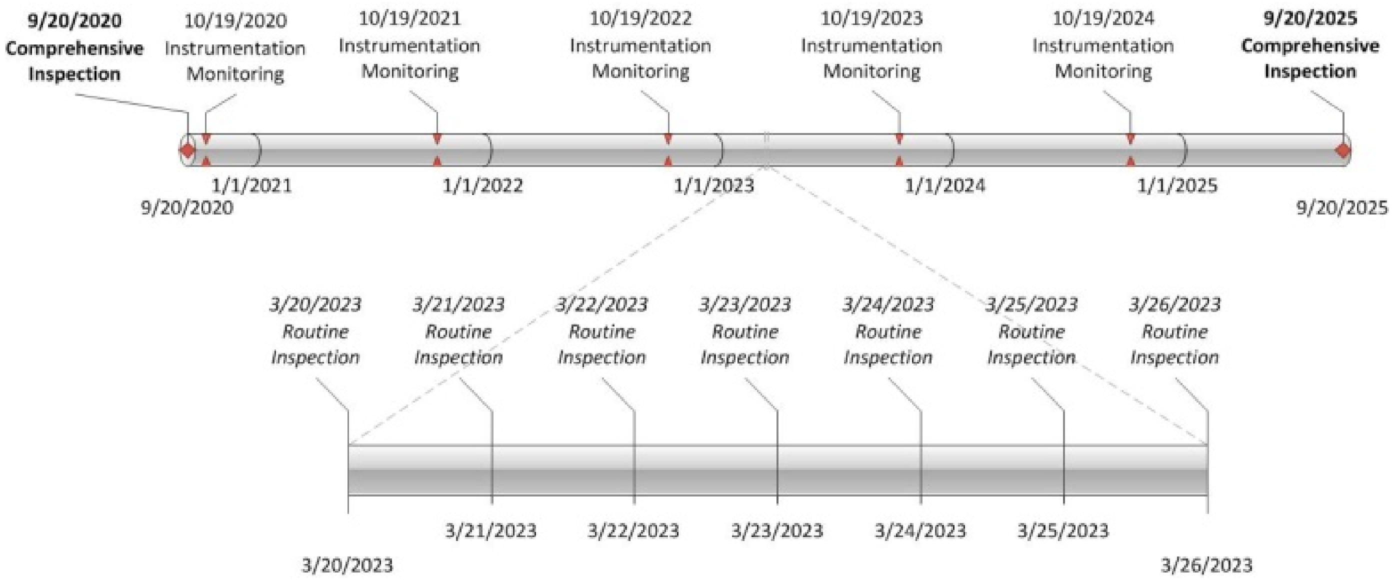

Figure 5: Generalized Timeline for Preventive Maintenance

the structures adjust to the imposed loads).

The schedule also captures the possibility of additional inspections or monitoring that would occur in the event of significant or unusual events (e.g. large earthquake).

Figure 5 presents a generalized schedule for the preventive maintenance tasks described above.

7 PARALLELS TO OTHER TECHNIQUES

The US Army Corps of Engineers (USACE) and US Bureau of Reclamation (USBR) have transitioned to a risk-informed decision-making (RIDM) approach for dam safety. The Best Practices in Dam and Levee Safety Risk Analysis (2012) outlines the agencies' approaches to risk analysis and risk assessment.

The basis of the approach is a potential failure mode analysis (PFMA). The PFMA exercise is a facilitated team exercise use to identify and evaluate potential failure modes (PFMs) for a structure or project. After identification, the PFMs are described from initiation through progression to the point of failure and resulting impacts are summarized. This approach can be outlined in an event tree.

An event tree is a "bottom-up" evaluation of a system. An event tree begins with the failure of a critical component of the system, and traces the necessary propagation path that is required to cause system failure. Probabilities can also be assigned to event trees, with the likelihood of occurrence of each step contributing to the probability of system failure due to failure of a specific system component.

The event tree traces a route similar to that which could be followed from a root cause up to the top event in a fault tree. A possible event tree branch for the sediment accumulation example is presented in Figure 6.

Event trees are particularly useful for evaluating an existing system where knowledge of the system behavior and performance over time can inform the selection and evaluation of credible PFMs. Factors that make the occurrence of an event along the tree more or less likely can be captured in the assigned probabilities.

Potential consequences from full propagation of a failure mode are accounted for in the calculation of project risk. Finally, the calculated risk is compared to the tolerable risk to inform decision making on repair and upgrade decisions.

The overall RIDM approach closely parallels the FMECA and RCM principles. The fundamental goals of the techniques are: to prevent an undesirable consequence through the use of engineering judgment and timely intervention; and to provide appropriate system information to allow educated decision making.

8 APPLICATION TO INLAND WATERWAYS AND NAVIGATION

The goals of reliability, availability, and ease of maintenance are also applicable to inland waterways and navigation projects. Inland projects serve a vital role in marine transport and can benefit from application of the same maintenance management techniques as those employed on the

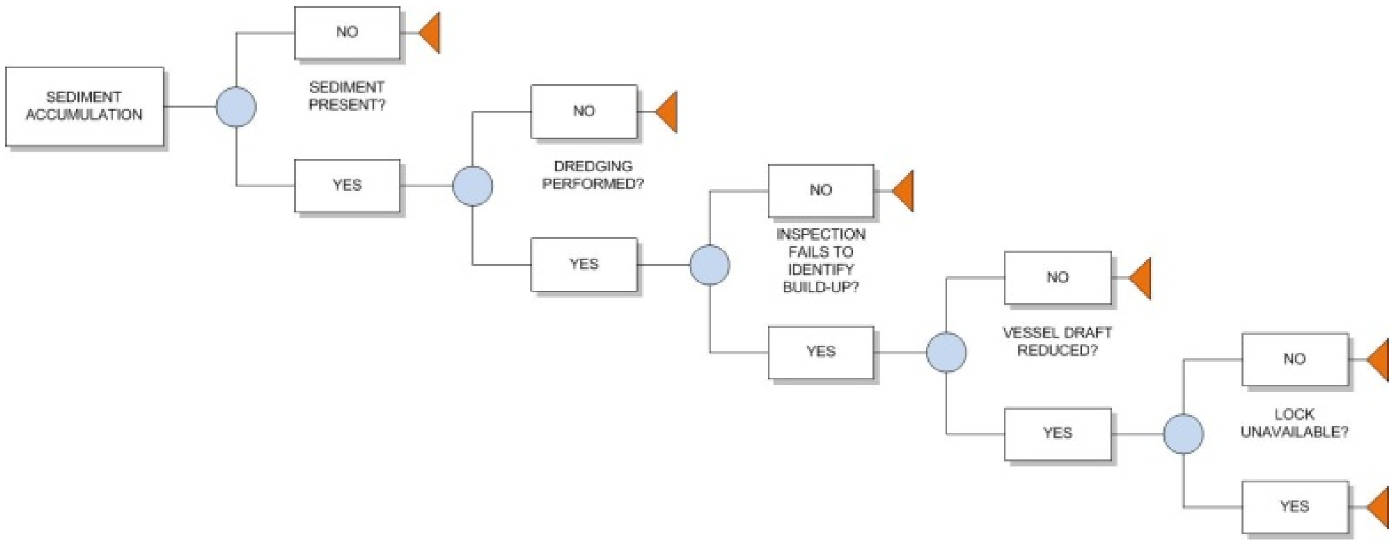

Figure 6: Example Event Tree Branch

Third Set of Locks Project.

Inland projects could be comprised of a single structure or stretch of waterway. On a broader scale, a portfolio of projects along a river could be evaluated to inform maintenance planning for the entire system.

Given the age of many inland navigation projects, root causes of failure might include age-related deteriorations or historical insufficient maintenance. Criticality of the failure of an individual component will be captured in the FMECA and can be used to inform resource allocation.

Application of appropriate preventive and corrective maintenance, coupled with a robust planned maintenance schedule, will increase system reliability, availability, and maintenance efficiency.

9 REFERENCES

FERC (1991). Engineering Guidelines for the Evaluation of Hydropower Projects, Chapter 9 – Instrumentation and Monitoring.

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