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A Need for a Sustainable Asset Management Framework for Hydroelectric Run-of-River Infrastructure

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Abstract: Hydroelectric civil infrastructure is a significant asset domain in Canada. Hydroelectric plant owners need to maintain plant availability and efficiency at their highest level to maximize generation revenue over its long life at minimal costs and risks. Hydroelectric run-of-river plants are expected to have operational lifetimes of about 50 to 100 years with proper maintenance and renewal. The more a plant ages, the higher the risk of failures and the cost of maintenance, repair and rehabilitation. Major asset categories are intake, penstock, powerhouse including turbines and generators, switchyard including transformers, and transmission line. Assessing, maintaining, upgrading or replacing these assets in a sustainable manner is essential for low risk and profitable operation of the plant. This paper provides an overview of asset management in the hydropower industry; emphasis is placed on evaluating asset management frameworks, condition assessment protocols and decision-support tools for hydroelectric infrastructure. The study identifies the extent of asset management culture in the hydropower industry, addresses the need for condition and risk assessment, service life prediction, life-cycle costing and decision-support tools for run-of-river plants, and identifies the challenges for condition monitoring, maintenance, repair and renewal planning faced by run-of-river asset owners and managers. A literature review leading to this paper has traced a limited number of asset management applications, and none provides a comprehensive solution to address the current needs for optimal management of run-of-river infrastructure. As a result, a research programme is undertaken into the development of a risk-based sustainable asset management framework for hydroelectric run-of-river infrastructure.

1. Introduction

This paper describes research to develop a risk-based sustainable asset management framework for hydroelectric infrastructure, primarily Run-Of-River (ROR) projects. The research develops a sustainable framework that leads to advances in understanding how these assets deteriorate and how innovative engineering management can mitigate Canada's challenges with issues of "crumbling infrastructure."

Hydroelectric assets are a significant asset domain. ROR projects are small-scale plants that require no dam or reservoir to generate electricity but use natural flow and river elevation to generate power by diverting part of the river through a large pipe (penstock), possibly kilometres long, to a turbine to generate electricity. Hydroelectric plant owners need to maintain ROR plant availability and efficiency at its highest level to maximize life cycle revenue at minimal risk. Risk includes loss of service and potential damage to the infrastructure and the environment. ROR plants have operational lifetimes of 50 to 100 years, with proper maintenance and renewal: older plants have higher risks of failure and higher costs for maintenance, repair and rehabilitation. Assessing, maintaining, upgrading or replacing these assets "sustainably" is essential for mitigating risk and maintaining profitable operations.

This research concentrates on: (a) life cycle management of major assets – condition assessment and risk analysis, (b) research and development of tools for decision support for operations, repair and replacement, and (c) transferring this acquired knowledge to hydroelectric professionals.

2. Literature Review

There has been considerable and well-documented concern about the current state of Canada's infrastructure (FCM 1996, Mirza and Amleh 2003, Mirza and Haider 2003, Vanier and Rahman 2004, Cowe Falls, Haas and Tighe 2006, Mirza 2006, FCM 2007, Brox 2008, Lounis and Vanier 2008, ASCE 2009, INFC 2009, Mirza 2009, InfraGUIDE 2004). These challenges relate generally to causes or symptoms endemic to all sizes of utilities and at government offices at local, provincial, and national levels.

The total value of civil infrastructure systems in Canada is estimated at over $ 5.5 trillion (Vanier and Rahman 2004): a considerable amount to manage or replace, as the majority is nearing end of service life (Gaudreault and Lemire 2006). Studies show that large government and para governmental organizations (municipalities, utilities, crown corporations, provincial territorial/federal government agencies, etc.) have levels of unfunded deferred maintenance equaling 10% of the value of their infrastructure (Vanier and Rahman 2004). In fact, there is little documentation about the extent of Canada's civil infrastructure or extent of deferred maintenance (Brox 2008), although unvalidated deferred maintenance is tagged at $123 billion (FCM 2009). In any instance, large governmental and para-governmental organizations need to be technically, economically, socially and environmentally sustainable.

A definition of 'sustainability' in the construction industry (Agenda 21 1999) is: *"development that meets the needs of the present without compromising the ability of future generations to meet their own needs."* The question remains for civil infrastructure owners: "are we sustainable?" This question not only relates to "greening", but to a larger, and more important, view of sustainability: Can we sustain our infrastructure? This is fundamentally an engineering and economic challenge. A sustainable organization must have adequate funding, as well as, optimal allocation of funds to: (1) operate and maintain existing infrastructure, (2) replace assets at the end of service life, and (3) accommodate growth -- all while minimizing health and safety concerns and providing the desired level of service.

Given the current situation of aging and deteriorating infrastructure, inadequate levels of funding, changing climate and population demographics, and the need for addressing sustainability, the following challenges are identified in the past for public and private organization (Lounis and Vanier 2008, Lounis et al 2009): they do not know the extent and/or value of their infrastructure assets; they are not aware of the amount of deferred maintenance or renewal needs; there is little knowledge how specific asset classes deteriorate or how quickly; "in situ" service life of asset classes is not known, even to experts; data about these assets are primarily paper-based, and decision support tools are not available to managers or decision makers.

As noted earlier, the hydroelectric industry has recently been adopting the concept of asset management (Berger et al 2011). However, considerable work is still required to produce standards and guidelines to assist practitioners make decisions about the optimal direction for maintenance and replacement at plant and corporate levels. The research literature is leaning toward acceptance of well accepted "generalized" protocols (PAS 55-1 PAS 55-2 2008) and this has been confirmed by asset management expert in British Columbia and North West USA (Dunlop 2011, Rux 2011). Significant challenges still exist in the industry relating to the lack of protocols on condition assessment, risk analysis and decision support.

2.1 Condition Assessment

Literature review suggests that the development of condition assessment tools for hydroelectric assets has not yet been completely successful; that is, evaluation processes require too many tests, inspections, and measurements, and the data is not properly managed, validated or calibrated. It also reveals that many guidelines on condition assessment techniques for critical assets such as penstock are old and out of print (ASCE 1993, HydroAMP 2006, McStraw 2000 2011).

2.2 Risk Analysis

Risk analysis is a significant challenge for the industry. Failures can happen at different stages of an asset's life and its remaining life cannot be accurately predicted deterministically. The reliability models used in the industry are either physics-based (understanding failure mechanisms such as crack propagation, corrosion) or data-based (empirical prediction by counting number and type of components in the system and the stress they undergo, without considering mechanisms of failure). Various reliability analysis tools such as reliability block diagrams for prediction, assessment, and optimization, FMEA/FMECA (failure mode, effects, (and criticality) analysis) for bottom-up (component to system) failure analysis, FTA (Fault Tree Analysis) for top-down (system to component) analysis, and ETA (Event Tree Analysis) are popular in the industry (Rausand and Høyland 2004, ANSI 1987).

2.3 Decision Support

Advanced decision support methodologies, such as results from ETA have been used to judge the acceptability of a system, identify improvement opportunities, make recommendations for improvements, and justify allocation of resources for improvements. Results from FMEA/FMECA are currently being used for system improvements, maintenance task planning, spare parts inventories, and troubleshooting guidelines (USCG 2011). Opportunities also exist with operations research: an interdisciplinary mathematical science that focuses on the effective use of technology by organizations. Employing techniques from other mathematical sciences – such as mathematical modeling, statistical analysis, and mathematical optimization – operations research arrives at optimal or near-optimal solutions to complex decision support problems (Wikipedia 2011).

3. Recent Progress

The proposed research takes an innovative approach and bases its direction on work recently completed by the National Research Council (NRC), and the National Round Table on Sustainable Infrastructure (NRTSI) to develop a *Model Framework for Assessment of the State, Performance and Management of Core Public Infrastructure* (NRC/NRTSI 2009). This work was supplemented by the NRC with research details on the Core Public Infrastructure (CPI) model framework (Lounis et al 2009). In addition, this research is modeled after NRC's Municipal Infrastructure Management Framework (MIIP 2011, Vanier et al 2006 2009), adopted by many Canadian cities for strategic asset management.

The proposed research extends these two initiatives from the domain of civil infrastructure (i.e. primarily municipalities, provinces and federal departments) to the ownership of hydroelectric assets, primarily provincial crown corporations and small ROR plant corporations. More specifically, the research focuses on specific assets (i.e. penstocks). This class of infrastructure was selected owing to its significant asset value, high construction and repair cost, and the dearth of information, condition assessment methods, service life prediction techniques and decision support protocols, as well as to its similarity to conventional municipal infrastructure (water mains).

Detailed investigation of the assessment of penstocks indicates there is some preliminary work in the area of inspection of this type of asset (ASCE 1993 1995 1998), but there are currently no corporate, national or international standards or guidelines on how a methodical assessment of the physical condition of these assets are established (Kwon 2011). It also appears that preliminary work in the area of asset management in the hydroelectric industry (mainly for large hydro projects) is emerging (Benson et al 2011, Hadjerioua et al 2011, Hannaford et al 2010 2011, André and Mailhot 2011).

4. Research Objective and Methodology

The proposed research has the following objectives:

a) Identify and document the state of art (i.e. research), as well as state of practice (i.e. best practices), for the life cycle performance of ROR infrastructure in seven major asset management functions (Vanier et al 2009): (i) inventory identification, (ii) asset valuation, (iii) condition assessment, (iv) service life prediction, (v) life cycle costing, (vi) risk analysis, and (vii) decision support.

b) Advance the state of art, as well as the state of practice, for the life cycle performance of ROR assets through the research and development of quantitative condition/performance and risk indicators, as well as, the research of innovative decision support and optimization techniques using the indicators.

c) Develop software prototypes to capture knowledge gained from research of aforementioned functions that can be used by software vendors and hydroelectric companies as proofs of concept.

d) Transfer the knowledge gained from research discoveries and prototype development to hydroelectric professionals through software distribution, workshops, reports and conference and journal articles.

The following tasks address the four aforementioned objectives and seven asset management functions in an effort to develop a risk-based sustainable asset management framework.

4.1 Identification of the State of Practice

The proposed research determines the current state of practice and state of art for the life cycle performance of ROR infrastructure in the seven major asset management functions:

a) inventory identification – identify prevalent/important asset classes and components for ROR,
b) asset valuation – identify, investigate and compare suitable methods, protocols and techniques to value operational, tactical and strategic costs of ROR projects,
c) condition assessment – identify, investigate, and compare condition assessment protocols for a representative selection of assets, as well as generalized protocols for ROR projects,
d) service life prediction – identify, investigate and compare innovative and leading-edge techniques (best practices) to calculate future condition/performance of a limited number of ROR asset classes,
e) life cycle costing - identify, investigate, and compare life cycle costing in the industry,
f) risk analysis - identify, investigate, and compare risk analysis in the industry, and
g) decision support – investigate, evaluate and compare innovative methods for selecting and prioritizing alternatives for operations, maintenance and replacement in the industry.

This preliminary, comprehensive evaluation will be accomplished through a series of sequential tasks related to: reviewing recent NRC/Infrastructure Canada report (Lounis and Vanier 2008, Lounis et al 2009) and related research in the ROR industry; formulating and distributing questionnaires to hydroelectric professionals relating to current practices; interviews (in person and by phone) of different hydroelectric utilities to determine current state of practice and use of software tools; identifying gaps and opportunities in states of art and practice and existing software tools; identifying opportunities for research and development related to ROR projects; providing synopsis of findings for managing ROR projects, and presenting findings at a national venue (conference or workshop).

4.2 Contribution to State of Knowledge

The proposed research contributes to state of knowledge in each of the seven asset management functions.

4.2.1 Inventory Identification

Firstly, the research analyses accepted data structures and practices for asset inventories for ROR projects. This includes classification of intake structures, penstocks, powerhouse components (turbines, generators, etc.), substations, and associated transmission lines. Secondly, it extends accepted practice and/or develops innovative structures for ROR data. Technical challenges include identification of mandatory data attributes, divergence of data structures across Canada, need for integration between engineering disciplines, and integration with GIS and other enterprise resource planning (ERP) systems.

4.2.2 Asset Valuation

Firstly, the research analyses accepted data structures and practices for setting values on major assets such as large diameter watermain projects and penstock infrastructure. Secondly, it extends accepted practice and develops innovative valuation methods for ROR projects similar to valuation in related industries. Technical challenges include developing robust valuation for both ROR projects and generic assets.

4.2.3 Condition Assessment

A critical aspect of all asset management initiatives is the development of quantitative methods to evaluate asset condition and performance. Existing research work on methods relating to condition assessment of ROR assets is lacking. The scientific challenges are many: need for accurate imaging of pipe distresses, dearth of condition assessment ratings that represent degree and extent of severity distresses, and need for condition rating systems that reflect rehabilitation alternatives. The condition assessment protocols developed in this research is integral to the process used to predict future condition/performance and in reliability and risk analysis. The condition assessment methods developed shall be based on accepted methods and standards where available; otherwise new techniques or applicable methodologies from other industry sectors (such as inspection of water mains, sewer pipes and gas transmission pipelines) are to be adapted and/or adopted. Vibration monitoring techniques for rotating machines are also to be investigated and developed. This research also focuses on high pressure large diameter thin wall buried penstocks that pose a greater and disastrous risk and significant challenges in terms of condition assessment and monitoring compared to other assets. Not only the condition of the penstock itself is assessed and monitored, but also the condition of surrounding soil, ensuring soil restraint against horizontal motion of buried penstock. Penstocks in mountainous terrains, some buried below water crossings or on steep slopes, are prone to natural slope instability, earthquake induced ground movement, rock fall and avalanches. Thus a fitness-for-purpose assessment for penstock integrity, soil restraint, configuration and alignment is required to determine if there is adequate performance. The development of suitable condition assessment protocols is a key to this research.

4.2.4 Service Life Prediction

Research concentrating on methods to assess the service life cycle of major project components such as penstock is another key component of this proposal. For penstocks, this research concentrates on large diameter pipe assessment methods using on visual inspection such as the CSA Guideline on Sewer Defect and Distress Coding (CSA 2009). Techniques such as regression analysis, Markov chain (Newton and Vanier, 2006), fuzzy Markov (Kleiner et al, 2006) and limit states design (LSD) are to be investigated. Opportunities exist currently with LSD techniques, for the first time in this industry, to determine ultimate limit states, serviceability limit states, and load and resistance factors for pipe segments.

4.2.5 Life Cycle Costs

The research proposes to establish protocols to determine the maintenance, repair and replacement costs of ROR projects. These must follow known practices (ASTM 2007), but must be adapted to suit the industry.

4.2.6 Risk Analysis

The research proposes to investigate methods to quantify risk of failure of ROR projects, specifically to determine the probabilities and consequence of failure. This task is also a key component of the proposal and builds on current practices to develop accurate methods to quantify both the probability and consequences of failure (HydroAMP 2006, USCG 2011). Newer approaches in asset management are migrating towards risk-based methodologies to provide greater confidence in operational and capital investment decisions (Lounis et al 2009). Levels of service including health and safety of public and plant staff, financial impact on the plant, investors' confidence, environmental compliance, and system reliability all affect the impact of an ROR's failure and the reliability of the overall system. Risk analysis methodologies that are to be investigated include reliability based optimization, utility based decision support, and uncertainty analysis. Risk analysis processes to be studied include qualitative and quantitative risk assessment (e.g. colour coded fever charts, failure modes and effects/criticality analysis FMEA/FMECAs), risk management (e.g. risk avoidance, reduction, retention or transfer) and risk communication (e.g. through meetings, reviews, and reports). Little work has been completed in this field for any type of civil asset.

4.3 Develop a Framework for Decision Support

This research proposes to synthesize the requirements for decision support for utilities for life cycle performance of ROR projects. In addition, it will develop a framework for hydroelectric utilities for decision support and for software tools.

4.3.1 Decision Support

The research will develop innovative techniques such as stochastic (probabilistic) analysis, benefit-cost analysis, multi-objective decision making, and fuzzy synthetic evaluation for selecting alternatives for operations, maintenance and replacement of major components of ROR projects. The goal of this activity is to research methods to prioritize repair and rehabilitation alternatives using logical, objective and systematic processes. The proposed decision support system (DSS) incorporates advanced operation research optimization methodologies to define a set of optimal investment strategies for optimal operation of the plant based on performance, economic and risk analysis. The proposed DSS will generate a series of investment planning scenarios for consideration by plant owners.

Due to high uncertainty involved in calculating remaining service life of assets and the consequence of failure, stochastic optimization techniques will be investigated to see if they can be applied to determine optimal maintenance, repair and renewal schedule with minimal cost and risks while maximizing generational revenue and considering the budgetary, operational, environmental and market constraints. To ensure sustainable operation of ROR plants, the proposed DSS will perform multi-objective optimization by combining objectives of facility management (maintaining and improving the availability and reliability of generating facilities, reducing or mitigating risks, minimizing costs, and maintaining regulations and safety requirements) and resource planning (maximising revenue, minimizing generation costs, optimize generation, and meeting the needs of stakeholders).

4.4 Validation and Knowledge Transfer

To validate the proposal and prove the benefits on the asset management framework in practice, a practical case study will be performed. The case study will compare current hydroelectric industry practices to those of associated industrial sectors such as municipal infrastructure, as well as to best practices proposed for sustainable and strategic asset management (SSAM-I 2007). To verify and validate the expert systems, strategy described by Lee and O'Keefe (1994) will be considered.

The research proposes to develop prototype software tools to capture findings and offer solutions to practitioners and test prototype tools with a representative number of Canadian organizations. Software prototypes will be developed to embody knowledge from previous activities. Successful and useful software prototypes developed in a previous activity will be tested and evaluated in a work environment in hydroelectric utilities. Software tools will be tested at representative hydroelectric utilities. Third party reviews of prototype implementations will also take place.

Furthermore, the research will recommend life cycle protocols for small, medium and large Canadian organizations. It will also develop protocols for data collection/exchange for ROR projects for large utilities and small hydroelectric companies.

Finally the researched and developed technology for managing ROR projects will be transferred to practitioners through contributions to scientific conferences or journals or through client. The research will also provide a handbook on protocols for data collection/exchange and life cycle ROR performance and user manuals for software prototypes. Lastly, it will develop curriculum material for introductory courses on the management of ROR projects.

5. Conclusion

A literature review leading to this paper has traced a limited number of asset management applications, and none provides a comprehensive solution to address the current needs for optimal management of run-of-river infrastructure. As a result, research will be undertaken into the development of a risk-based sustainable asset management framework for hydroelectric run-of-river infrastructure. The proposed research will develop a sustainable framework that leads to advances in understanding how ROR assets deteriorate and how innovative engineering management can mitigate the challenges faced by the hydroelectric industry. The framework will help manage the asset inventory effectively, improve asset maintenance and operation, maintain safety and reliability, prioritize budget needs and manage risk based on condition and risk of failure of assets, and optimize investment.

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